



## Case Report Water Engineering at Precolumbian AD 600–1100 Tiwanaku's Urban Center (Bolivia)

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Abstract: The pre-Columbian World Heritage site of Tiwanaku (AD 600–1100) located in highland altiplano Bolivia is shown to have a unique urban water supply system with many advanced hydraulic and hydrological features. By use of Computational Fluid Dynamics (CFD) modeling of the city water system, new revelations as to the complexity of the water system are brought forward. The water system consists of a perimeter drainage channel surrounding the ceremonial center of the city. A network of surface canals and subterranean channels connected to the perimeter drainage channel are supplied by multiple canals from a rainfall collection reservoir. The perimeter drainage channel provides rapid draining of rainy season rainfall runoff together with aquifer drainage of intercepted rainfall; water collected in the perimeter drainage channel is then directed to the Tiwanaku River then on to Lake Titicaca. During the dry season aquifer drainage continues into the perimeter drainage channel; additional water is directed into the drainage channel from a recently discovered, reservoir connected M channel. Two subterranean channels beneath the ceremonial center were supplied by M channel water delivered into the perimeter drainage channel that served to remove waste from the ceremonial center structures conveyed to the nearby Tiwanaku River. From control of the water supply to/from the perimeter drainage channel during wet and dry seasonal changes, stabilization of the deep groundwater level was achieved—this resulted in the stabilization of monumental ceremonial structure's foundations, a continuous water supply to inner city agricultural zones, water pools for urban use and health benefits for the city population through moisture level reduction in city ceremonial and secular urban housing structures.

**Keywords:** pre-Columbian; urban Tiwanaku; Bolivia; hydraulic/hydrological analysis; surface canals; CFD; perimeter drainage channel; moat; subterranean channels; societal structure

## 1. Introduction

Archaeological studies of ancient pre-Columbian Peru and Bolivia have not thus far brought forward the technical engineering achievements at major archaeological sites in those countries.

To address this missing element of Andean archaeology, the new field of PaleoHydrology is intended to bring forward new perspectives on what ancient New and Old-World water engineers accomplished together with the scientific base they used for their hydraulic engineering works. While many urban and agricultural water delivery and transport structures of the ancient world are well known from the archaeological literature, the engineering methodologies and theoretical basis used by ancient water engineers in their design and operation of complex water systems await discovery. Surviving literature from ancient authors on water engineering methodologies reveals the absence of hydraulic engineering principles and parameters vital to any water conveyance design—yet recent analysis using modern hydraulic engineering methodologies to analyze ancient water conveyance structures reveals use of versions of modern water engineering principles—albeit in indigenous formats yet to be discovered. By use of Computational Fluid Dynamics (CFD) methodologies and modern hydraulic engineering principles, ancient water structures of South America, the ancient Mediterranean, and dynastic Asian societies can now be modeled and analyzed to extract ancient versions of the water technologies used in their design. From investigations of this nature, the civil engineering base used by these societies can be brought forward together with the knowledge base used to support their water system designs. Use of CFD methodology involves the numerical solution of the Navier-Stokes mass, momentum and energy conservation equations governing water flow. A CFD model (shown as Figure 1a) of the Tiwanaku urban center showing the network of surface and subterranean canals and channels, the sub-ground surface aquifer and surface drainage channels shows the components of the complete water supply and distribution system of the Tiwanaku urban center. Since these networked water transfer features interact with each other to transfer surface and groundwater in different ways during the rainy and dry seasons, the water flow transfers through these interacting features is computed using CFD methodology to show the water engineering put into practice by Tiwanaku water engineers' design and construction of their urban water system. The investigation to follow then provides insight into the engineering technology that underlies the water control system at the Tiwanaku urban center.

The present paper is intended to bring forward in detail the water engineering used at the AD 600–1100 pre-Columbian World Heritage site of Tiwanaku located on the high (~4000 m) altiplano of Bolivia; this site demonstrated an advanced use of hydrologic and hydraulic science for urban and agricultural applications that is unique in the Andean world. From recently discovered aerial photos taken of the site in the 1930s prior to excavations that began in the early 1980s, new perspectives of the water system of the city that extend previous interpretations of the dividing moat between ceremonial and secular parts of the city is possible based upon a network of water channels not previously known but now displayed from the early aerial photographs surrounding the ceremonial structures of urban Tiwanaku. The perimeter drainage channel served as the linchpin of an intricate network of reservoir and spring supplied surface canals and subterranean water channels that served many hydraulic and hydrological functions. These functions include: (1) collect and drain rainy season rainfall runoff and aquifer seepage from infiltrated rainwater into the nearby Tiwanaku River to limit flood damage; (2) accelerate post-rainy season ground drying by collecting aquifer seepage from infiltrated rainwater into the perimeter drainage channel and transfer collected water to the nearby Tiwanaku River to lessen ground moisture to promote health benefits for the city's population; (3) provide water from a newly discovered M channel to two subterranean channels under ceremonial core structures to flush human waste to the nearby Tiwanaku River; (4) maintain the groundwater level constant throughout rainy and dry seasons to stabilize foundation soils underneath massive pyramid structures to limit structural deformation; (5) facilitate rainy season water accumulation drainage from the floor of the Semisubterranean Temple into the groundwater layer to rapidly dry the temple floor; and (6) provide drainage water to inner city agricultural zones. The water control network in urban Tiwanaku is analyzed by CFD modeling of transient surface and groundwater aquifer flows to illustrate the function of the perimeter drainage channel in both rainy and dry seasons as well as its role in the (1) to (6) functions.



(a)



(**b**)







**Figure 1.** (a) Representative FLOW-3D Computational Fluid Dynamics (CFD) model of hydrological and architectural features of the Tiwanaku ceremonial center. The CFD model is a best-estimate representation of the site geometry scaled from aerial photos, historical sources and ground survey. Line a–b represents a later drainage path interpretation compared to earlier curved versions by Poznansky 1945 and Bandelier 1911 used for the model. The A'-B' channel represents the Tiwanaku River. (b) Schematic of several main ceremonial sites within the perimeter drainage channel; P and Q represent subterranean drainage channels under the Putuni's palace floor. The perimeter drainage channel surrounds this area (Figure 1a). (c) Excavated P subterranean channel section located below the Putini floor- note scale from Figure1. (d) Two top-slab excavated canals below floor level at La Karaña leading water to subterranean channels P and Q. (e) Slab-covered channel originating from the top platform of the Akapana and running at high slope down the side of the Akapana pyramid to drain the room complex located on the top platform.

### 2. Overview of the Hydrological Regime of Tiwanaku

The pre-Columbian AD 300–1100 city of Tiwanaku located in the high altiplano (~4000 m.a.s.l) region of Bolivia demonstrated use of advanced hydraulic/hydrologic principles to maintain city drainage during the long rainy season through a complex network of surface and subterranean channels coupled into a main perimeter drainage channel. The urban water control system was designed to regulate seasonal deep groundwater levels constantly by regulating rainfall runoff and aquifer drainage into the perimeter drainage channel during the rainy season and by providing supplemental water supplied from a reservoir to surface canals connected to the perimeter drainage channel to maintain constant groundwater level during the dry season. This was accomplished by the perimeter

drainage channel bottom designed to intersect the seasonally maintained deep water table top surface so that excess drainage water arriving into the perimeter drainage channel bottom during the rainy season was not infiltrated into the saturated perimeter drainage channel bottom surface but rather drained away to the Tiwanaku River. In the dry season, additional water supplied from a reservoir supplied M channel plus continued aquifer seepage to the perimeter drainage channel maintained a constant deep groundwater height. Excess water entering the saturated bottom perimeter drainage channel was delivered to the Tiwanaku River by a separate channel. Constant groundwater height maintained by the presence of the perimeter drainage channel through seasonal rainfall changes promoted many hydraulic/hydrological engineering functions. These include year-round surface dryness in urban Tiwanaku through continuous aquifer drainage into the perimeter drainage channel that promoted health benefits to city inhabitants together with maintaining constant monument foundation soil strength properties to limit monument settling distortion. The spring and reservoir supplied canal network coupled to the perimeter drainage channel together with dual subterranean channels under the ceremonial center bounded by the encircling perimeter drainage channel provided comprehensive hydraulic system design and demonstrated complex hydrologic engineering not seen at any other pre-Columbian South American site. The city's ceremonial center, composed of monumental architecture and elite residential compounds circumscribed by the perimeter drainage channel, is shown in Figures 1b, 2 and 3 with W-D-V-X describing the perimeter drainage channel. Figures 2 and 3 are derived from aerial photographs taken in the 1930s prior to excavations started in the early 1980s; Figure 4 is derived from Google photographs. Figure 1a is a CFD model representing the Tiwanaku urban water system based upon early explorer diagrams of the site features, CFD model dimensions approximate the scale of the site features as determined from aerial photographs and site exploration measurements.



**Figure 2.** Aerial photograph view of the inland perimeter drainage channel (denoted above as the Moat) surrounding the ceremonial core of Tiwanaku indicating the intersecting Mollo Kontu M canal, qocha regions and the Tiwanaku River to the north.

Previous researchers interpreted a main purpose of the encircling perimeter drainage channel as a boundary 'moat' separating sacred and secular urban areas of the city [1,2]; the perimeter drainage channel additionally served as a vital part of a complex network of supply and drainage channels together with aquifer drainage to promote rapid post-rainy season soil dry-out with health benefits to city inhabitants. Excess water collecting into the perimeter drainage channel from aquifer drainage,

rainy season runoff and flow to and from surface and subterranean canals then rapidly exited through a connecting canal to the Tiwanaku River connection to Lake Titicaca thus forming an integrated hydraulic/hydrological network designed to perform the (1) to (6) functions listed above.



**Figure 3.** Details of the (red) intersection path of the Mollo Kontu M channel with the southern arm of the perimeter drainage channel. Note that excess perimeter drainage channel water is drained to the Tiwanaku River through channel C and the floodplain agricultural (green) area C'. The Akapana East Channel shown supplies water to qocha agricultural and (green) pasturage areas to the southwest and served to drain excessive water to the perimeter drainage channel to maintain required moisture levels for agriculture and pasturage.



## MOLLO KONTU (M) CANAL A-B



Shown in Figures 2 and 3 are the 1930s aerial photographs of the main ceremonial center enclosed by the perimeter drainage channel; Figure 4 is a recent Google aerial photograph of the same area.

