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Hydraulic Landscapes and Social Relations in the Middle Horizon Andes

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Abstract. Between A. D. 600 and 1000, two great states dominated the Peruvian Andes. Archaeological investigations have revealed their direct overlap in only one place: the Moquegua Valley of Southern Peru. Satellite imaging and GIS models are used to recreate the hydraulic landscape of the valley during this time period, a landscape which represents the economic basis for the survival of each colony. A network analysis of water distribution systems and paleoclimate records provide an intriguing assessment of the changing dynamics of imperial interaction over the 400 years of co-occupation of the valley. Results of the analysis of digital landscape models are used to assess the charismatic nature of social exchange during periods of cooperation and conflict based on water availability in the driest desert in the world.

1 Introduction

A seminal problem in understanding the relationship between prehistoric societies in the Peruvian Andes is the nature of the differential access to that most precious of resources: water. Water feeds the rivers and canals that make agriculture possible on the dry mountain slopes. Without irrigation, only the hardiest of desert cactus grows, and no grasses or domesticated crops can survive for long in the desert without water. Once agriculture became the predominant means of subsistence in the sierra ecozones, water became the limiting resource that curtailed population growth and served to define productive success. There is an ample supply of desert land that with sufficient labor can be turned into productive terrace systems, yet without water nothing will grow.

Thus, the nature of social relations among irrigation societies within a bounded hydrological system is predicated on the distribution of water. If environmental or social variables change to alter the availability or distribution of that most precious resource, it upsets the water balance and forces cultural agrarian productive systems to change. In this study, I present a model of water availability and social distribution mechanisms for the Moquegua Valley, Peru during the Middle Horizon (A. D. 500 - 1000). Moquegua is the only valley in the Andes in which colonies of both Wari and Tiwanaku, the two great polities of this era, reside within the same hydrological unit (Figure 1). The model assesses the impact of social water distribution practices on the agrarian systems of the two colonies throughout the four hundred year duration of their co-occupation of the Moquegua sierra.

2 Creating the Database

The first step in creating a model of landscape use in Middle Horizon Moquegua involved the acquisition of topographical, hydrological, and archaeological data. Although significant alterations to the landscape have occurred over the past 1500 years, the general topographic and hydrological characteristics of the Moquegua sierra have not been substantially altered.

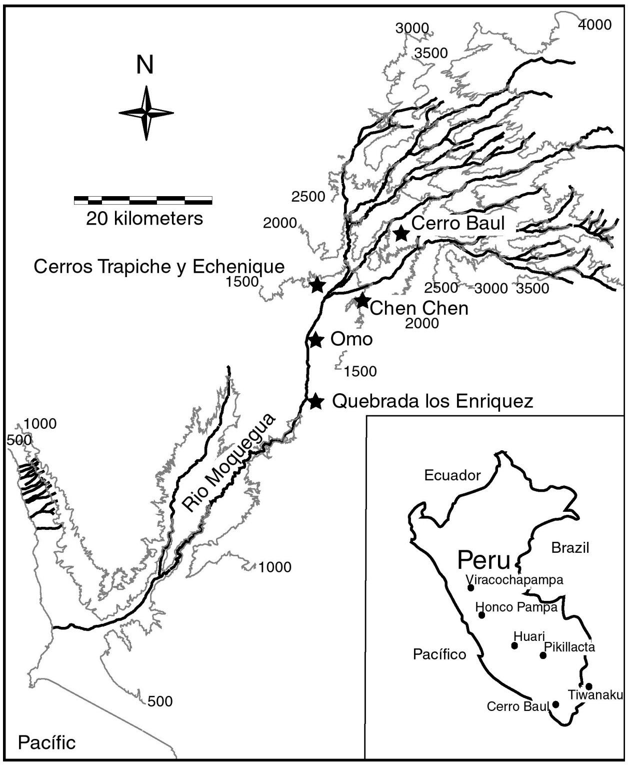

Fig. 1. The Moquegua Valley of Southern Peru, showing prominent Middle Horizon settlements

The presence of archaeological remains, including standing architecture, dating to this time period on the modern surface attests to the age of those surfaces. The natural hydrology of the valley includes steeply entrenched tributaries that merge into a single river below the city of Moquegua. Fluctuations in river discharge have substantially affected the valley bottoms, but these areas are circumscribed by the steep topography of the region, and unlike the flat plains of a meandering river basin, the reworking of sediments by hydraulic resources is limited to a narrow, entrenched canyon. There have been significant tectonic and climatic events including volcanic eruptions, earthquakes, and landslides that have substantially effected ancient human systems and have altered the surface geography of specific locales in the valley, but at a regional scale, the topography and natural hydrology of the Moquegua Valley has been fairly consistent over the past millenia. Thus, the topographic and natural hydrologic databases for the study region can be approximated by a modern digital elevation data. In this case, the source for the DEM is a photogrammetrically created 30 m resolution DEM based on the ASTER image on the Terra Platform acquired on October 12, 2000 and identified by DEM file number 20011025110437 (Figure 2).

