

CLIMATE, AGRICULTURAL STRATEGIES, AND SUSTAINABILITY IN THE PRECOLUMBIAN ANDES

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INTRODUCTION

Throughout ancient South America, millions of hectares of abandoned farmland attest that much more terrain was cultivated in precolumbian times than at present. For Peru alone, the millions of hectares of abandoned agricultural land show that in some regions 30 to 100 percent more terrain was cultivated in precolumbian times than at present (Clement and Moseley 1991:425). While many cultural explanations for agrarian collapse can be formulated, the most compelling reason for the loss of cultivatable land is changing climate, including shifting rainfall patterns and amounts. Agriculture was expanded many times in many places when conditions favorable to land reclamation were perceived by past populations. When climatic trends led to diminished water supplies, temporary or permanent agrarian regression ensued, with consequences for social structure.

Ancient Andean civilizations utilized a wide diversity of agricultural techniques in different ecological zones, and developed agricultural strategies consistent with local climate patterns, hydrological characteristics, soil and crop types, and local labor supply. The strategies chosen depended upon a society's hydraulic engineering, surveying, and civil engineering skills combined with its perception of ecological and hydrological conditions. Taken together, these

allowed each society to design and manage complex water supply networks and to adapt them as climate changed. While shifts to marine resources, pastoralism, and trade may have mitigated declines in agricultural production, damage to the sustainability of the main agricultural system often led to societal changes and/or additional modifications to those systems.

To achieve agricultural sustainability, Andean administrators needed to record changes in climate patterns, weather events, and natural disasters, then conduct analyses to plan modifications allowing agricultural systems to function in the face of changing water supplies. Modifications took the form of physical alteration of existing water delivery systems, and the development of new agro-systems suitable to new hydrological conditions. When climate deteriorated beyond a system's ability to make modifications to maintain sustainability, field system abandonment was an inevitable outcome. A sustainable agricultural base, on the other hand, can lead to overall population growth and patterns of population concentration and/or dispersal, with specialized labor to work and manage the system. Such a division of the workforce underlies urban centers that controlled and administered adjacent agricultural zones and may have exerted centralized control of labor.

Even if water supplies are adequate for sustainable agriculture, inappropriate strategies of agro-engineering and labor management can interrupt the development of otherwise well-functioning societies. Agricultural sustainability requires administrative skills to guide adaptive technical innovations in the design and management of an agricultural system to maintain high yields in spite of changing weather and climate. A degree of flexibility to modify an agricultural system should, therefore, be part of the original design of a system if knowledge of prior weather and climate patterns, and their consequences for sustainability, exists. As an integral part of system design and the potential for innovative and adaptive design change, an understanding of the dynamics of water flow from original highland rainfall sources to lowland and coastal regions must be in place. The effects of excessive rainfall or drought are disproportionately felt in the highlands compared to the run-off dependent coastal field systems. The differences arise from altitude-dependent soil types and their water infiltration and water retention characteristics, soil saturation levels, and porosity, as well as transport, evaporation, and seepage loss rates from water source to final destination for agricultural use. Based upon such considerations, reconstructions of interactive, climate-related, and societal-dependent structural factors have a hydrological component and are thus key to understanding highland-lowland interactional dynamics and their possible relation to Andean development.

THE SETTING: REGIONAL CLIMATE NORMS

The central Andes consists of parallel eastern and western cordilleras. In the north-central Andes the higher eastern range and the lower western range enclose intermontane uplands that drain mostly into the Amazon and its tributaries. In the southern altiplano region rainfall drainage is mostly into Lake Titicaca with a high degree of infiltration that maintains

high groundwater levels on the altiplano throughout wet and dry seasons. Drainage from western cordillera rainfall is mostly directed to coastal river valleys (Figures 1, 2) with outflow to the Pacific Ocean with the exception of the intermontane source of the Santa River.

Biotic diversity is pronounced in the many highly varied ecological zones of Peru. For example, with 35 of the world's life zones, Peru contains the largest number of ecological zones of any country on earth (Perú, ONERN 1976; Tosi 1960). However, diversity is asymmetrically distributed by altitude, latitude, and longitude. As in all mountain ranges, ecological zones are stratified by altitude and far fewer species of plants live at high elevations than at low ones.