Of major interest is the trace of a canal not previously noted in research studies—the Mollo Kontu channel (Figures 1a and 2, Figures 3 and 4) is now designated the M channel. The M channel segment shown in Figures 2–4 aerial photographs is supplied through a stone-lined transfer channel constructed through a marsh region supplied from springs and reservoirs located at the base of the Corocoro Mountain range to the south of the ceremonial center. The newly discovered M channel adds the missing link to the design function of the urban water system conceived, designed and implemented by Tiwanaku hydraulic engineers. With the discovery of this canal and its function, the ingenious water supply and distribution system of urban Tiwanaku, new insights about the water engineering knowledge base of a pre-Columbian society are revealed for the first time in report sections to follow. Figure 5 indicates the presence of one (P) of the two subterranean canals (P and Q) whose location is given in Figure 1a,b. This discovery adds a third dimension to the intricate water supply and distribution network not previously known. The totality of this water network's design and use and the water engineering involved is described in sections to follow.



Figure 5. Photo and plan view of the excavated portion of the subterranean channel P.

Figure 5 is illustrative of one of the dual subterranean water channels located under structures within the ceremonial center bounded by the perimeter drainage channel. These subterranean channels are designated the P and Q channels with their positions illustrated in Figure 1a,b. Given the preliminary details of the ceremonial area and its encircling perimeter drainage channel, the network of surface canals and subterranean channels connected to the perimeter drainage channel is illustrated in the Figure 1a model together with detail of ceremonial structures within the perimeter drainage channel shown in Figure 1b. The FLOW-3D CFD model consists of several million grid cells necessary to preserve accuracy for both surface water and internal aquifer water flows. Canal and channel water flows are characterized by a k- $\varepsilon$  turbulence model; aquifer flow physical properties are given in a

subsequent section. Transient calculations initiate from initial conditions on water flow rates at canal origin locations and initial aquifer fluid fraction (ff) saturation values within the phreatic evaporation layer surface and groundwater layers. Figures 6–10 represent sample CFD calculation results of transient aquifer and ground surface fluid fraction levels occurring during water transfer processes and illustrate aspects of the urban water system in operation. Boundary conditions are estimated canal flow rates at canal origin locations on the computational grid boundaries.

During the dry season, continued aquifer seepage from rainy season infiltrated rainwater and flow from the M channel recharged the groundwater to maintain and stabilize its height through seasonal changes. During the rainy season, excess runoff and aquifer seepage water was directed into the perimeter drainage channel. With the depth of the perimeter drainage channel set at approximately the height of the stabilized groundwater profile, the saturated perimeter drainage channel bed limited further internal seepage past the perimeter drainage channel bottom and thus transferred arrival water to dispersal areas by the C channel to the Tiwanaku River and the C' farming area (Figure 1a). Water directed to the Tiwanaku River by transfer from the perimeter drainage channel then flowed directly into Lake Titicaca. Figure 1b illustrates the major sites within the perimeter drainage channel boundary shown in Figure 1a; although two subterranean channels P and Q are known through excavation, more subterranean channels likely exist as several surface channels with major structures have slopes that lead water away from P and Q drainage exits.

Figure 1d illustrates two canals below the floor of the La Karaña complex (Figure 1a) that extend to and drain into channels P and Q. The extension of additional perimeter drainage channels surrounding three sides of the base of the Akapana are as yet unexcavated but must have a channel path either on the ground surface or a subterranean channel (or both) connection to the perimeter drainage channel. Of interest is a large highly sloped channel that runs from the top platform of the Akapana down the pyramid's side to the pyramid's base; the slab-covered top platform part of this channel is shown in Figure 1e.

In summary, one additional effect of the stabilized groundwater level through rainy and dry seasons was to maintain the bearing strength of soil under large monuments within the ceremonial center to limit structural distortions [3]. Water accumulating in the perimeter drainage channel from aquifer drainage and channeled spring water flow provided flow through dual subterranean channels P and Q (Figure 1a,b) to flush human waste delivered into the subterranean channels from elite compound structures to maintain hygienic conditions in the compounds. Figure 1c illustrates a section of the P canal below the Putini floor.

The multi-faceted hydrological aspects of the perimeter drainage channel served city environmental and hygienic conditions through rapid soil drying in city housing areas while promoting structural stability for the site's many monuments as well as aiding in rainy season drainage from the Semisubterranean Temple floor (F, Figure 1a,b). While groundwater control mastery is apparent in the urban setting, additional research on Tiwanaku raised-field agriculture [4–20] indicates similar advances in use of groundwater control technology in urban settings.

To demonstrate the seasonal interaction of surface and aquifer water flows more fully, the porous media aquifer CFD model (Figure 1a) is utilized in later discussions using CFD analysis to demonstrate the perimeter drainage channel's role as a hydrological control element vital to the city's sustainability during wet and dry seasons.

### 3. Settlement History

The ancient city of Tiwanaku, capital of a vast South American empire, has been the subject of research starting from early 20th century scholars that continues to the present day [21–30]. The city, located at the southern edge of the Lake Titicaca Basin in the south-central portion of the South American Andes at an altiplano altitude of ~4000 m.a.s.l. incorporated an elite area bounded by an encompassing perimeter drainage channel that enclosed temple complexes, palace architecture and the seven-stepped monumental Akapana pyramid (Figure 1b) designed to serve ceremonial sacrifice

functions and provide rooms on the top surface for special ceremonies. Recent excavation of one of the top rooms indicated a large collection of llama bones used in ceremonial functions. Outside of the center lay a vast domain of secular urban housing structures. An intricate network of canals acting in conjunction with the perimeter drainage channel performed hydrological functions that included rapid ground drainage during both wet and dry seasons to promote health advantages for the city's 20,000 to 40,000 inhabitants as well as flood defense to preserve the ritual center and surrounding urban structures. The management of water systems within the city demonstrates hydrologic engineering expertise consistent with that found in Tiwanaku's raised field agriculture and demonstrates Tiwanaku hydrologic engineering mastery. The 1930s aerial photographs provide data to interpret the extent of, and insight into, the hydrologic function of the perimeter drainage channel. The early photographs reveal traces of the perimeter drainage channel's north and south arms in addition to the Mollo Kontu M channel as well as traces of the support structures within the ceremonial center (Figures 1a and 2, Figures 3 and 4). Additional channels intersecting the southern part of the perimeter drainage channel southern arm are indicated in Figure 1a. The perimeter drainage channel collected flow from adjacent channels and canals, rainfall runoff and infiltrated rainfall seepage from the saturated, near-surface phreatic layer of the aquifer as well as from the deep groundwater aquifer as the perimeter drainage channel depth intersected to top portion of the deep groundwater layer to transfer water into the nearby Tiwanaku River during the rainy season to prevent deep groundwater recharge. During the dry season, continued phreatic aquifer seepage into the perimeter drainage channel plus water from the intersecting M channel maintained the deep groundwater aquifer level relatively constant while surface evaporation and recession of the near-surface phreatic aquifer served to rapidly dry the ground surface promoting health and livability benefits for city inhabitants. The design intent of the builders of the perimeter drainage channel thus envisioned control of the deep groundwater level through wet and dry seasons to maintain the physical integrity of monumental structures by preventing the dry-out settling of the deep aquifer soils underlying the main ceremonial core as water continually occupied aquifer pore spaces. Given a stable upper boundary of the deep groundwater layer throughout the year, physical strength properties of foundation soils were maintained thus limiting structural distortion and settling of the massive platforms of the Kalasasaya and Akapana pyramid (R, Figure 1a,b) within the ceremonial center. Additionally, with the stable groundwater layer well below the floor of the Semisubterranean Temple (F, Figure 1a), rainy season drainage from the site floor into the aquifer region above the deep groundwater level was facilitated. This excess water then percolated toward the perimeter drainage channel's sidewalls for delivery to the Tiwanaku River. Thus, beyond the perimeter drainage channel's role in creating a ritual and social boundary between the elite residence ceremonial center and secular residential city districts, its engineering design contributed many practical benefits to living conditions for city residents throughout wet and dry seasons.

### 4. Tiwanaku Hydraulic Analysis

To demonstrate the perimeter drainage channel's hydrologic functions, multiple data assemblages used to construct a CFD hydraulic/hydrological model (Figure 1a) include results of archaeological mapping and excavation [31–33], Google Earth imagery and the aerial photos taken over the site of Tiwanaku. These aerial photos reveal the site decades before modern urbanization and monument reconstruction began and were taken at a time of year when many features held water thus providing a clear view of Tiwanaku's hydrological features. From these 90-year-old photographs, the outline of the perimeter drainage channel is shown in Figure 2 as the dark encircling boundary to the ceremonial center. The curvature of the drainage canal V-D-W-X shown in Figure 1a is derived from earlier observations of the channel made before years of erosion and soil deposition infilling that continues to the present day Previous explorers of decades past listed in [13,14,17,18] provided the foundation for current studies of the perimeter drainage channel.

The east drainage canal arm (denoted 'Moat' in the east arm in Figure 2) averages 5 to 6 m deep and ranges 18 to 28 m in top width. Subterranean canals originating from the perimeter drainage channel's

south arm were drainage conduits for Tiwanaku's monumental and elite residential structures [2,34–38]. Since the south arm of the perimeter drainage channel is shallower in depth than the north arm as determined by ground contour measurements, a fraction of the water that accumulated in this arm flowed down-slope through the perimeter drainage channel's east and west arms toward the Tiwanaku River while a portion of accumulated water in the south arm flowed into the dual subterranean P and Q channels (Figures 1a and 5) underlying the ceremonial center. Given the two-degree declination slope of the subterranean channels, water accumulating in the perimeter drainage channel's bottom during the wet and dry seasons provided flush water cleaning for the Putuni palace's waste removal/drainage facilities (Figure 1b). North of Tiwanaku's monumental center, the shallow alluvial plain drops sharply downward toward the Tiwanaku River's marshy floodplain. One portion of the east arm of the canal turns west and disappears into the floodplain (C', Figure 2) while canal C continues north toward the Tiwanaku River. One portion of the west perimeter drainage channel arm led into the marsh north of the Kalasasaya Platform (Figures 1a and 3) while an ancillary arm continued northeast toward the river. The north portion of the perimeter drainage channel divided into several branch canals that intersected the floodplain and drained accumulated water from the north arm of the perimeter drainage channel. Water not directly shunted to the Tiwanaku River through canal C (Figures 1a and 5) drained water in the floodplain's aquifer into the Tiwanaku River. The floodplain area served as a nearby productive agricultural area for the urban center.