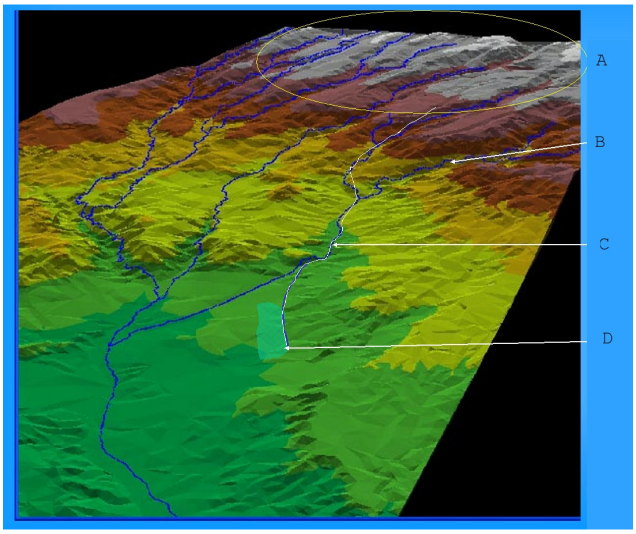

Fig. 2. Digital Elevation Model (orthographic perspective) of the Moquegua Valley derived from ASTER data. Water flows from the humid basin (A) through the natural hydrological network (B), which is assigned network friction values based on water loss rates. The best route through the network of man-made and natural water systems (C) is calculated using network analysis methods, and the derived water transport cost is assigned to the agrarian plot (D) based on its network travel costs and irrigable area

However, due to the extreme topographic variability in one portion the upper sierra of the drainage where slopes actually reach 90 degrees vertical, the photogrammetric DEM proves inadequate. In this area, around the unique geological mesa formation known as Cerro Baúl, shadow created by the vertical cliff faces make the DEM algorithms unresolvable. Since this mesa was critical to the development of Middle Horizon agriculture, a second DEM was created for this area based on a 1:5000 scale topographic map created by the Lockwood Survey company for the Southern Peru Copper Corporation. This high resolution map with a 5 meter contour interval was digitized and a 10 m DEM interpolated from the resultant data set. I used Arc/Info's Topogrid command to complete the interpolation, but the results did not accurately reflect the topography, instead providing a stepped contour model instead of the more smoothly differentiated surface. However, by applying a 5 x 5 kernel mean filter to the dataset, the steeped edges were removed, and the surface conformed to topographic data points collected with a total station within tolerable limits. It should be noted that this 5x5 kernel, which covered 50 meters on the ground, represented the average distance between adjacent major 25 m contour lines on the image (Figure 3).

After much experimenting, it was determined that this distance removed the stepped effect without compromising the integrity of the DEM. Thus , when choosing a mean filter to apply to a DEM derived from topographic contours, the best result might be obtained by using a kernel which will span the average inter-contour distance, but no greater.

The ancient cultural features of the valley were incorporated into the geographic information system based on archaeological survey and site specific studies over the past 15 years by researchers affiliated with the Contisuyo research program. The location and cultural context of major archaeological settlements and their associated agricultural systems was recorded from previous publications and from the author's own infrastructure reconnaissance in the valley. Positional data was obtained using a Topcon ET-1 total station with bench marks located by differentially corrected global positioning systems data. Systematic archaeological survey of the coastal section

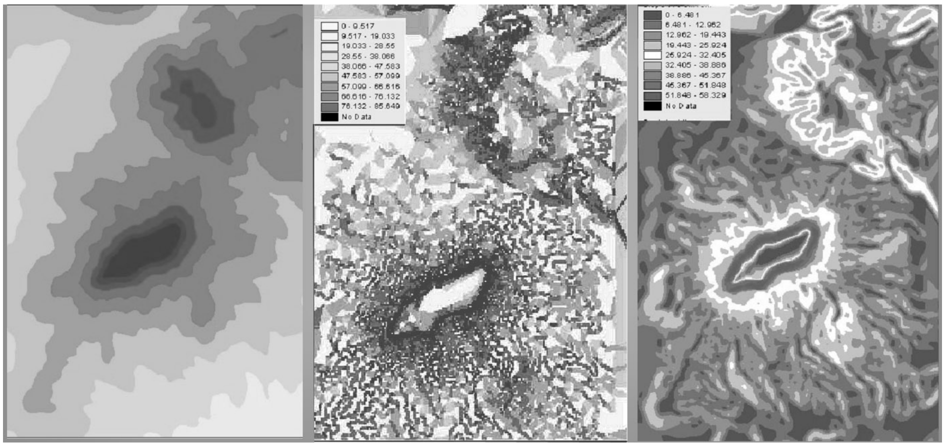

Fig. 3. DEM derived from topographic interpolation of contour lines around Cerro Baúl (left) using Arc/Info's Topogrid function. A slope derivative of the DEM reveals the flaws in the interpolation method (center), resulting in a "stairstepped pattern". After applying a mean filter to the data, slope derivates are more representative of the land surface (right).

and Otora tributary of the valley has been published (Owen 1993; Stanish 1985) and systematic archaeological survey of the middle valley and Torata and Tumilaca tributaries was completed (Goldstein 1993; Owen 1993). Although the analysis of the latter is still in process and significant new data has resulted from these studies, the preliminary results fall in accord with the data included in this analysis.

The author's archaeological infrastructure reconnaissance was undertaken coincident with the latter systematic survey projects and was designed to obtain specific location data on ancient agricultural systems and major archaeological settlements. Since systematic surveys were already in progress, the purpose of the reconnaissance was to document permanent infrastructure remains associated with agricultural production. The methodology for this reconnaissance involved the identification of all archaeological features identifiable from three aerial data sources including a SPOT satellite image, a SIR-C synthetic aperture radar image, and a set of black and white aerial photographs that were converted to digital products and orthographically corrected. Infrastructure features from these sources were confirmed by pedestrian survey and mapped in from the georeferenced data source. In order to document major infrastructure features that were not identified from remotely sensed data, several pedestrian transects were completed between each river tributary in the upper valley and along either side of the river in the middle and lower valley. While these transects do not represent a complete and systematic archaeological survey of the region, they did serve to identify all major archaeological settlements and all extensive ancient irrigation systems.