The Andean mountain ranges form South America's continental divide. Normally, all rainfall in the eastern cordillera comes from the Atlantic Ocean with a longitudinal gradient in precipitation. Fronting the Amazon Basin, the high eastern Andean escarpment receives abundant precipitation, creating a rain shadow to the west. Consequently, bio-diversity is greatest along the lower eastern flanks of the eastern cordillera. The eastern escarpment is exceptionally steep and therefore difficult to farm. Because the eastern watershed reaches deep into the intermontane sierra, it receives and discharges approximately 90% of all moisture in the range. Sierran basins have relatively modest slopes amenable to rainfall and runoff farming. Cultivation, in conjunction with the use of high altitude grasslands for herding, sustains agro-pastoralism and was the basis for large sierran populations in prehispanic times.

DROUGHT EVENTS

Analysis of the ice cores from the southern region Quelccaya peak (Thompson *et al.* 1985, 1986, 1994) and from the north Andean Huascarán mountain (Thompson *et al.* 1995a), and

analysis of the Lake Titicaca sediment cores (Abbott *et al.* 1997; Binford *et al.* 1997; Ortloff and Kolata 1993; Seltzer 1991) reveals dramatic climate shifts. The Quelccaya ice cores indicate periods of wet and dry climate, as well as dust maxima, over a 1500 year span of time. The Huascarán ice cores show similar climate variations with dust concentration events characterizing dry periods. The Lake Titicaca sediment cores present limnological data corroborating the major wet and dry period climate shifts found in the Quelccaya and Huascarán ice core data (Ortloff and Kolata 1993:200). Initial analysis of the cores documents a 25 to 30 percent decline in precipitation between 563 and 594 C.E. (Shimada *et al.* 1991:261). This drought is notable for both its rapid onset and exceptional severity (Schaaf 1988; Shimada *et al.* 1991:248, 261-262). A protracted precipitation downturn between 1100 and 1500 C.E. occurred when rainfall was, on average, 5 to 15 percent below previous norms before precipitation returned to long term averages around 1700 C.E.

The limnological cores from Lake Titicaca have provided a 3500 year record of precipitation induced lake level variation. These cores show early Holocene aridity, mid-Holocene lake filling around 1400 B.C.E., drought-induced lake level low stands at about 900-800 B.C.E. and 400-200 B.C.E., as well as at 1-300 C.E. and 1100-1450 C.E. (Abbott *et al.* 1997; Binford *et al.* 1997).

Huascarán ice cores from northern Peru reveal a glacial record of climatic conditions extending back to late Pleistocene times (Thompson *et al.* 1995). Evidence of the drought beginning around 1100 C.E. is also found in dust maxima and elevated temperature variations seen in the Huascarán cores.

To reconstruct the effects of changing climate on Andean highland and coastal societ-

ies we review the record of cultural change through time using the Uhle-Rowe chronological sequence. The sequence begins with Formative and Preceramic Periods of long duration (c. 9500-1800 B.C.E.), and continues with the Initial Period (IP; 1800-900 B.C.E.), the Early Horizon (EH; 900-200 B.C.E.), the Early Intermediate Period (EIP; 200-600 C.E.), and the Middle Horizon (MH; 600-1000 C.E.). This last division is followed by the Late Intermediate Period (LIP; 1000-1476 C.E.), then climaxed by the Late Horizon (LH; 1476-1534 C.E.).

Climate data show that early and middle phases of the EIP climate were sufficiently stable to provide adequate water resources for the development of canal based irrigation agriculture by the Peruvian north coast Gallinazo and Moche polities, as well as by the south coast Nasca and central coast Lima polities. Highland Wari and early phase Tiwanaku also flourished during this time, reinforcing the conclusion that water supplies and runoff were adequate in both the coastal and highland zones, although agricultural techniques varied greatly from locale to locale.

Towards the end of the EIP, a dry period (Thompson *et al.* 1985:973) apparently played some role in the decline of the Moche state around 640 C.E. (Shimada *et al.* 1991), as well as in the collapse of Recuay and Lima polities, and that of the south coast Nasca polity. During the MH there was a dramatic expansion and rise in influence of the highland Tiwanaku and Wari states with their highland-adapted agricultural strategies and plentiful water supplies. By contrast, in coastal areas there was a decline in the area of irrigated land and highland states expanded into coastal regions (e.g., Tiwanaku colonies in the Moquegua Valley and Wari influence on southern coastal regions, at Cerro Baúl in the Moquegua Valley, and at Beringa in the Majes Valley; Owen 2007:287-289; 291-292, 305-316, 321-325; Tung 2007:254-255).