### 5. The Perimeter Drainage Channel in the Urban Hydrological Network

Where the groundwater surface emerged from depressed land areas, springs formed. Several canals in the southern portion of Tiwanaku were engineered to utilize the canal's water input. The westernmost Choquepacha area's canal [36] is derived from a natural spring on a bluff southwest of the Pumapunku complex (Figure 1b). The spring was fitted with a reservoir basin that included several incised stones carved to convey water. Combined with the output of an adjacent stream that drained the marshy area, the Choquepacha area supported extensive terrain amenable to pastoral grazing and farming immediately to the west of the Tiwanaku urban area. Other features relate directly to the hydrological function of the perimeter drainage channel. The first feature is the north-south Mollo Kontu region M canal that supplied water from springs and reservoirs originating from the southwest portion of the site near the Pumapunku complex into the southwest portion of the perimeter drainage channel (Figure 1(S-M), Figure 2(M), Figure 3(M) and Figure 4(M)). The second feature is an interlinked cluster of sunken basins (qochas) that occupied the southeast portion of the site (Figures 1a and 2). Qochas are pits excavated into the aquifer layer that capture and store rainwater and serve to expand planting surfaces and pasturage while creating micro-lacustrine environments that attract waterfowl [37]. Figure 2 depicts a series of canals dendritically linking the qochas to one another with a branch connecting to the Akapana East canal (L, Figure 1a) that drained into the east arm of the perimeter drainage channel. The third major feature is a long, narrow, outer canal (J) on the east side of Tiwanaku (Figures 1a, 2 and 3). While the role of this canal is unclear, its southern portion is straight and follows an alignment that mirrors that of the Pumapunku complex to the west; its northern portion shifts course and bounds the east edge of the site. The east canal (L, Figure 1a) links with the perimeter drainage channel (Figure 1a (W-D-V-X)), Figure 2) by connector canal I and indicates that the outer canal was part of an encompassing urban hydraulic network. The areas immediately east of the perimeter drainage channel contain Tiwanaku's residential sectors that include Ch'ijiJawira, a barrio of ceramic producers that depended on a constant water supply [39]. Immediately east of the Ch'ijiJawira sector is a low brackish marsh; from this marsh, the outer canal (J) provided fresh water from springs for Tiwanaku's easternmost residential sectors and drainage of excessive canal flow during the rainy season.

The east and west arms of the perimeter drainage channel directed water around the monumental complex area toward the Tiwanaku River to the north (Figure 1A'-B' and Figure 2). The C' floodplain was an integral part of Tiwanaku's larger hydraulic network that served to facilitate drainage of both

groundwater seeping from the perimeter drainage channel arm D-V (Figure 1a) and rainwater runoff during rainy season peaks. Intricate surface canals and dual subterranean stone-slab constructed canals (Figure 1a,c,d and Figure 5) provided additional drainage and water transfer within the elite compound area bounded by the perimeter drainage channel. The elaboration of surface canals on the interior floor of the Semisubterranean Temple (F, Figure 1a) and areas outside the Kalasasaya (G, Figure 1a) indicate a drainage connection to either (or both) the perimeter drainage channel and the subterranean channel P (Figure 1a,b); additional drainage by seepage into the stabilized low groundwater layer below the temple floor helped to keep the temple floor dry throughout the rainy season. The Akapana pyramid (R, Figure 1a,b) incorporated an intricate, stone-lined canal that routed water from the uppermost level down through successively lower platforms and finally out through several portals in its basal terrace (Figure 1e). Water delivered to several open surface basins draining into vertical pipes (and/or surface channels leading to the perimeter drainage channel) conveyed water into the subterranean channels (Figure 1c,d) then into the perimeter drainage channel arm V, Figure 1a. Subterranean channel P (Figure 1a,b and Figure 5) provided flushing water to remove human waste from the Putini residential compound bounded by the perimeter drainage channel for conveyance to the Tiwanaku River. Water was temporarily pooled in the sunken courtyards near platform monuments rendering them lakes for ritual events and reservoirs for controlled water distribution.

Excavations between Putuni and Kerikala complexes (Figure 1b) indicated structures within the ceremonial core region that articulated with Tiwanaku's subterranean drainage network. This area housed high status groups until, at approximately AD 800, the construction of the Putuni palace repurposed the space to support recurring state-sponsored ceremonies [40–43]. Located~2.5 m below the current ground surface, subterranean channel P (Figures 1 and 5) consisted of sandstone slab masonry with vertical side slabs approximately 1. 0 m high and horizontal slabs about 0.8–0.9 m in width. Several vertical pipes consisting of multiple stacked, perforated stone disks conducted surface water from features within the Putini into the lower subterranean channel P (Figures 1a and 5). Water from the perimeter drainage channel's southern arm V supplemented by water from canals L and M (Figure 1a) together with seepage water from both phreatic and top portions of the deep aquifer was used to flush waste water through subterranean channels P, Q located in the west portion of the monumental core.

### 6. Water Management at Tiwanaku

To demonstrate insights related to the hydrological function of the perimeter drainage channel, use of CFD is made for cases that address seasonal variability in water input. Here the equations were numerically solved by finite difference methods [44] governing aquifer percolation [45,46] to show transient water transfer within the aquifer for two seasonal water availability cases. Case 1 considers effects existing at the termination of a rainy season on Tiwanaku's canal systems and city open surface areas. The rainy season in the south-central Andean altiplano generally runs from November through March. Case 2 considers effects of limited water input from springs and aquifer seepage into the deep groundwater layer during the April through October dry season. Data from aerial photographs, Google Earth imagery, contour maps and ground survey provided the basis for the CFD computational model (Figure 1a) to demonstrate hydrological features of the perimeter drainage channel and its encompassing hydrological network. A porous soil model of the subsurface aquifer is used to demonstrate hydrological responses of the canal network and perimeter drainage channel for the two cases. The Figure 1a CFD model surface and subterranean features are on the same scale as Figures 2–4 and represent best estimate water supply and distribution network canal paths inferred from photographic and ground survey data. The canal inlets shown (J, N, O Figure 1a) are sourced by canalized Corocoro springs and reservoirs located south of the modeled area as are canals (S-M) leading from the Pumapunku area. Key monument architectural and hydrologic features are:

A'–B': the Tiwanaku River, flow direction A' to B' C: perimeter drainage channel to A'-B' Tiwanaku River C': floodplain drainage and agricultural complex supplied from the perimeter drainage channel V: arm

E: La Karaña residential complex

F: Semisubterranean Temple

G: Kalasasaya Platform

H: Putuni Palace

I: Connecting channel between canals L-K-L and J

K: multiple interconnected qocha region supplied by canal N arm D

L: Akapana East canal, which drained qocha region K toward perimeter drainage channel

M: Mollo Kontu canal linking supply canals O and S to perimeter drainage channel arm W

N: Supply canal to qocha region K

O: Connecting canal to canal M

P and Q: subterranean channel pair with declination slope of two degrees to the Tiwanaku River; channels P and Q run underneath the Putuni Palace H (Figure 1b)

R: Akapana seven-stepped truncated pyramid

S: branch canal to Mollo Kontu canal M

T: lateral transverse canal to L; shunt canal I to canal J and/or canal drainage to the perimeter drainage channel U: Mollo Kontu monument

Z: the Kalasasaya compound—a connection to the perimeter drainage channel indicated in Figures 1a and 6–10.

W-D-V-X: the perimeter drainage channel circuit around the monumental core of Tiwanaku; original depth of the channel estimated at~5–6 m at location D.

Y: drainage canal from V to the Tiwanaku River (from the 1930's aerial photographic source); its inclusion in the model has a minor drainage effect compared to drainage features C, C' P, Q originating from the perimeter drainage channel's Z canal below the west side of the Akapana (R, Figure 1a) draining toward drainage canal segment D. (Figure 1a).

The CFD model is composed of a porous medium aquifer duplicating soil material properties (porosity, permeability) found at the site through which aquifer water percolates. The CFD model incorporates both the east-to-west ground slope declination and a south-to-north declination observed from field measurements. The momentum resistance to flow in the porous medium representation of an aquifer [46] is expressed as a vector drag term  $F_d$  u where  $F_d$  is the porous media drag coefficient and u the velocity vector  $\mathbf{u} = q_x \mathbf{i} + q_y \mathbf{j} + q_z \mathbf{k}$  with  $q_x$ ,  $q_y$ ,  $q_z$  velocity components in the i, j, k (x, y, z) coordinate directions (Figure 1a). The permeability k is defined ask =  $V_f \mu / \rho F_d$  where  $V_f$  is the volume fraction (open volume between soil particles/total volume),  $\mu$  is the water viscosity and  $\rho$  the water density. For the present analysis, k is on the order of  $\sim 10^{-11}$  cm<sup>2</sup> based upon the site soil type [43] within the model area excepting elite monumental paved areas for which k is on the order of  $\sim 10^{-5}$  cm<sup>2</sup>. For model area soils,  $0.43 < V_f < 0.54$ . Based on these estimates, the average drag coefficient  $F_d$  is estimated to be ~0.80. While deviations from this value occur due to varying soil properties with depth and location, flow delivery rates from the saturated part of the aquifer to the perimeter drainage channel's seepage surface (defined as the exposed interior wall soil surface of the perimeter drainage channel exposed to the atmosphere) will be affected but calculations will nevertheless demonstrate qualitative conclusions regarding the perimeter drainage channel's function. In the CFD model, the deep groundwater layer is composed of saturated soil and is stabilized throughout the year at ~5 to 6 m below the ground surface as well probe data indicate. The saturated phreatic aquifer layer is assumed to lie above the deep groundwater surface for Case 1 calculations indicative of an intense, long duration rainfall period. The bottom depth of the perimeter drainage channel intersects the upper portion of the deep groundwater layer in the Figure 1a CFD model and the capillary fringe zone and saturated phreatic top surface water layers provide seepage water into the perimeter drainage channel together with runoff water and canal water supplied by springs and reservoirs south of the city (Figure 1a). For a less intense

rainfall period, a capillary fringe zone extends upward from the deep groundwater zone to intersect the bottom reaches of a surface saturated phreatic layer; the contact region size depends upon the amount of intercepted rainfall. Thus, deep aquifer recharge can occur when the surface phreatic layer extends sufficiently downward to penetrate the groundwater capillary fringe zone during long duration rainy periods. For minimal rainfall, surface phreatic layer is considered a small depth evaporation zone that vanishes in depth as the dry season continues. Again, when seasonal rainfall is intense and of long duration, the phreatic and deep groundwater layers merge; for this case, aquifer seepage into the saturated perimeter drainage channel bottom cannot occur and excess drainage water is rapidly shunted to the nearby Tiwanaku River. This effect limits the height excursion of the deep groundwater layer to the base depth of the perimeter drainage channel.