Three primary sources of cultural data were extracted from this study and incorporated into the geographic information system. These data layers included polygons representing archaeological settlements, polygons representing areas modified by human agriculture past and present (Figure 4), and a polyline coverage of the modern canal systems of the valley. The last data layer is incomplete for ancient time periods because entire ancient canal courses are rarely completely preserved. However, fragments of these canal systems do exist, and their locations were noted in the reconnaissance phase as point data. In order to complete the cultural hydrology data layer, principal canal courses were reconstructed from the fragmentary evidence using ARC/INFO's GRID module.

The reconstruction of canal courses is a complex process that involves a number of steps. First, a digital elevation model of the valley with a resampled 5 meter spatial resolution was created based on the topographic data layers. The ancient canal fragment point data was input into an equivalent resolution GRID file. Each point was then assigned to an ancient canal whose course would be reconstructed in the subsequent step. These assignments can be made because there is a recognizable canal typology in the Moquegua sierra and because the number of principal canals on a hillside rarely exceeds four stratified systems. Canal types include ridge top canals that follow the crest of a hill, contour canals that follow the contour of a slope with a very slight declination, and drop canals that run perpendicular to the contour (Stanish 1985).

The first two canal types represent the principal canal course that draws directly from the natural water source: a river or a spring. The drop canal is most often found as a secondary distribution mechanism that brings water to the farming surfaces and is rarely part of the principal canal line (canal madre). By examining the canal fragment's orientation to the slope in the field, one can distinguish the canal type. Associated fragment's can then be located by following the contour towards the water source for contour canals, following the ridge crest upslope for ridge top canals, and following the perpendicular to the slope for drop canals.

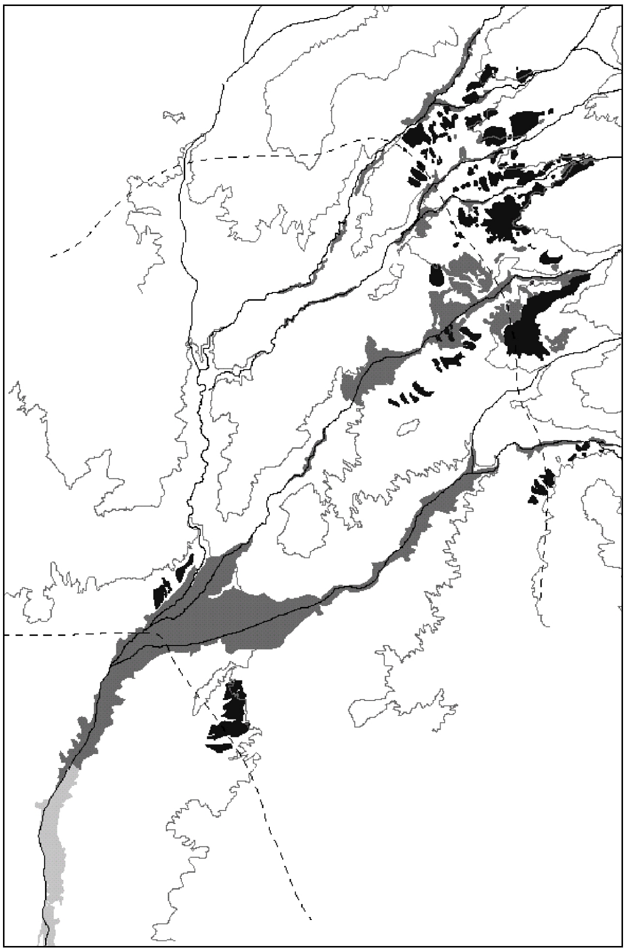

Fig. 4. Imagery classification and survey results for agricultural land use in the Moquegua Valley. Dark gray represents abandoned terracing, medium gray represents modern irrigation fed agriculture, and light gray represents areas irrigated today by wells.

Once canal fragments have been assigned to a canal system, the next step is the interpolation of the ancient canal course. This is accomplished by modifying the digital elevation model (DEM) to reflect the slope of the canal between two adjacent fragments. The first step involves the calculation of the average slope between the two points, which is defined as the elevation difference ex

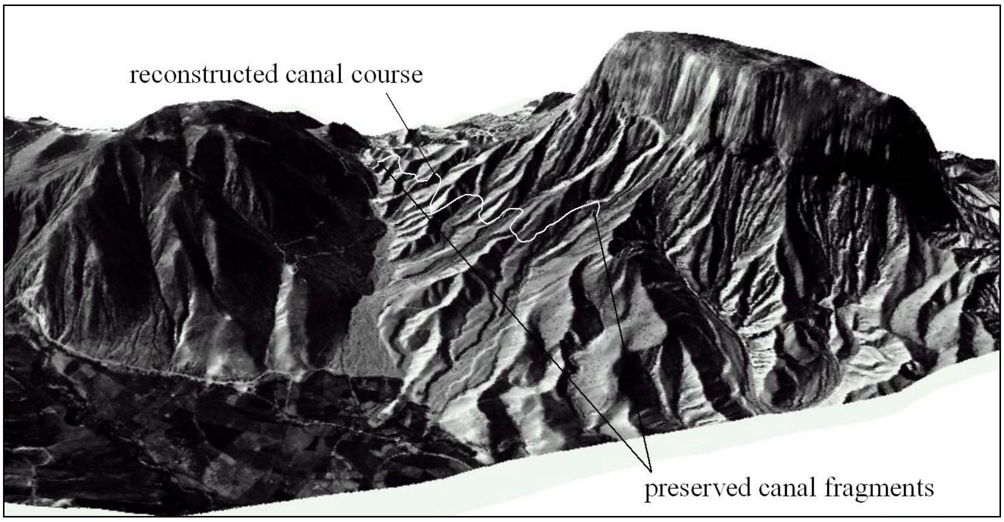

Fig. 5. Methodology for reconstructing a canal course based on preserved fragments and a DEM. Here, an orthographically corrected aerial photo is draped over the DEM to provide a visual context from an orthographic perspective.