Towards the end of the Middle Horizon the decline of the Tiwanaku and Wari states (c. 1000-1200 C.E.) may have been due to a prolonged drought. Chimu, Chancay, and Ica-Chincha societies continued to sustain their agricultural bases through efficient use of limited irrigation water supplies, and dependence upon marine resources.

Late kingdoms in the altiplano (the Lupaqa, Colla, and minor local groups) arose concurrently with the fragmentation of the dominant Tiwanaku state. Towards the end of the LIP, a decline in agricultural productivity in the Chimu Moche Valley region is associated with sierra rainfall decline as shown by sequential canal cross-section area decreases and flow rates (Ortloff *et al.* 1985:78, 86-89, 94, 96-97). Highland polities (Wanka, Chanca, and early Cusco) arise in this period, but are of lesser regional influence compared to the Chimu state. A shift to a wetter period during the start of the Late Horizon (Thompson *et al.* 1985:973, 1986: 364, 1994:85) was followed by political dominance of the highland Inca state over coastal, highland, and altiplano regions extending from present-day Ecuador to mid-Chile.

Significantly, the Titicaca lake cores, Quelccaya ice cores, and Huascarán dust maxima are concordant in their documentation of a long-term decline in rainfall levels beginning around 1100 C.E. This decline appears to be an Andean expression of the worldwide perturbations in rainfall and temperature known as the Medieval Warm Period. The long duration of this dry period allowed coping strategies to be developed over many centuries. Drought defensive responses that can be inferred from the archaeological record can be viewed as a measure of a society's accomplishments in technical innovation to reconfigure agro-systems towards greater sustainability under climate stress.

Rainfall farming is more efficient than canalized runoff farming (per unit of water input) because of the evaporation and seepage associated with rivers and canals. In the arid sierra at elevations around 2250 m, the Moquegua River's flow forfeiture reaches 4 percent per kilometer (Williams 1997). Mountain runoff is greatly diminished by the time it reaches the lower coastal valleys. Drought, therefore, always has a more severe effect in coastal desert zones than in mountain headwater zones. On the other hand, when water is adequate, irrigated farming produces far higher yields on average than rainfall farming. Thus, there is substantial investment in irrigation reclamation during protracted episodes of normal or above normal precipitation. However, growth is not sustainable when long term precipitation rates decline on the order of 5 percent or more from average because runoff drops disproportionately. Consequently, over the millennia, populations dependent on irrigation agriculture have repeatedly pulsed outward over arid landscapes in wet periods and defensively reconfigured in times of rainfall and runoff decline. This process is reflected in ruins of vast agrarian works that blanket the arid Andean landscape.

ADAPTATION TO PROTRACTED DROUGHT

The recurrence of protracted drought raises the probability that indigenous populations reacted to episodic dessication in patterned ways based on prior experiences, and that some of these responses are evident from the archaeological record. A very high degree of subsistence mobility characterizes highland agro-pastoral adaptations because they are based upon the exploitation of multiple, dispersed ecological zones stratified by altitude (Murra 1972). Annual hazards associated with short growing seasons and poorly developed mountain soils include topsoil erosion, erratic precipitation, temperature fluctuations, saturated soils, frost, and hail. Mediation requires rapid transmission

of information so that agricultural and pastoral activities can be reprogrammed on short notice (Earls 1996:302, 304-305). It also requires preserving, storing, and stockpiling food reserves because poor harvests are frequent (Orlove and Guillet 1985:10). Drought exacerbates many negative factors affecting human adaptations in the central Andes and contributes to declines in productivity, botanical variability, and increasing distances between valued commodities.

Large, dense population areas are also affected by drought because these had long traditions of complex social organization, culminating with the LH Inca imperium. Inca political formation was a slow process that began shortly after 1000 C.E. with the gradual consolidation of local ethnic groups (Bauer 1992:1, 40-48, 72, 90-94, 109-123, 124-139, 149-147). Thus, the nascent polity was formulated and grew during the long periods characterized by low average rainfall. After 1400 C.E., as average rainfall levels increased, the Inca adapted corporate styles of art, architecture, and construction on a monumental scale both in the capital region and in the provinces. *Corvée* labor was employed for large-scale agrarian reclamation of land that was not farmed, or that was underutilized. Initially, much of the reclaimed terrain was at high elevations along the eastern Andean escarpment, utilizing terracing in high rainfall zones, although such terracing was a drought response at the folk level. Later, as rainfall levels increased even more above normal, *corvée* labor was used to reopen farming in lower, warmer elevations where conquered communities were often resettled. Therefore, certain Inca *corvée* policies over time may be considered as adaptations to both drought and to increased rainfall.