For Case 1 analysis, the post-rainy season phreatic layer is saturated and lies above the saturated deep groundwater layer; as no further infiltrated rainwater can be absorbed into the deep saturated groundwater layer's bottom surface, water accumulation occurs by aquifer seepage from the perimeter drainage channel walls. The aquifer drainage flow into the perimeter drainage channel then flows out to the Tiwanaku River through channel C and seepage to the C' farming area. As the dry season progresses, surface evaporation shrinks the phreatic layer upward toward the ground surface and soil drying occurs to a depth enhanced by aquifer drainage. In 1000–1400 AD times of extended drought, the phreatic top layer and ultimately the deep groundwater layer contracted leading to soil dry-out conditions to a large depth. This climate condition is the basis for the extended drought reason for collapse of Tiwanaku's raised-field agricultural systems in the AD 1000–1100 time period (Figure 17) that ultimately led to Tiwanaku's demise [47–50].

### 7. Case 1—Post-Rainy Season Ground Saturation Conditions

Case 1 examines post-rainfall conditions typical of the end of the altiplano rainy season characterized by phreatic zone saturation and continuous water flow through canals O, S, N, M and J from Corocoro springs and reservoirs (Figure 1a). Aquifer seepage to the bottom of the perimeter drainage channel from the saturated phreatic layer is transferred to perimeter drainage channel arms D, V and W to X-Y and then to the Tiwanaku River (A'-B', Figure 1a) and ultimately to Lake Titicaca as all canals and channels have a down-slope toward the river. Additional seepage occurs from the top reaches of the deep groundwater layer into the perimeter drainage channel. Water from the perimeter drainage channel's east and west arms then led to the Tiwanaku River through the C canal branch and seepage from to C' area. Water arriving into inlet N (Figure 1a) was conducted by canals K and L into either (or both) canals D and then from I to J. A summary of rainy season water inflows/outflows from a representative section of the perimeter drainage channel is shown in Figure 11 and indicates seepage from the top surface saturated aquifer region together with runoff from the saturated soil surface collecting at the saturated drainage canal bottom then transferring down-slope to the Tiwanaku River (A'-B' in Figure 1a). For dry season conditions (subsequently discussed in a later section), Figure 12 summarizes continued seepage flows from the vadose near-surface aquifer region and input flows channeled from the Corocoro spring/reservoir region by the M channel deposited on to the saturated perimeter drainage channel bottom then directed down-slope to the Tiwanaku River. For both cases, additional drainage from the eastern branch of the perimeter drainage channel is provided by subterranean channels P and Q (Figure 1a) directly to the Tiwanaku River.

In figures to follow, the (red) fluid fraction ff = 1 indicates aquifer saturation; ff = 0 indicates no water content to dry aquifer soil; intermediate ff values indicate intermediate levels of water content in aquifer soils. Numerical solutions of equations governing saturated aquifer and surface/subterranean canal flows give a picture of transient water transfers to and from the perimeter drainage channel from aquifer seepage and canal flows given estimates of flow rates based on supply flow rates in canals. Given Case 1's post-rainy season conditions, surface runoff has been largely collected into the perimeter drainage channel and transferred to the Tiwanaku River; further water transfer to the bottom of the perimeter drainage channel is from aquifer seepage and adjacent canal M water flow

input—a fraction of this water supply goes into subterranean channels P and Q with accumulated water in the perimeter discharge channel's V arm discharged into the Tiwanaku River. Figures 6 and 7 show a time progression of water seepage from the perimeter drainage channel's open surface area and progressive surface drying as the phreatic layer deflects downward due to drainage into the perimeter drainage channel.



**Figure 6.** Post rainy season fluid fraction detail from FLOW-3D calculations of the east arm of the perimeter drainage channel showing the perimeter drainage channel's surface walls conducting seepage water to the saturated bottom of the perimeter drainage channel and the start of progressive surface drying for Case 1 conditions.



**Figure 7.** Later time fluid fraction surface drying achieved by aquifer seepage and surface evaporation at the end of the rainy season; note that channel M continues to provide water flow to subterranean P and Q channels and the perimeter channel bottom. Note low values of fluid fraction starting eastward on the drying ground surface for Case 1 conditions as the dry season initiates.

Rapid water removal from the perimeter drainage channel via channels C and C' to the Tiwanaku River (Figure 1a) limited water transfer from the phreatic aquifer to the deep groundwater layer causing deep groundwater level stabilization. The Akapana monumental internal core experienced limited rainfall infiltration due to extensive terrace and side wall paving and compound roofing that ultimately promoted runoff into the perimeter drainage channel aided by the exterior Akapana sloped channel (Figure 1e) originating from the Akapana top surface. Water that managed to infiltrate between paved areas of the Akapana then drained into the interior of the Akapana where it reemerged from base openings to join drainage canal and subterranean channel extensions P and Q (Figures 1a, 5 and 8) that directed water to the Tiwanaku River through C' drainage and C, channels. As the perimeter drainage channel depth extended to the top fringe of the deep groundwater layer, water drainage in the rainy period and water addition during the dry period helped to stabilize the deep groundwater level through season changes.



**Figure 8.** Case 1 fluid fraction results at P-Q depth from the ground surface; water input from channel M to subterranean channels P and Q flush wastewater from the Putuni Palace complex to drainage canal arm V then on to the Tiwanaku River A'-B' and Lake Titicaca. Z indicates a water channel connection from the Kalasasaya Platform to the perimeter drainage channel.

The location of the Semisubterranean Temple floor (F, Figure 1a) above the stabilized deep groundwater level and its nearness to the perimeter drainage channel helped to promote a dry floor through seasonal changes. Rainfall accumulating on the temple floor infiltrated into the phreatic layer then drained to the nearby perimeter drainage channel and groundwater layer. Fluid fraction results at the inner face of the perimeter drainage channel bounding the ceremonial center confirm runoff and aquifer seepage was minimal from what little infiltrated rainwater existed in this largely paved and roofed elite area. What little infiltrated water was conducted to the saturated perimeter drainage channel's bottom and quickly removed by canals C and field area C' aquifer water transfer to the Tiwanaku River. From the paved elite areas, rainy season rainfall runoff constituted a major water contribution to the perimeter drainage channel. Figure 8 shows the water transport in subterranean channels P and Q in the dry season (Case 2). Channel P lies below the floor of the Putuni palace; channel Q lies at the same depth as P but ~10 m west of P. Vertical pipes connected drainage areas in the Putuni courtyard and palace to canal P with collected water directed toward the V arm of the perimeter drainage channel (Figure 1a–c). The P and Q subterranean channels required a constant input of flowing water from canal M and aquifer seepage water into the perimeter drainage channel arm W to maintain dry elite residential area hygienic conditions. As the P, Q channels, the C canal, the C' area and the perimeter drainage channel bottom all sloped downhill toward the Tiwanaku River, water flow from the perimeter drainage channel arm W directed water and waste solids into the Tiwanaku River.

### 8. Case 2—Dry Season Initiation

Case 2 considers the perimeter drainage channel function under dry season initiation conditions (zero rainfall and continuous, but limited, water supply from Corocoro springs and reservoirs into

surface canals N, O, S and M as well as regions K and C'. Figure 9 indicates that water supply from the M canal plus aquifer seepage continues to supply subterranean P and Q channels to flush human waste from the Putuni Palace compound structures during dry season initiation. Figure 10 shows the situation during the late part of the dry season—only limited aquifer seepage and water from the M canal constitutes the near total water supply into the perimeter drainage channel.



# fraction of fluid

**Figure 9.** Dry season (Case 2) fluid fraction results on a plane below the ground surface; moisture levels in qocha region K and depressed area C' indicate sustainable pasturage and agriculture due to contact with the deep-water table and discharge from the V arm of the perimeter drainage channel. Water input from canal M delivers water to the perimeter drainage channel that enters subterranean channels P and Q.



**Figure 10.** Late dry season (Case 2) fluid fraction results for the east arm of the perimeter drainage channel indicating dry season decreased seepage water into the perimeter drainage channel and extensive surface drying.

The C' and K regions (Figure 1a) remained functional due to their depth penetration into the receding phreatic zone water level indicating agriculture and pasturage were possible during the dry season. By transfer of seepage water and M channel water, the deep-water table remained stabilized throughout the dry season. Figure 10 indicates the situation well into the dry season with dry ground conditions and aquifer seepage from the perimeter drainage channel walls minimal; the ground surface is dry (fluid fraction approaches zero) and the W arm of the perimeter drainage channel indicates water supply mainly from the M channel. Figure 12 summarizes the water transfer mechanisms associated with dry season operation. Subterranean channels P and Q have continued water transport and flushing activity from perimeter drainage channel segment W as the dry season progresses with the M channel providing water supply during the dry season.

### 9. Newly Discovered Features of the Perimeter Drainage Channel

During the construction of the platform base of the Akapana pyramid, the phreatic aquifer layer was compressed by the heavy construction base's rock and gravel fill within stone compartments. As a result of the compression, water was expelled from the pyramid base aquifer into the nearby perimeter drainage channel. As additional heavy platforms were added (seven total) and the structure weight increased, further consolidation and compression of the aquifer below the pyramid resulted in reduction in aquifer porosity. While some rainfall infiltration into the increasingly consolidated foundation base soil occurred, less water was available due to low foundation soil porosity and increased aquifer drainage into the nearby perimeter drainage channel. As platforms were added and the compressive structural weight increased, a consolidated foundation impervious to water infiltration was created ensuring further minimal structural deflection and distortion. It is likely that Tiwanaku city planners included the creation of the perimeter drainage channel contemporary with construction of heavy ceremonial core region structures to promote monument stability. The Akapana to this day still retains its structural integrity without settling distortion as a testament to this original planning.