tracted from the DEM divided by the length of the course between them. The latter measurement is estimated by calculating the length of the least cost path between the two points on a slope model derived from the DEM. This path is close in length to the actual canal course, but does not necessarily follow a steadily declining canal course, so a second step must be undertaken to create a new cost surface. Once the average slope between the two points is calculated, the DEM is effectively tilted by that same slope so that the two points on the modified DEM will have the same elevation. The DEM tilting is accomplished by running a Euclidean distance operand on the entire DEM, adding the product of the average canal slope and the Euclidean distance from the higher canal point to the elevation of each cell in the DEM. A least cost path along the slope derived from the modified DEM provides the model for the actual path of the ancient canal between the two points. In effect, the contour between the two points of the modified DEM represents the course of the canal (Figure 5).

This procedure is repeated for each set of adjacent canal point fragments within each canal system until there is a complete canal course created. The final step involves undertaking the procedure between the highest canal point and the nearest water source, usually a linear river. Since a linear feature does not have a single elevation equivalent on the DEM, an alternative estimate of the canal slope between the river and the highest canal point is needed. The best estimate is the slope between the highest preserved canal remnant and the next highest canal point. Thus, one can use the slope model from the same modified DEM, but the least cost path in this case will be between the linear river and the highest canal point. The raster based canal courses are then converted to a vector canal system and imported into the vector GIS hydrology layer. At this point, a systemic perspective of ancient cultural water distribution networks is in place. However, the hydraulic characteristics of these ancient canal systems and the temporal extents of their utility still need to be addressed. Furthermore, areas of ancient agricultural production, partially accounted for by the agriculturally modified polygon layer, need to be associated with each canal system. In order to obtain additional data to address these issues, samples of preserved canal fragments for each ancient system were excavated.

3 Canal Excavation Methods

Ancient preserved canal fragments were bisected by a 50 cm wide excavation trench perpendicular to the course of the canal. These trenches 1) revealed information on construction techniques, 2) allowed examination of the post-abandonment depositional patterns, and 3) permitted the reconstruction of maximum discharge capacity. Excavation proceeded stratigraphically by natural levels with a 40 g soil sample from each level taken as sedimentological evidence and for hydraulic analysis. In addition, a one liter sample of the bed material which constituted the base of the canal was collected in order to evaluate bed material composition. A second trench was cut approximately ten meters upstream or downstream of the first, depending on preservation, in order to estimate instantaneous slope of the canal at the primary trench. Instantaneous slope differs from the average slope along the canal course in that it represents the exact slope at the point of the cross section. The elevation difference between the mean base of the canal in the two trenches was divided by the exact horizontal distance to obtain an estimate of the instantaneous slope, although it is more accurately described as the average slope over a short distance in the proximity of the trench. A profile was drawn for all primary trenches and basal views were drafted when canals were lined with stones or uncommon construction techniques were encountered. Canals that were too poorly preserved, had been re-excavated for failed revitalization attempts, or were in modern use were not excavated, although some modern canals were profiled to confirm the Ministry of Agriculture's maximum capacity measurements (Moquegua Ministry of Agriculture, 1983).

In the lab, the 40-gram samples were evaluated on color and size to identify water deposited layers. Bed material samples were passed through a set of nested sieves in order to calculate D84 values (diameter which exceeds 84 percent of the particles). These numbers are used in the Chezy, Manning, and Darcy-Weisbach equations for calculation of maximum discharge. Based on measured discharge rates from modern operating canals and calculations of their estimated discharge rates using the discharge equations, the Darcy-Weisbach equation best estimates the actual flow regimes of these canal systems. The Darcy-Weisbach equation is defined by $ff = 8gRs / v2$ where $1/(ff)^{½} = c \log (aR/D84)$. In these equations, ff is the resistance coefficient; c and a are constants; R is the hydraulic radius of the channel, defined as the cross-sectional area divided by the wetted perimeter; s is the slope of the energy gradient; and g is the gravity constant. An estimate of mean water velocity (v) can be calculated for an ancient channel. Multiplying v by the channel cross-sectional area (A) yields the discharge capacity (Q) of the ancient channel (Knighton, 1984). Each canal trench that was excavated was subjected to hydraulic discharge analyses in order to better understand the amount of land under cultivation and to account for differences in preservation and cultural practices. By reconstructing discharge capacities of ancient canals, we can approach a more complete understanding of the relationship between hydraulics and cultivation.