Inca food storing and stockpiling are unsurpassed in the annals of South American civilizations (LeVine 1992:15). The monumental construction and prominent display of warehouses (*qollka*) frequently surpassed the quality

and placement of commoners' houses. Erected in rows, hundreds, and in some cases, thousands of *qollka* were strategically positioned on high hills and could be seen from great distances. Although prominently displayed for reassurance that the state provided contingency food supplies, their locations on mountainsides also provided cold air currents to help preserve food quality by removal of heat that serves as a catalyst for the spoilage of organic material (Morris 1992; Rowe 1946). Although the stores were generally used for state purposes, they were also used to mitigate food shortages among the common people (Rowe 1946:266-267).

In contrast, the coastal Chimu polity responded to low rainfall periods by contracting its agricultural base commensurately with its lower water supplies. While canals were infilled to create smaller channels during drought, no evidence of the reverse process is evident for the late MH to LH times when water supplies increased. This may be attributed to the domination of the north coast by the Inca and the disassembly of the Chimu state's agricultural multi-valley domains to suit Inca political goals for the region.

In EIP times, it appears that some shift from the Mochica capital in the Moche Valley center occurred to incorporate, through conquest, larger northern valleys, the Jequetepeque and Lambayeque in particular, with rivers less subject to flow rate intermittency and large land areas suitable for agriculture. In the late LIP, a similar expansion into northern valleys by the Chimu, who were centered at Chan Chan, in the Moche Valley, had, as its goal, an increase in agricultural sustainability to support an expanding population. This expansion was likely driven by similar drought effects that challenged agricultural sustainability in the Moche Valley with its small land area and intermittent river water supplies. Territorial expansion into large,

irrigable valleys is also a coping strategy, albeit a last resort when innovation is lacking.

HIGHLAND AGRICULTURAL STRESS AND RESPONSE

Recent work has postulated that the 1100 C.E. drought played a role in the collapse of the Tiwanaku polity centered around Lake Titicaca (Kolata and Ortloff 1996:110, 151; Ortloff and Kolata 1993). This is premised upon the fact that the agricultural base of Tiwanaku was anchored in some 80 square kilometers of raised fields in the extensive low-lying areas along lake margins north of Tiwanaku (Binford *et al.* 1997: 235, 243, 245). The raised field mounded ridges are elevated 1-1.5m above the water table and have planting surfaces 2-10 m wide that range from 10 m to 200 m long (Kolata and Ortloff 1996:118). Built in parallel row segments, each ridge is separated from the next by a depressed trough of similar dimensions that held slow moving spring-supplied or standing ground water which is essential to the high productivity of ridged field systems (Kolata 1996:118-120).

Warmed during the day by solar radiation absorbed by dark, decomposing organic material in the water troughs, heat is released during cold nights into the soil mounds to maintain internal mound temperatures near the freezing point, but insufficiently cold to cause a phase change to ice, thus limiting damage to root crop biomass. The mound phreatic zones are also effective in collecting and storing solar radiative heat due to the high specific heat of moist soils (Kolata and Ortloff 1989: 252, 256-260).

As lake and runoff levels declined after 1100 C.E., the water table subsided, desiccating raised field systems and reducing their thermal storage potential. By the time the lake fell to its -12m low-stand, more than 50,000 hectares of raised fields had been abandoned. The population of Tiwanaku's urban core dispersed to utilize

higher fields located near high water table zones, and occupy small rural settlements (Alberracín-Jordán and Mathews 1990:146-148).

While creation of small sunken gardens as a drought response was tenable in limited regions of the land-locked Titicaca Basin, where water was not far below the ground surface, this was not an option in most sierra basins with steep drainages. Along the western Andean escarpment there were few means to compensate for food loss in the dry sierra below 2000 m. Here slopes are steep, ground-water is deep below the land surface, runoff is limited, and natural vegetation is sparse. In this region of the Moquegua Basin, Tiwanaku colonies and later post-Tiwanaku Chirabaya populations dependent upon rainfall and irrigation agriculture declined significantly during the post-1100 C.E. dry period (Ortloff 1989:472-475, 477).