### 10. Rainy and Dry Season Groundwater Profiles

Figure 8 shows a constant depth transect through location D (Figure 1a) that indicates a fluid fraction of unity (ff = 1) consistent with ground saturation during the rainy season. As the rainy season concluded, seepage from the perimeter drainage channel side walls from adjacent saturated soil areas accelerated ground surface drying. Figure 11 summarizes all water supply and drainage paths relevant to maintain the deep groundwater level constant during the rainy season; Figure 12 summarizes all water supply and drainage paths during the dry season. Figures 11 and 12 summarize drainage and water supply conditions necessary for deep groundwater level stabilization during seasonal rainfall change. Figure 13 indicates a y plane transect through the Figure 1a CFD model—under heavy rainfall conditions, the aquifer is completely saturated down to the deep groundwater level as indicated by the fluid fraction ff = 1 as the CFD calculation verifies. With the onset of the dry season, the surface aquifer region contracts due to seepage into perimeter drainage channel together with surface evaporation while the deep aquifer level remains constant.

Additional water arrives into the Tiwanaku urban area by percolation from infiltrated rainfall into areas far to the east of the site. Given the slow percolation rate of water through an aquifer, intercepted rainfall originating from past decades arriving to the site from distant sources is a further contribution to groundwater level maintenance although the rate of water delivery is not constant due to the randomness of post year climate events that influence rainfall rates and amounts of water infiltrated into groundwater. Under severe long-term drought conditions in the 10–11 century AD time period, the Titicaca Lake level dropped severely [43,44] affecting the lowering of the groundwater level close to the lake edge; this effect then reduces the water level in raised-field swales and severely contracts agricultural production [45–48].



**Figure 11.** Summary fluid fraction diagram on water input/output flows on a typical perimeter drainage channel section near Figure 1a, and represent typical flow conditions near the end of the rainy season.



**Figure 12.** Dry season (Case 2) fluid fraction results for the monumental center with decreased water supply from spring-supplied canals; rainfall infiltration and seepage limited by large paved and roofed areas of the ceremonial center.



**Figure 13.** Constant y transect through the D drainage channel (Figure 1a) of groundwater profile for rainy season ground saturation conditions. The ff = 1 fluid fraction condition indicates layer aquifer saturation and bottom saturation of the perimeter drainage channel bed proceeding from design depth of the perimeter drainage channel.

The perimeter drainage channel bottom (e) depth is designed to intersect the top of the seasonally stabilized groundwater layer. In a severe rainy season, infiltrated water penetration may extend to the depth of the deep groundwater layer; in a normal rainy season, ground saturation extends the depth of the near-surface evaporation layer. For normal rainy season conditions, water infiltration drainage and surface runoff into the perimeter drainage channel proceeds to drain the evaporation layer; for normal dry season conditions, limited evaporation layer drainage continues but now Corocoro spring and reservoir water channeled into the perimeter drainage channel is added to maintain the deep groundwater level. Note that in the rainy season, Corocoro spring water continues to flow into the perimeter drainage channel but the excess beyond that to maintain the deep groundwater height is shunted into both the subterranean channels P and Q and the perimeter drainage channel to discharge into the Tiwanaku River. Figure 12 indicates that the role of water input from M channel prevents further recession of the deep groundwater layer as the dry season progresses. Thus, the intersection of the perimeter drainage channel bottom with the deep groundwater layer provides groundwater stabilization that underlies the conclusions of the prior sections. Although a case has been made for large monument foundation stability and its relation to the perimeter drainage channel, this result may have been fortuitous as knowledge of aquifer dynamics under compressive forces known to Tiwanaku engineers is as yet subjective with the present case the only known example to draw from.

### 11. Hydrologic Applications Exterior to City Precincts: Further Examples of Tiwanaku

### Mastery of Groundwater Science

Research conducted on Tiwanaku's raised-field agricultural systems in the Pampa Koani region and water systems under Tiwanaku influence on the northwest regions of Lake Titicaca have indicated use of advanced hydrological methodology underlying crop sustainability and yield improvement [51–53]. Raised-fields are described as trenches dug to penetrate the water table by about 1.0 m with excavated soil piled up to form planting surface berms. Typical aerial views of berm geometry and placement are shown in Figures 14 and 15. Among the advances in agricultural science is the use of solar heat transfer technology to limit crop destruction by freezing during cold altiplano nights [4] as well as hydrological

and hydraulic control mechanisms providing groundwater height control to stabilize raised-field swale water height through seasonal changes in water availability. Additionally, raised-field technology has been shown to be the most efficient design choice to limit short term drought effects on crop yield—this is due to continual groundwater supply from intercepted rainfall over vast eastern collection areas continually flowing toward the Lake Titicaca basin. Further analysis [54] demonstrates that Tiwanaku raised-field berm design is optimum to yield the maximum agricultural output per unit land area. Analysis of groundwater control mechanisms in the Pajiri agricultural area [52] reveals different berm heights and swale water depths appropriate to different crop types. These observations coupled with management of different nutrient chemical compositions of swale water from different springs and river sources necessary for maximum growth of different crop types point to an advanced agricultural science used by Tiwanaku water engineers to maximize and sustain crop yields in the Tiwanaku heartland.

# TARACO RIDGED FIELDS



Figure 14. Tarraco raised-field aerial view.



Figure 15. Lakaya sector raised-field geometry in the Pampa Koani system.

In the Pampa Koani and northwest Tarraco regions of Lake Titicaca, different patterns of raised-field lengths, widths, orientations and berm heights are frequently inserted within more regular patterns (Figures 14 and 15) with each pattern is appropriate for the water needs of different crop types [49]. Excavation of raised-field berms in the Pampa Koani area indicated stone base lining and clay layers to limit cold capillary water transfer from deep groundwater regions into berm interior regions; capillary water transfer to the berm interior region is mainly provided from swale water.

Due to higher swale water temperature from solar radiation input [4] the additional storage heat to berm interior regions limits berm outer surface convection and radiation heat withdrawal during cold altiplano nights to prevent freezing damage to crop root systems. The latent heat removal for water to ice transition within berm interiors during cold altiplano nights is limited by additional heat transfer from elevated temperature swale water heat transfer into berm interiors Examination of early Tarraco raised-field berm patterns [54] in northernmost regions of Lake Titicaca and raised-fields in the Pampa Koani region north of urban Tiwanaku reveals an average berm shape consistency. Figures 14 and 15 show that swales are interconnected leading to a continuous water path surrounding berms. When a typical berm is described as an elongated ellipse with major axis a and minor axis b, then the a/b ratio from 10 to 15 appears to characterize the average of berm geometries. This ratio for an elongated ellipse (a >> b) is significant in that the ellipse perimeter is a maximum for the given berm surface area  $(\pi a b)$  for this class of ellipse. This indicates that the average berm pattern configuration yields the maximum wetted berm perimeter [54] and thus requires a minimum of interconnected swale widths to provide capillary water transfer to narrow berms. Thus, the berms can be placed closer together to maximize agricultural surface per unit field area. Here the narrow berms provide an easy path for elevated temperature capillary water to reach berm interiors. This, in turn, reduces the exposed water surface area of the interconnected swales reducing evaporation loss that helps to locally maintain a constant groundwater profile to maintain swale water height. The net effect is that a greater number of closely spaced berms can be watered properly per unit field area to maintain the crop freezing defense while the greater area under cultivation produces more agricultural yield per unit field area. These advantages are a key indicator of an advanced agricultural science being employed to protect and increase the yields of raised-field agricultural systems. Thus, the a/b ratio of individual berms contains important information related to Tiwanaku water engineering practice as their design incorporates a level of optimization to limit swale water area to reduce evaporation losses and maximize the farming area per unit field area. Further analysis results [54] show that a/b ratios from 10 to 15 are an optimum berm design to yield the maximum wetted boundary perimeter for berms.

The conclusion that applies for the Tarraco raised-field geometry also applies in the Pampa Koani region as Figures 14 and 15 indicate similar use of a technology to maximize agricultural land area per unit field area. Although regional differences exist in raised-field designs at different locations built at different times and the Tarraco system design reflects different groundwater water availability, ambient air temperatures and crop types than those for the Tiwanaku Pampa Koani raised-field design, both systems reflect knowledge of berm designs to maximize agricultural production per unit field area.

### 12. Retrospectives on Tiwanaku Societal Structure

Ceramics and other objects in Tiwanaku style are widely distributed throughout the south-central Andes from the southern coastal valleys of Peru and Chile to the lowland eastern slopes of the Andes. The distribution of Tiwanaku cultural artifacts exhibit stylistic variations with different types and quantities of Tiwanaku style materials occurring in different regions. The governance principles operational in the Tiwanaku polity that led to the distribution of cultural material provides insight about the social structure of the Tiwanaku polity and their expansionist policies. Current theories related to Tiwanaku territorial and agricultural expansion are broadly summarized as:

(1) The distribution of high-status cultural artifacts results from Tiwanaku imperial expansion outside the Titicaca Basin with colonies and conquest aimed at lowland, highland and tropical base resource extraction.

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- (2) The widespread distribution of cultural materials results from the growth of an archipelago system where discontinuous territorial and ecological niches were exploited through placed colonies.
- (3) Tiwanaku style materials spread spatially through trading networks headed by the Tiwanaku administrative polity.
- (4) Tiwanaku expansion was ideological and/or ritual in nature devoid of political control from the central government of Tiwanaku. Tiwanaku expansion occurred as a combination of these paths and is characterized by a cultural rather than military expansion policy.