The estimated bankfull discharge, the maximum carrying discharge of the canal, is then compared to a regression equation created by comparing bankfull discharge to irrigation area for the 77 modern canals in the Moquegua Valley today, including several that were probably originally built by prehistoric farmers. Bankfull discharge represents the maximum discharge capacity of the canal before it begins to overflow its banks. This regression analysis yields a Pearson's R of 0.689, indicating that a majority of the variance in irrigation area is attributable to discharge (Williams 1997). Furthermore, an F-statistic test at the .01 level allows us to easily reject the null hypothesis that no correlation exists between canal discharge and irrigation area. Excavation evidence for bankfull discharge analysis of abandoned canals is coordinated with survey data to determine the reliability of agricultural area interpretations based on this relationship. Canal systems whose bankfull discharges do not correlate with the polygonal areas of land modified by human agriculture are examined in detail. Lack of preservation of agricultural infrastructure or the use of lands for agricultural purposes without investing in substantial infrastructure can lead to underestimation of the irrigated area of a canal system. These "lost parcels" can be accounted for by the bankfull discharge equation. New agricultural polygons representing the lost agrarian parcels are added to the agricultural infrastructure coverage so that a complete, systemic perspective is achieved. The exact locations of the lost parcels could not be modeled for this analysis, and polygons were randomly located within the potentially irrigated area of the canal that was not occupied by other agrarian infrastructure. This method does not significantly affect water distribution models at the regional scale, such as the valley wide analysis this study undertakes. Attempts to determine exact locations for detailed analyses of intra-system hydraulic dynamics by soil chemical analysis and remote sensing methods are underway.

4 Assigning Agricultural Land Use to Time Periods

The most difficult task in reconstructing the evolution of agriculture is dating agricultural systems. One of the problems is that land use in the Moquegua valley is extremely dynamic. Over the centuries, canals are constructed, used, abandoned, revitalized, and reused over and over again. Within a functioning canal system, certain parcels may only be used in the wet season, while over the decades, distal parcels may be abandoned in favor of parcels more proximal to the water source or vice versa. The dating method used in this analysis is the association of principal canal and terraced areas with archaeological sites, accompanied by superposition analysis and dating criteria derived from canal excavations.

I date sites and the use of their associated agricultural fields using radiocarbon dates from published excavation reports, major temporal ceramic styles associated with radiometric dates in other areas, and topological arguments. Superposition of one canal system over another, or of a site over a canal, augments the direct association method of dating by providing information on relative chronology within a small area. Differences in surface patination and preservation are also used to understand the relative chronology within a local area of the drainage. Finally, canal deposits can be used to estimate the period of last use of a canal. The volcanic eruption of Huaynaputina leaves a thick deposit of volcanic ash in those canals abandoned before but close to 1600 A.D. The depth and purity of the ash deposit can be used to provide a relative age of the abandonment of the canal. Those canals associated with late prehispanic sites tend to have large deposits of ash while canals associated with earlier sites (circa 1000 A.D. and before) have little to no ash deposits. This is due to the fact that earlier abandoned canals had an opportunity to fill in with eroded sediment before the ash fall.

The association of agricultural areas with archaeological habitation sites is based on the concept of the site catchement area (Vita-Finzi and Higgs 1970), which argues that the most intensively accessed resources will be located within a certain proximity to the site. The spatial relationship between habitation sites and agricultural fields is especially strong in highland irrigation communities for several reasons. Irrigated agricultural fields require a great deal of monitoring. They need to be protected from animals, theft, or destruction. The feeder canals must be opened and closed during the designated cyclical watering cycles. The terraces and canals must be regularly inspected for damages and repaired if necessary. Most modern farmers live on or adjacent to their agricultural lands, and their community centers are located within the agricultural system or near the principal canal that feeds it as well. Those few landowners who are not resident near their agricultural fields must rely on a neighbor to keep vigilance over their fields. There is also a strong correlation between certain isolated archaeological sites and irrigation systems that indicates that this resident habitation pattern is characteristic of prehispanic societies as well. Thus, one factor in dating a canal system is to look at site distribution patterns for each archaeological time period in the valley.

Defining the actual agricultural area for a specific time period involves further considerations, including the association of architectural features of known age with the canal and irrigation infrastructure. For example, an aqueduct at the Wari site of El Paso channeled water across a divide. This same aqueduct formed part of the wall of a group of rooms at the site, and was covered by a later period plaza, indicating its temporal contemporaneity with the rooms, and its abandonment by the time of the construction of the plaza. At the site of Camata, the terraces associated with an Inca agricultural system (ca. A. D. 1500) cover the principal canal associated with the Late Intermediate (ca. A. D. 1300) village of Cerro Huayco. Thus, local features of architectural compatibility and superposition can refine the functioning of irrigation system components and bring entire canal systems into chronological focus.

The attribute table associated with the agricultural polygons to this point only contains the standard information: an id and an area. The table is updated with a series of temporal boolean fields that define whether or not a plot was under cultivation during a specific time period. The chronological resolution of the current model is on the order of a century, so fields for each century were added to the attribute table and a value of True or False is coded for each agricultural polygon for each century since A. D. 500. While AMS radiocarbon dates on organics within the construction matrices of irrigation works could provide additional chronological information, a substantial number from each irrigation system would need to be analyzed in order to further refine the irrigation chronology. Bulk soil dates from the final silts on one canal had a high error range (a one sigma range of 200 years), and the date was incompatible (too recent) with architectural associations and depositional characteristics. Bulk soil dates do not seem to be an effective means of dating irrigation works in Moquegua. Future refinement of the agrarian chronology may be realized through the application of AMS dates to organic materials in construction contexts, but the present methods do provide an assessment of patterns of agricultural use at a broad regional scale. In discussing changes over a 500 year period, the present dating methods permit us to compare the long term effects of highland water use and drought on down river irrigation systems. The dynamics of water availability are modeled through an additional set of hydraulic analysis methods that are used to reconstruct the availability and distribution of water throughout the time periods represented in this analysis.