From the analysis thus far detailed and its relevance to the characteristics of Tiwanaku expansion policy, the increase and diversity of agricultural resources available to the Tiwanaku urban center, it is apparent that technical transfer of Tiwanaku water technologies to outlying areas and societies provided an additional economic and social inducement to associate with the central Tiwanaku polity. For the Tiwanaku urban center, agricultural systems incorporated groundwater-based raised-fields, rainfall supplied terraces, spring and groundwater-supplied raised-field areas, qochas and urban canal-supplied agricultural basins (K, Figure 1a). For sites distant from the Tiwanaku heartland that exploited different ecological conditions for farming, typical agricultural systems incorporated lowland valleys with river supplied canal irrigation systems, channeled spring-supplied agricultural fields and a variety of field systems located at different altitudes with different soil, water supply and temperature conditions that permitted a different range of crop types not possible to cultivate at the high altiplano elevation of urban Tiwanaku. Individual satellite sites required mastery of different hydrological regimes for irrigation. From the analysis of Tiwanaku urban and raised-field hydraulic/hydrological knowledge aspects of this technical base were likely exported to remote sites to maximize food production to economically justify the effort to maintain extensive trade and food import supply networks. The presence of cultural artifacts at many Tiwanaku colonies and subject areas verifies that association with central Tiwanaku had occurred based upon mutual economic benefits for all concerned. As some site areas were already occupied by different societies, some cooperative and others not accommodating an intrusion from a dominant competing society for use of limited water and land resources, the existing agricultural technology at distant areas outside of direct influence from the Tiwanaku urban core may not have initially generated sufficient surplus to interest incorporation into the Tiwanaku archipelago. However, by incorporation of advanced agrotechnical knowledge from urban Tiwanaku's hydraulic/hydrology experts, the agricultural output could be increased to justify mutually beneficial import/export status and cooperation between independent societies and the Tiwanaku core administrative region. Thus, the establishment and economic success of satellite archipelago sites appears influenced from a central authority based in the Tiwanaku urban center that included advice and council of technical experts versed in hydraulic and hydrological matters. This observation is best stated [55] as the challenge of new technologies: "... certain individuals were probably empowered by technological or knowledge status and decisions made regarding the adoption, invention and use of certain technologies must have been made by technocratic and expert-centered individuals..." Thus, technical knowledge was a valuable export item. While trade in sumptuary goods to outlying societies was prevalent in the Tiwanaku sphere of influence and served to expand Tiwanaku influence and cultural traits into outlying areas, the exportation of agricultural knowledge had value to outlying societies that promoted economic benefits of association with the Tiwanaku urban core. While export of ally groups and technical experts from the Tiwanaku urban core experienced in agricultural production was manifest, the conversion to full agricultural potential of new resource-rich areas, given the different ecological conditions and challenges than those existing in the Tiwanaku urban core altiplano heartland, required indigenous creativity and invention in hydraulic and hydrological science. Given the sophistication of the urban Tiwanaku water system thus far described, it is clear that engineering creativity was a major focus of the Tiwanaku administration. In this respect, the many surface and subterranean canals that were found associated with the urban Tiwanaku perimeter drainage channel as well as water control canals in the outlying Pampa Koani raised-field heartland contain a comprehensive technology base that would be of vital use in the Tiwanaku-influenced

Moquegua Valley canal irrigated areas of Omo and Chen Chen. While some researchers claim that that individual farming communities could invent optimum agricultural field systems in a bottom-up manner without the need of a central controlling administration overview group, they underestimate the technical complexity involved in surface and groundwater control related to agricultural production over vast raised-field areas together with city water control engineering. Thus, a central planning (top-down) administration able to collect and invent farming methodologies and urban water control systems for use in areas under its direct control and manage the labor force for implementation of complex water technologies was vital to the expansion, development and integration of satellite areas to the Tiwanaku Empire.

The subterranean channels P and Q (Figure 1a,b) are examples of advanced technology applied to this end. The ~25,000 hectares of Pampa Koani raised-fields required expertise in local groundwater height control by means of a canal supply and drainage network operational over vast areas to provide tailored agricultural berm moisture levels and different berm geometries for different crop types. The agricultural system at the outlying site of Pajchiri is a prime example of water control mechanisms of this type developed for specialty crops. Thus, extrapolating from the bottom-up agricultural success at the local level by small independent ally kin groups exploiting small farming areas to what is required to reliably support food supply for an urban Tiwanaku population of 20,000-40,000 through seasonal variations in groundwater and swale water level water, the management structure must logically incorporate a top-down overview structure [56] capable of assigning and relocating local and satellite agricultural zones to maintain a constant city food supply throughout seasonal weather changes. Despite this capability in agricultural technology, during the last stages of the 10–11th century drought, the groundwater level coupled with declining lake levels [5] forced abandonment of near lake edge raised-field agriculture as groundwater levels declined below swale bottom levels. This caused agriculture to move to the outer fringes of Pampa Koani, as noted by [54], where the water table remained high in swales far from Lake Titicaca due to incoming intercepted groundwater from distant sources and earlier rainfall events. This drop in agricultural output from major field system areas then led to city population dispersal to sustainable farming zones by different segments of the city population and the ultimate decline of the Tiwanaku Empire.

Summarizing, an overview of vast agricultural land and water management to ensure successful agricultural yields required knowledge of optimum berm designs and groundwater height control only possible from a top-down overview perspective of land, water and labor management for vast areas under their control. While other sites had value for imports of non-agricultural resources, sites with the potential for optimization of agricultural resources could be improved by optimization technologies for raised-fields and other agricultural methodologies at coastal valley sites to improve the economic basis for agricultural imports. Clearly optimization of river/spring source irrigation, raised-field agriculture and control of urban water supplies for hygienic advantage to the city population demonstrated that exported Tiwanaku oversight to apply engineering methodology to optimize food production and city living benefits would of advantage for candidate sites to associate with the Tiwanaku hierarchy and share the mutual benefits of association. It would be expected that this oversight activity was applied to rate potential archipelago satellite sites for incorporation given that the economic burden of long-distance transport of perishable goods to urban Tiwanaku. Within the Tiwanaku governmental structure were religious rites, rituals and ceremonies elaborated with elaborate ceremonial, royal and administrative architecture to provide the religious accompaniment to the worldly success of their agroscience, both locally and distant from the urban core of Tiwanaku. Thus, aspects of all the above (1) to (4) categories provided the basis and rationale for Tiwanaku expansion from its heartland—this was only made technically and economically possible with the underlying centrally planned agrotechnical base provided by a top-down corporate management structure at urban Tiwanaku. Thus, the Tiwanaku corporate structure provided the success basis for satellite trade networks in agricultural goods together with the export of cultural traits and artifacts from the urban center of Tiwanaku to cement cultural ties back to the homeland source as observed from the archaeological record. A further argument for a

top-down Tiwanaku management structure can be posited on an economic advantage basis. From similitude analysis methods [54] a mathematical model of two competing ally groups is considered: the first arrival group (1) sets up localized, near lake raised-field agriculture supplied with a local spring-fed canal system; the second group (2) arriving at a later time sets up available outlying raised-field system with long canal lengths to irrigate their distant fields. The first group clearly has an economic advantage due to better water access (shorter canals) requiring less labor to tend to the agricultural land. Analysis [54] shows a computable economic advantage for both (1) and (2) groups to combine land and water resources by use of a newly designed canal irrigation network that more effectively irrigates both land areas and reduces labor input from both groups to maintain the combined agricultural land area while raising the agricultural output of the combined land area. The advantages to both groups to combine their resources under collective management that demonstrates economic advantages to both groups serves to promote top-down oversight of the combined raised-field area to the advantage of all participating ally groups through a governing organization that provides direction and oversight on project activity. Here the formalism of the similitude methodology [54] permits a calculation of the increase in food production through collective top-down management oversight compared to the bottom-up system of disconnected groups managing localized field plots.

While certain researchers suggest less centralization and more local autonomy in the Tiwanaku core region as opposed to other archaeologist's vision of a highly centralized state-directed agrarian production, the present discussion demonstrates that the agricultural engineering base together with knowledge of urban Tiwanaku water control design and operation essentially defines the success of the Tiwanaku society. Thus, massive public reclamation and construction projects requiring a large and coordinated labor force supported by an advanced technology base much in the same way that modern progressive societies function appears to verify top-down management directing complex high technology projects. As to the demise of Tiwanaku colonies located in the Moquegua Valley, collapse dates are consistent with, or follow somewhat, the final collapse dates of Tiwanaku urban complexes. As detailed by Sharatt et al. [57], evidence of Moquegua colonies persisted into Ilo-Tumilaca-Cabuza coastal phases and highland Tumilaca Phases l past~1000 AD, indicating in many cases the extension of some of the Tiwanaku city traditions and stylistic practices in textile and ceramic designs. As the slow development of altiplano drought initiates in the 10th century AD, the rainfall runoff-based canal agriculture of Moquegua Valley colonies invariably responded to rainfall runoff decrease in vulnerable valley rivers challenging the continuity of their irrigation agricultural field systems. This leads to ultimate population contraction of Moquegua societies. The establishment of Moquegua Valley Estuquiña highland valley society at higher altitudes with higher rainfall levels is a natural survival consequence compared to valley societies dependent on river-sourced agriculture. As groundwater decline for the altiplano Tiwanaku is a slow process due to recharge from distant infiltrated rainwater sources continually flowing through the aquifer toward Lake Titicaca, slow groundwater level decline permits longer continuation of raised-field agriculture in outlying regions of the Pampa Koani area well past that of rainfall runoff river supplied agricultural system of the outlying Tiwanaku Moquegua colonies. Thus, it is expected that the colonies also ultimately diminish in size due to drought but at a different rate than hardier raised-field systems of highland Tiwanaku due to their different agricultural water supply means. To assign the Tiwanaku societal collapse to socio-political mechanisms would likely reflect the catalytic effects of drought-induced agricultural contraction on the sustainability of a society. The Tiwanaku collapse appears to be a slow process over decades as the near lake raised-fields decline first as the Titicaca lake level subsides due to rainfall decrease. Agriculture continues at a minor level at more distant raised-fields where groundwater decline lags that of near lake fields.

### 13. Visions of the Last Days of the City of Tiwanaku

The final stages of urban Tiwanaku due to extended drought are described in [44]. Establishment of extended drought conditions that led to the gradual demise of urban Tiwanaku and its associated raised-field systems is well substantiated through geophysical means originating from ice core data.

Figure 16 summarizes the drought decline by integration of the nine year moving averages of ice cap thickness derived from [49,50,58] references. As drought initiates, yearly rainfall declines leading to smaller distances between successive ice deposit layers. Essentially the drought slowly lowered the water table supporting raised-field agriculture for the Tiwanaku city's 20,000 to 40,000 inhabitants; additionally, nonexistent water levels in raised-field swales promoted loss of any surviving crops to freezing events and water unavailability to plant root systems. Given the vast area devoted to raised-field agriculture, restoration of the fields by excavating swale depths to penetrate the declining groundwater level together with lowering field system berm heights to accommodate crops with root system depths necessary for plant growth proved to be an impossible task given the vast labor requirements to perform these tasks. Evidence of use of raised-field systems remote from the edge of Lake Titicaca where the groundwater height remained high exist requiring relocation of elements of city population to distant areas from the city. The presence of scattered qocha farming pits excavated to groundwater phreatic levels located distant from the city center indicated population fragmentation in order to conduct localized survival farming. New information pertinent to the last days of Tiwanaku city life [57,59] is available from the use of multiple stable isotope methods involving analysis of skeletal remains dating from the ~1100 AD time period which corresponds to city abandonment dates at the contemporary site of Wari. Noted are dietary changes from previous norms experienced by city population as drought intensified: these changes include absence of fish from the diet and no reported instances of child remains incorporating nutrients from fish or marine sources. This later observation may represent partitioning high nutrient food types to the most productive society members capable of generating food resources in emergency situations. As population decline and migration continued in this time period, specialized industries randomly lost key members necessary to sustain the group's function effectively; hence the loss of skilled fisherman can diminish the amount of fish available from the lake source. From modern observation of villages' use of lake resources, small minnows can be gathered from the near shoreline by nets which provide a protein source for site inhabitants.



**Figure 16.** In the time period AD 800–1400, the 9 year moving average of Huascaran Mountain ice core yearly deposit layer thickness begins a decline indicating the start of extended severe drought conditions. Ordinate scale is in centimeters [49,50].

However, as lowered lake levels resulted from extended drought conditions, limited access to shallow shoreline depths together with increased salinity that affected fish stocks, marine resources by lake fishing and shoreline collection was likely reduced from previous norms. Results from Miller et al. [60] indicate the substantial presence of maize as a food source in the ~1000 AD time period—this indicates a likely increase in importation from different satellite areas where this crop could be successively raised and transported in dried kernel form. Throughout the existence of Tiwanaku, maize importation constituted a large fraction of the population's diet and source of chicha

for celebratory, social binding rituals. Although the totality of effects on population decrease and dispersion are yet to be brought forward under extended drought conditions, the use of stable isotope methods opens new paths to understand the final days of Tiwanaku city closure. Recent studies [59] detail the societal collapse of a contemporary Middle Horizon Wari site due to food shortages in the same time period; here dietary shifts, associated with the extended AD 10–11th century drought, assign limited food resources to productive society members and leadership individuals capable of sustaining and guiding the society into a recovery period. As both highland societies are contemporary and experience the same drought period conditions, it is of interest to note similar responses to protect vital members of their societies. Figure 17 indicates that severe drought conditions at AD 1000–1100 and AD 600–700 altered the survival fate of different societies—in some cases, certain societies survived by altering their farming methodologies (or conquest of other societies with significant land and water resources) while other societies disappear from the archaeological record (Figure 17), of interest is the Medieval Warming Period post-drought recovery period in the 13–14th century AD period (Figure 17) that led to Inka expansion and control over vast areas of Peru and Ecuador with no state level polities left to contest their dominance.



**Figure 17.** The AD 10–11th century drought led to societal decline for both the highland Tiwanaku and Wari polities as well as for Peruvian north coast societies. Occurrences of El Niño, La Niña and other ENSO climate change effects on continuity of major Andean societies constitute a vital part of understanding Andean prehistory.

### 14. Conclusions

CFD results suggest that the perimeter drainage channel accelerated Tiwanaku's ceremonial center and the surrounding urban areas seasonal dryness throughout the year's seasonal changes in rainfall promoting the city's hygienic benefits. For example, reduction of dampness in indoor habitable structures limits the occurrence of many respiratory and mould-borne diseases [61]. In the rainy season, the deep groundwater level was stabilized by runoff and aquifer drainage into the perimeter drainage channel. In the dry season, additional seepage from the aquifer and the M channel flow kept the deep groundwater boundary from subsiding. The resulting stabilization of the deep groundwater level prevented the settling of monumental structures in the ceremonial core that originated from the design feature of the perimeter drainage channel's depth intersection with the top fringe of the deep groundwater layer and introduced the possibility of water resource availability during local drought periods. The stable groundwater level promoted the existence of wells and qochas for localized water supplies (Figure 2) to urban districts and inter-city agricultural zones. Subterranean channels P and Q

largely served the hygienic requirements of the Putuni and Kerikala structures by providing continuous water flow from perimeter drainage channel aquifer seepage water and the M channel water arriving into perimeter drainage channel arm W. Each major monumental structure maintained an intricate drainage system that simultaneously served practical and symbolic purposes as exemplified by the Akapana's elaborate drainage network that limited rainfall infiltration into its compartmentalized earth-fill interior to preserve its structural integrity. Canals O and N south of the perimeter drainage channel directed water to the qocha complex K for inter-city agricultural and pasturage purposes (Figure 2). Rainy season runoff water that washed into canals N, O and S exceeding their carrying capacity was diverted into canals L, I and J leading to the Tiwanaku River, thus protecting urban regions from canal overflow flooding. In totality, the perimeter drainage channel was the linchpin of an intricate hydraulic network that controlled surface and aquifer flows as rainfall amounts varied from rainy to dry seasons.

Analysis of the perimeter drainage channel's hydrological function indicates that qochas and wetland systems C' and K were an integral feature of urban Tiwanaku. Interlinked by canals fed by Corocoro springs and reservoirs, qocha clusters C' and K occupied massive portions of the city and likely supported camelid herds and caravans brought to the center during key social gatherings. Recent excavations in adjacent Mollo Kontu residential compounds support the hypothesis that llama and alpaca herds were important in this part of Tiwanaku and were served by C' and K qocha pasturage areas. Raised-field and qocha systems that occupied the edges of some of the city's canals are evident from aerial photos of the edges of canals I, J, L and C to support localized in-city agriculture and pasturage. The C' floodplain at the south edge of, and several meters below, the main portion of the city area of Tiwanaku supported an extensive cluster of integrated raised-field networks and qochas to support additional intra-city agriculture and pasturage.

Prior studies focused on Tiwanaku's hinterland demonstrated an understanding of hydrologic principles to develop intensive raised-field farming systems. Present research indicates that the urban center of Tiwanaku incorporated a complementary intricate hydrological network focused on the perimeter drainage channel that effectively managed seasonal water variations through surface canals, subsurface channels and aquifer drainage manipulation. CFD results detail many practical hydrological features of the perimeter drainage channel related to environmental and population livability concerns—these include rapid drying of subsurface soils surrounding elite ceremonial and secular housing districts to limit soil dampness and its negative health effects on the city's population. The perimeter drainage channel further supplied water to flush the subterranean channel network underlying the elite ceremonial core region to transfer human waste material to the nearby Tiwanaku River. These health-related features and remarkable plumbing features are the first reported for any Andean pre-Columbian city. Tiwanaku city planners demonstrated an extraordinary level of knowledge regarding hydrologic and structural maintenance principles based upon surface and groundwater manipulation to maintain high livability standards for their population under harsh altiplano environmental conditions. Building on prior studies of the groundwater-based raised-field systems that supported agriculture for the large population of Tiwanaku, analysis results demonstrate that knowledge of surface and groundwater flows within urban Tiwanaku merit further consideration in assessing New World engineering science.

The raised-field technology devised by the ancient Tiwanaku has been brought back to life once again after ~1000 years of raised-field abandonment by inhabitants of local altiplano villages many of whom participated in the original NSF Proyecto WilaJawira project. Restoration of segments the ancient raised-fields followed by planting native crops resulted in yields~5X over that of their current agricultural practice. The lesson here is that reexamination and restoration of agricultural methodologies of societies in past millennia may have great benefits for third world societies with large labor resources but who have limited access to modern machinery and chemical fertilizer supplements that are beyond their means to acquire.

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## References

- 1. Kolata, A.L. Agricultural Foundations of the Tiwanaku State. Am. Antiq. 1986, 1, 748–762. [CrossRef]
- 2. Kolata, A.L. The Technology and Organization of Agricultural Production in the Tiwanaku State. *Lat. Am. Antiq.* **1991**, *2*, 99–125. [CrossRef]
- 3. Peck, R.; Hanson, W.; Thornton, T. Foundation Engineering; John Wiley and Sons: New York, NY, USA, 1974.
- 4. Kolata, A.L.; Ortloff, C.R. Thermal Analysis of the Tiwanaku Raised-Field Systems in the Lake Titicaca Basin of Bolivia. *J. Archaeol. Sci.* **1989**, *16*, 233–263. [CrossRef]
- 5. Kolata, A.L.; Ortloff, C.R. Agroecological Perspectives on the Decline of the Tiwanaku State. In *Tiwanaku and its Hinterland: Archaeology and Paleoecology of an Andean Civilization;* Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 1996.
- 6. Ortloff, C.R. Engineering Aspects of Groundwater Controlled Agriculture in the PreColumbian Tiwanaku State of Bolivia in the Period 400-1000 AD. In *Tiwanaku and its Hinterland: Archaeology and Paleoecology of an Andean Civilization;* Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 1996.
- 7. Ortloff, C.R. Engineering Aspects of Tiwanaku Groundwater Controlled Agriculture. In *Tiwanaku and its Hinterland: Archaeology and Paleoecology of an Andean Civilization;* Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 1996; Volume 1.
- 8. Kolata, A.L.; Ortloff, C.R. Tiwanaku Raised-field Agriculture in the Titicaca Basin of Bolivia. In *Tiwanaku and its Hinterland: Archaeology and Paleoecology of an Andean Civilization;* Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 1996.
- Binford, M.W.; Brenner, M.; Leyden, B.W. Paleoecology and Tiwanaku Agroecosystems. In *Tiwanaku and its Hinterland: Archaeology and Paleoecology of an Andean Civilization*; Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 1996.
- 10. Bruno, M. Beyond Raised-fields: Exploring Farming Practices and Processes in the Ancient Lake Titicaca Basin in the Andes. *Am. Anthropol.* **2014**, *116*, 1–16. [CrossRef]
- 11. Ortloff, C.R. Water Engineering in the Ancient World: Archaeological and Climate Perspectives on Societies of Ancient South America, the Middle East and South-East Asia; Oxford University Press: Oxford, UK, 2010.
- 12. Ortloff, C.R. New Discoveries and Perspectives on Water Management and State Structure at AD 300–1100 Tiwanaku's Urban Center (Bolivia). *MOJ Civ. Eng.* **2016**, *1*, 57–66.
- 13. Créqui-Montfort, G. Fouilles de la Mission Scientifique Française à Tiahuanaco. Ses Recherches Archéologiques et Ethnographiques en Bolivie, au Chile et dans la République Argentine; International Congress of Americanists: Stuttgart, Germany, 1906; pp. 531–550.
- 14. Bandelier, A. The Ruins at Tiahuanaco. *Proc. Am. Antiqu. Soc.* **1911**, *21*. Available online: https://www.americanantiquarian.org/proceedings/44817263.pdf (accessed on 1 December 2020).
- 15. Denevan, W. Cultivated Landscapes of Native Amazonia and the Andes; Oxford University Press: Oxford, UK, 2001.
- 16. Means, P. Ancient Civilizations of the Andes; C. Scribner's Sons Publishers: New York, NY, USA, 1931.
- 17. Bennett, W.C. Excavations at Tiahuanaco. Anthropol. Pap. Am. Mus. Nat. Hist. 1934, 34, 354–359.
- 18. Posnansky, A. *Tihuanacu: The Cradle of American Man, Volumes. I & II*; J. Augustin Publishers: New York, NY, USA, 1945.
- Ponce Sangines, C. Informe de Labores. La Paz: Centro de Investigaciones Arqueologicas en Tiwanaku: Espacio, Tiempo y Cultura: Ensayo de Sintesis Arqueológica; Academía Nacional de Ciencias Publication: La Paz, Bolivia, 1961.
- 20. Ponce Sanguines, C. *Descripción Sumaria del Templete Semisuterraneo de Tiwanaku;* Juventud Publicaciones: La Paz, Bolivia, 2009.
- 21. Kolata, A.L. The Tiwanaku: Portrait of an Andean Civilization; Wiley: Hoboken, NJ, USA, 1993.
- 22. Kolata, A.L. Tiwanaku Ceremonial Architecture and Urban Organization. In *Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an Andean Civilization;* Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 2003; Volume 2, pp. 175–201.