5 Hydraulic Analysis Methods

The hydraulic analysis is basically a water cost/availability function and is based on two principal data sources. The first is a record of precipitation over the past 1500 years based on glacial ice cores from the Quelccaya Ice Cap near Cuzco (Thompson, 1992). While year to year fluctuations will change from region to region, long-term general trends are characteristic of Peruvian climate as a whole. It is these decadal trends that will also most profoundly influence major changes in agricultural production strategies (Shimada et al., 1991). The ice cap as a proxy for long term precipitation trends in the South-Central Andes is confirmed by recent lake core evidence from Lake Titicaca (Binford et al., 1997). The securely dated portions of lake level fluctuations from the Titicaca cores over the past 1500 years parallel long term ice accumulation trends. An examination of fifty-year averages of Quelccaya accumulation converges with securely dated lake core records in all cases, while the variation between the two records exists only for the dates for which lake level measurements are less secure (Fig. 6).

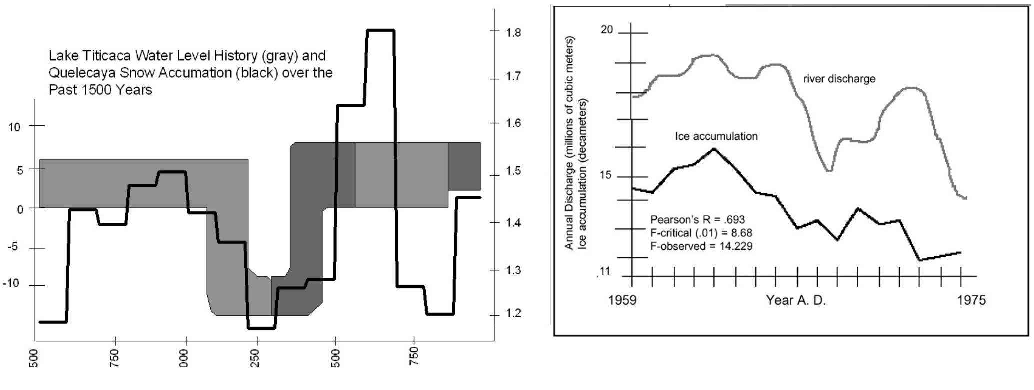

Fig. 6. Correlation of long term paleoclimate records (left) and short term river discharge of the Moquegua Valley (right) with Quelccaya ice accumulation (Thompson 1992). Dark gray shading represents secure interpretation of lake levels, while light gray is representative of less secure interpretations (after Binford et al 1997). Ice data is shown on the left in half century averages for ease of water balance comparisons. River discharge and ice accumulation graphs are depicted using decadal running averages (Williams 1997)

cords as models of past precipitation values (Williams 1997).

The second data source in the water availability model is the geography of precipitation and runoff in the Moquegua drainage. Only the area of the drainage above 3900 meters, referred to as the humid basin, actually contributes water to the river system (Rice, 1989). Therefore, the farther water must travel from the 3900 meter contour, the more water is lost to evaporation and seepage.

Each plot of river irrigated agricultural land in the valley, past and present, can be assigned a water transport cost that accounts for water lost to evaporation and seepage per unit area (Fig. 2). This cost is calculated using the ArcView Network Analyst applied to the hydrology coverage (rivers and canal systems) for Moquegua. The Network Analyst is employed to calculate the best route from the humid basin to each field plot along the natural and human made hydrological system. The terminal locations of the route are specified by choosing the point at which the canal first intersects the field plot and the point at which the river that feeds that canal enters the humid basin. The best route is calculated, and the linear route distance along the hydraulic path is derived. Since water loss is a relatively consistent four percent in unlined canal beds and river channels in highland areas between 1500 and 3000 meters above sea level, the route length is the principal factor in determining the evaporation and seepage cost of bringing water to a field system. A new field named hydraulic cost ratio is added to the attribute table for the field plot and is defined as 0.96 x, where x is the linear distance in kilometers along the best route. Based on discharge measurements and water loss calculations made by the author, an irrigated unit's hydraulic cost ratio can be calculated as $HCR = 1 / (.96 D)$, where .96 represents the amount of water conserved per kilometer traveled and D is the distance in kilometers from the humid basin above 3900 meters via the hydraulic route (Williams 1997).

The hydraulic cost for the plot is defined as the product of the area of the field plot, the hydraulic cost ratio, and a constant that represents the conversion from agricultural area (square meters) to the water volume needed to sustain that area (cubic meters). The constant is derived by solving the equation for the sum of all agricultural plots of the modern time period, which has a known average discharge of the humid basin. Thus, the constant can be calculated in the following equation: $\Sigma (HC) / \Sigma (HCR \times A) = C$ where HC is the hydraulic cost and its sum is the total modern discharge of the humid basin, HCR is the hydraulic cost ratio for each plot of modern cultivated land, A is the area of each plot, and C is the constant. In this manner, each plot of land within the drainage is assigned a hydraulic cost ratio that represents its relative efficiency in the use of water in comparison to other plots within the system and a hydraulic cost that represents the amount of water from the humid basin needed to travel the specified distance and irrigate the plot with an equivalent amount of water to all plots in the basin. Likewise, the hydraulic cost field is added to the agricultural polygon attribute table. The water requirements of an entire production system at a specific period of time can be calculated by summing the hydraulic cost fields in the attribute table for all plots within the system that are coded as operating in that century.