- 23. Ortloff, C.R. Hydraulic Engineering in Ancient Peru and Bolivia. In *Encyclopaedia of the History of Science, Technology and Medicine in Non-Western Cultures;* Springer Publications: Heidelberg, Germany, 2014.
- 24. Janusek, J. Ancient Tiwanaku; Cambridge University Press: Cambridge, UK, 2008.
- 25. Kolata, A.L. Tiwanaku and its Hinterland. In *Archaeology and Paleoecology of an Andean Civilization;* Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 1996.
- Erickson, C. Lake Titicaca Basin: A Precolumbian Built Landscape. In *Imperfect Balance: Landscape Transformations in the Precolumbian Americas*; Lentz, D., Ed.; Columbia University Press: New York, NY, USA, 2000; pp. 311–356.
- 27. Ortloff, C.R.; Janusek, J. Water Management and Hydrological Engineering at 300 BCE-1100 CE Precolumbian Tiwanaku (Bolivia). *J. Archaeolog. Sci.* **2014**, *44*, 91–97. [CrossRef]
- 28. Janusek, J. The Changing Face of Tiwanaku Residential Life: State and Social Identity in an Andean City. In *Tiwanaku and Its Hinterland: Archaeology and Paleoecology of an Andean Civilization*; Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 2003.
- 29. Janusek, J. Craft and Local Power: Embedded Specialization in Tiwanaku Cities. *Lat. Am. Antiq.* **1999**, 10, 107–131. [CrossRef]
- 30. Ortloff, C.R. Groundwater Management at the 300 BCE-CE 1100 Precolumbian City of Tiwanaku (Bolivia). *Hydrol. Curr. Res.* **2014**, *5*, 1–7.
- 31. Couture, N. The Construction of Power: Monumental Space and an Elite Residence in Tiwanaku, Bolivia. Ph.D. Disertation, Department of Anthropology, University of Chicago, Chicago, IL, USA, 2002.
- 32. Janusek, J.; Earnest, H. Excavations in the Putuni: The 1988 Season. In *Tiwanaku and its Hinterland, Report submitted to the National Science Foundation and the National Endowment for the Humanities*; Kolata, A.L., Ed.; University of Chicago Press: Chicago, IL, USA, 2009.
- Bentley, N. The Tiwanaku of A.F. Bandelier. In *Advances in Titicaca Basin Archaeology;* Vranich, A., Levine, A., Eds.; Cotsen Institute of Archaeology, University of California: Los Angeles, CA, USA, 2013.
- 34. Couture, N.; Sampeck, K. Putuni: A History of Palace Architecture in Tiwanaku. In *Tiwanaku and its Hinterland: Archaeology and Paleoecology of an Andean Civilization;* Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 2003.
- Ortloff, C.R.; Janusek, J. Water Management at BCE 300- CE 1100 Tiwanaku (Bolivia): The Perimeter Canal and its Hydrological Features; Encyclopaedia of the History of Science, Technology and Medicine in Non-Western Civilizations; Springer Publications: Berlin/Heidelberg, Germany, 2015.
- Bruno, M. Sacred Springs: Preliminary Investigation of the Choquepacha Spring/Fountain, Tiwanaku, Bolivia. In Proceedings of the 65th Annual Meeting of the Society for American Archaeology, Philadelphia, PA, USA, 5–9 April 2000.
- 37. Vallières, C. Taste of Tiwanaku: Daily Life in an Ancient Andean Urban Center as Seen through Cuisine. Unpublished Ph.D. Thesis, Department of Anthropology, McGill University, Montreal, QC, Canada, November 2012.
- 38. Rivera, C.; Ch'iji, J. Evidencias sobre la Producción de Cerámica en Tiwanaku. Licentiatura Thesis, Universidad Mayor de San Andrés, La Paz, Bolívia, 1994.
- Rivera, C.; Ch'iji, J. A Case of Ceramic Specialization in the Tiwankau Urban Periphery. In *Tiwanaku and its Hinterland:* Archaeology and Paleoecology of an Andean Civilization; Kolata, A.L., Ed.; Smithsonian Institution Press: Washington, DC, USA, 2003.
- 40. Browman, D. Political Institutional Factors contributing to the Integration of the Tiwanaku State. In *Emergence* and Change in Early Urban Societies; Manzanilla, L., Ed.; Plenum Press: New York, NY, USA, 1997; Chapter 9.
- 41. Janusek, J. Identity and Power in the Ancient Andes; Routledge Press: London, UK, 2004.
- 42. Doig, F.K. Manual de Arqueologia Peruana; Ediciones Peisa Publicaciones: Lima, Peru, 1973.
- 43. McAndrews, J.; Albarracin-Jordan, J.; Bermann, M.P. Regional Settlement Patterns of the Tiwanaku Valley of Bolivia. *J. Field Archaeol.* **1997**, 24, 67–83.
- 44. Flow Science. FLOW-3D User Manual V. 9.3; Flow Science Inc.: Santa Fe, NM, USA, 2019.
- 45. Bear, J. *Dynamics of Fluids in Porous Media;* Ch. 4, Sections 4.5 to 4.7; Dover Publications: New York, MY, USA, 1972.
- 46. Freeze, R.A.; Cherry, J.A. Groundwater; Prentice-Hall, Inc.: Englewood Cliffs, NJ, USA, 1979.
- 47. Ortloff, C.R.; Kolata, A.L. Climate and Collapse: Agro-ecological Perspectives on the Decline of the Tiwanaku State. *J. Archaeol. Sci.* **1993**, *16*, 513–542. [CrossRef]

- 48. Binford, M.W.; Kolata, A.L.; Brenner, M.; Janusek, J.W.; Seddon, M.T.; Abbott, M.; Curtis, J.H. Brenner Climate Variation and the Rise and Fall of an Andean Civilization. *Quat. Res.* **1997**, *47*, 235–248. [CrossRef]
- Thompson, L.G.; Mosley-Thompson, E.; Davis, M.E.; Lin, P.N.; Henderson, K.A.; Cole-Dai, J.; Bolzan, J.F.; Liu, K.B. Late Glacial Stage and Holocene Tropical Ice Core Records from Huascaran, Peru. *Science* 1995, 269, 46–50. [CrossRef] [PubMed]
- 50. Thompson, L.G.; Davis, M.E.; Mosley-Thompson, E. Glacial Records of Global Climate: A 1500-year Tropical Ice Core Record of Climate. *Hum. Ecol.* **1994**, *22*, 83–95. [CrossRef]
- 51. Goldstein, P. Andean Diaspora: The Tiwanaku Colonies and the Origins of South American Empire; University of Florida Press: Gainesville, FL, USA, 2005.
- 52. Stanish, C.K.; Frye, E.; de la Vega, M. Sneddon Tiwanaku Expansion into the Western Titicaca Basin, Peru. In *Advanced in Titicaca Basin Archaeology-1*; Stanish, C., Cohen, A., Aldenderfer, M., Eds.; Cotsen Institute of Archaeology: Los Angeles, CA, USA, 2008; pp. 103–114.
- 53. Henderson, M. The Ancient Raised-Fields of the Taraco Region of the Northern Lake Titicaca Region. In *Advances in Titicaca Basin Archaeology-III*; Vranich, A., Clarich, E.A., Stanish, C., Eds.; Memoirs of the Museum of Anthropology: Ann Arbor, MI, USA, 2012.
- 54. Ortloff, C.R. The Hydraulic State: Science and Society in the Ancient World; Routledge Press: London, UK, 2020.
- 55. Dillehay, T. (Ed.) Foundational Understandings. In *Where the Land Meets the Sea*; University of Texas Press: Austin, TX, USA, 2017.
- 56. Janusek, J.W.; Kolata, A.L. Top-down or Bottom-up Rural Settlement and Raised-Field Agriculture in the Lake Titicaca Basin, Bolivia. *J. Anthropol. Archaeol.* **2004**, *23*, 404–430. [CrossRef]
- 57. Sharratt, N. Tiwanaku's Legacy: A Chronological Reassessment of the Terminal Middle Horizon in the Moquegua Valley, Peru. *Lat. Am. Antiq.* **2019**, *30*, 529–549. [CrossRef]
- 58. Thompson, L.G.; Mosley-Thompson, E. One-half Millennium of Tropical Climate Variability as Recorded in the Stratigraphy of the Quelccaya Ice Cap, Peru. In *Aspects of Climate Variability in the Pacific and Western Americas*; Peterson, D., Ed.; American Geophysical Union Monograph 55: Washington, DC, USA, 1989.
- 59. Tung, T.; Vang, N.; Culleton, B.; Kennett, D. Dietary Inequality and Indiscriminant Violence: A Social Bioarchaeological Study of Community Health during Times of Climate Change and Wari State Decline; Institute of Andean Studies: Berkley, CA, USA, 2017.
- Miller, M.; Kendall, I.; Capriles, J.; Bruno, M.; Evershed, R.; Hastorf, C. The Trouble with Maize and Fish: Refining our understanding of the Diets of Lake Titicaca's Inhabitants using Multiple Stable Isotope Methods (1500 BC–AD 1100). In Proceedings of the 59th Institute of Andean Studies Conference, Berkeley, CA, USA, 8–9 January 2014.
- 61. Clark, N.; Ammann, H. *Damp Indoor Spaces and Health;* Ch.5: Human Health Effects in Damp Indoor Environment; National Academies Press: Washington, DC, USA, 2015.

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