The analysis assumes that each plot of land requires the same amount of water to be productive, and this is problematic as an exact reconstruction of each parcel's water requirements. Both local filtration rates (which is affected by soil type and human investment in terracing) and crop types will affect the rate of water consumption by a plot of land. Since these factors cannot be controlled for at this point, the analysis assumes that agricultural plots of equal area require similar amounts of water. Also, a large proportion of the water lost to seepage enters the groundwater system and feeds the aquifers and springs of the lower and coastal valley. This does not effect agricultural systems dependent on river fed irrigation, but it is possible that some of that seepage re-enters the surface hydrological system and contributes to water available for river fed irrigation agriculture at lower elevations. Without additional hydrological fieldwork, it is not possible to model seepage contribution to superficial hydrology. Once again, this limits the ability of the model to characterize differences on a highly local scale, but in the regional scale of the basin at large, we can still characterize changes in water availability between broad areas from time A to time B.

In order to compare water requirements with water availability and the social distribution of water, it is necessary to estimate average discharges of the humid basin for decades over the past 1500 years. Modern discharge values for the humid basin are divided by amount of modern Quelccaya ice core accumulations, and this ratio is applied to Quelccaya ice core accumulations of past decades to produce Moquegua humid basin discharge rates for the same time frame (Fig. 7).

Based on the earliest radiocarbon dates from a Tiwanaku context in Moquegua, the first Tiwanaku colonies appear ca. AD 550 at the site of Omo (Goldstein 1989). This colonization represents a major change in political dynamics in the valley. Although these early Tiwanaku settlements seem to be autonomous entities that did not necessarily exert binding political control over the valley inhabitants, their intrusion into the Huaracane production niche represents a usurpation of resources, especially water and irrigable land, that must have impacted the local populations. These settlements, characterized by imported Tiwanaku IV ceramics, intrusive altiplano house forms, and distinct communities organized around public plazas, focused on middle valley floodplain farming (Goldstein 1989).

By AD 650, a new imperial order had joined Tiwanaku in the settlement of Moquegua. The Wari colony on and around Cerro Baúl was established early in the expansion

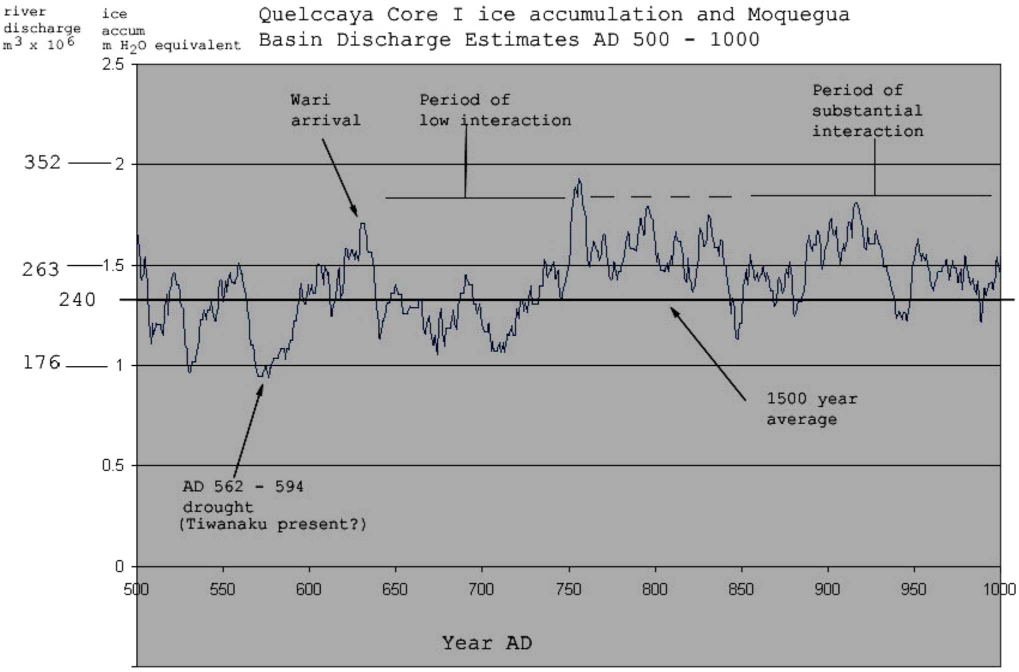

Fig. 7. Estimates of Moqegua River discharge based on Quelccaya ice accumulation data from Thompson (1992). Data is displayed annually for decadal running average of meters of water equivalence. Correlation between annual discharge of the Moquegua Basin is made by assessing discharge measured in recent decades to recent ice accumulation values. Periods of low and increased social interaction are also indicated.

of the first South American empire (Williams 2001). The Wari introduced the new agricultural technology of expansive high sierra terraced agriculture to the upper Moquegua Valley between 2000 and 2500 meters above sea level. This area was only sparsely occupied, if occupied at all, prior to Wari's arrival (Owen 1993), and thus Wari opened a new ecological niche to irrigation agriculture (Fig. 8).

An assessment of water use and water availability using the GIS network analysis model from AD 500 to AD 750 provides a provocative reason for hostilities between the two states early in their expansive periods.

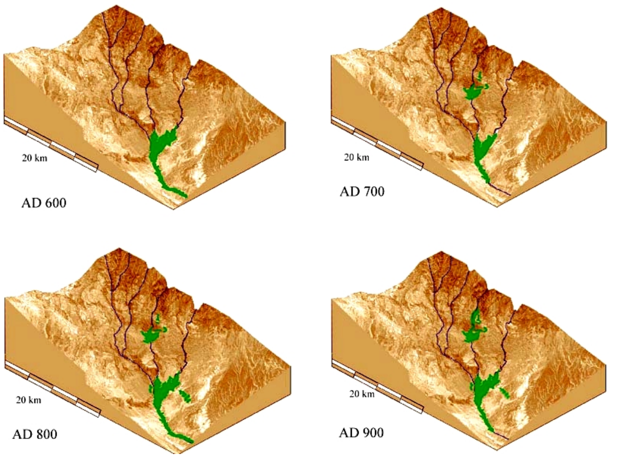

Fig. 8. Landscape models of agrarian land use during the centuries of Middle Horizon occupation in the Moquegua Valley.

During the sixth century AD, water availability is estimated to have averaged 220 million cubic meters annually, with significant deficit fluctuations between AD 525 and 550 and AD 560 to 590 to decadal averages as low as 175 million cubic meters. Huaracane fields could have been irrigated with 185 million cubic meters of annual discharge, and likely would have suffered some hardship during these environmental downturns. With the addition of Tiwanaku agricultural production to the system, the total water needs of the system would likely have grown slightly, to around 200 million cubic meters annually by AD 600.

The Wari expansion around AD 600 occurred after 30 years of 20-30% below normal precipitation (Shimada et al., 1991). High sierra farming radically improved the efficient use of water by decreasing the amount of water lost to evaporation and seepage in transport from the rainfall areas (Moseley 1992). In Moquegua, I estimate that the Wari canals could irrigate 2.5 times the area irrigated by the Tiwanaku lands, due to their closer proximity to the highland rains above 3500 meters above sea level and the use of stone masonry terracing. That is, Wari agriculture was more than twice as efficient in the use of water. However, the addition of a new zone of agricultural production in the upper sierra, despite its efficiency in water use, would still drain resources from the total hydrological system. Wari irrigation needed 25 million cubic meters of annual discharge to support itself. While less than 15 percent of the overall hydrological output, this became increasingly significant in times of drought.

Despite above normal levels of water availability between

AD 600 and 640 on the tails of the 3 decade long drought, the ice core data indicate fluctuating levels of water supply between AD 650 and 750, with pronounced deficits from the long term average between approximately AD 660 to 680 and AD 700 to 720. The water availability model suggests needs outstripped supply during these two intervals and conflict between the two groups over water usage is likely during these decades. In fact, the average annual discharge is still just over 220 million cubic meters, but the new Wari fields upstream of the middle valley reduce the average available discharge of the humid basin to 195 million cubic meters annually. Tiwanaku water needs of 200 million cubic meters annually were not being met.

By AD 750, however, water levels had recovered and were well above average (Figure 7). They would remain so with periods of substantial excess except for brief downturns around AD 850 and AD 950 until after AD 1000. Between AD 750 and 1000, average discharge is almost 270 million cubic meters annually, and decadal averages exceed 240 million cubic meters annually 9 out of 10 decades. Thus, after AD 750 the constraints on middle valley agriculture imposed by upland irrigation and below average rainfall are withdrawn. The result is an environment of decreasing potential conflict and détente between the superpowers.

Around AD 850, the Tiwanaku colony witnessed a political reorganization that resulted in the establishment of a demographic center at the site of Chen Chen and the construction of a Tiwanaku style temple at the site of Omo. This temple reflected the three-tiered platform of altiplano temple centers, and is the only such complex constructed outside the Titicaca Basin (Goldstein 1993). This phase of settlement also reflects the development of a three tier site size hierarchy in the Moquegua Valley, which mirrors the new political organization of provincial administration of the middle valley. Chen Chen, with thousands of burials, is a vast necropolis as well. Located at the neck of the valley where the river narrows significantly, the Pampa Chen Chen and its canal intake represent an important geographical nexus for the control of water flowing to the middle valley.

Chen Chen, with thousands of burials, is a vast necropolis as well. Located at the neck of the valley where the river narrows significantly, the Pampa Chen Chen and its canal intake represent an important geographical nexus for the control of water flowing to the middle valley.

The Wari colony in the high sierra continued to thrive, however, and may have even experienced agricultural expansion.

Around AD 900, the changes that were taking place in the Tiwanaku colony were also complemented in the Wari colony with a massive programs of urban renewal and institutional restructuring at the Wari provincial capital of Cerro Baúl (Williams 2001). This period of time also witnesses the intrusion of Tiwanaku settlers into settlements around the Wari administrative center and intermingled with Wari domestic settlements (Williams 2002). Furthermore, three rustic tripartite structures of public architecture, one of which Owen (1999) argues to reflect temple architecture in the Tiwanaku style, are established on the slopes of Cerro Baúl. These changes in the settlement data reflect the substantially increased interaction between the two groups. While they strictly maintain their separate identities in terms of material culture, their interaction in lithic exchange (see Burger et al 2001), in the sharing of water resources (Williams 2002), and in maintaining settlements necessitating confrontation with the other population in the course of day to day activities reflects a substantial change in the pattern of daily life for the two groups. This interaction is likely witnessed late in the Middle Horizon for several reasons, one of the most important of which is the reduction in potential hostilities afforded by the increased availability of water resources that are no longer stressed by agricultural expansion. This interaction, in fact, may have paved the way for the development and further expansion of the agricultural system of the upper sierra by local Tiwanaku peoples called Tumilaca in the tenth century AD. By AD 1050, both colonies had collapsed, perhaps survived slightly by the Tumilaca tradition. Collapse may also be assessed from the water availability model, which sees decadal rainfall levels drop to below 230 million cubic meters annually in the eleventh century AD for the first time in 3 centuries. Ironically, the interaction and expansion of upland agricultural fields may have been instrumental in lowland agricultural collapse that fed back into the social system and resulted in colonial abandonment on both sides (Williams 2002).

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