Unlike the coastal valleys, where tectonically-induced river down-cutting forced farmers to shift their river canal inlets to lower altitudes downstream to channel water into canals (Ortloff *et al.* 1985:77-78, 85, 90-91, 96-97), sierra farmers shifted to higher elevations in pursuit of higher rainfall rates and pre-drought quantities of subsurface water supplying moist pasture lands at altitudes about 100 to 400 m or more above the normal level of cultivation. There were many constraints on the uphill pursuit of rainfall and soil moisture. Fewer types of crops can be grown at higher elevations because soil quality decreases and the frequency of frost, hail, and erosion increases. While terracing can provide planting surface stability, the labor investment is high and time consuming to implement and thus does not constitute a short-term solution to climate variation. In the central highlands of Peru, by about 1300 C.E. colder, dryer climate conditions forced a downward shift of as much as 150 m in the altitude distribution of natural vegetation zones relative

to today's levels (Seltzer and Hastorf 1990:402, 405-408, 410).

Thus, as highland people moved agriculture and pastoralism into higher, wetter altitudes, the elevations at which plants, pasture, and crops could grow diminished, and drought-response farming moved from gentle to steep inclines. To reclaim upland mountain slopes, agriculturalists constructed terraces over a span of many generations to control soil loss and regulate moisture levels for specific crops. Along the Pacific watershed and sierra zones, terracing was combined with canal irrigation to capture high elevation runoff streams. In addition to permitting crop cultivation at higher altitudes, terracing was widely used to move farming eastward into the Atlantic watershed. Even during drought this region was better watered than the rest of the central Cordillera. Hence terracing allowed farming to expand into less extreme elevations where more types of crops can grow.

Over the course of many drought-influenced centuries in the latter part of the LIP, millions of terraces were built to reclaim vast areas of the Andean uplands in the eastern escarpment. Whereas both agrarian productivity and populations declined along the lower Pacific watershed, the drop in rainfall was a major catalyst for economic and demographic radiation into the upper and eastern highlands, culminating by about 1400 C.E. in large populations at high altitudes. Because normal sierra runoff farming produces higher yields than sierra rainfall farming, as the drought mitigated during the Little Ice Age, farmers reverted to lower, warmer settings better for plant growth. Thus, where mobility was possible, population concentrations shifted to maintain agricultural sustainability. For cases for which large fixed investment in a specialized agricultural method was tied intimately to the landscape (altiplano raised fields and coastal irrigation networks, for example),

innovation applied to these fixed systems was the only option for maintaining sustainability.

To augment agrarian tax revenues, the Inca imperium often forcibly resettled conquered high altitude communities on lower terrain made more productive by increased rainfall, soil moisture, and runoff. Although post-LH precipitation rose above long term normal levels, demographic decimation in the wake of European pandemics left Spanish overlords with few people to farm large expanses of arable land. Because above normal rainfall and runoff persisted until about 1700 C.E., remnants of the indigenous population could still be forcibly relocated to even lower elevations. This facilitated political control and religious conversion and imposed cultivation of Old World cultigens intolerant of extreme altitudes. If the drought had not broken neither Inca nor Castilian resettlement policies would have been tenable.

Thus, during the last millennium, farming, and the millions it supports, have shifted over the elevated slopes of the Andean range in concordance with long term changes in rainfall and runoff, with political boundaries set as constraints. This story of climate change and human response over the mountain landscape is shown in ubiquitous terraces, fields, and ruins of past agrarian endeavors during EIP to LH times.

REGIONAL ADAPTIVE AGRICULTURAL STRATEGIES

The adaptive strategies used to defend agro-production in the face of drought, excessive El Niño rainfall, or the presence of above-average rainfall over time, are summarized in Table 1 and Figure 3. Specific to different geographic sectors and cultural periods, these strategies represent sustainability programs devised to protect agricultural fields and water supply systems. The defensive measures give direct evidence of cultural memory of responses to past

catastrophic events and constitute evidence of the importance of such events in shaping the technological response pattern relevant to specific areas and polities.

Table 1 - Regional and Adaptive Agro-engineering Technological Strategies

	EH	EIP	MH	LIP	LH
North Sierra					
high rainfall	–	–	–	–	–
drought	11	–	19	11, 19	11
Southern Altiplano					
high rainfall	–	5, 8	2, 5, 8, 12, 14	6, 14	6
drought	–	8, 12	3, 5, 8, 12, 13, 19	4, 6, 7, 8, 13, 14	7, 19
North Coast					
high rainfall	2	2	1	1, 5, 16	–
drought	4, 11, 17, 18	3, 4, 11, 17, 18	3, 4, 12, 15	3, 4, 7, 10, 15, 16, 18	–
South Coast small valleys					
high rainfall	17	–	–	1, 2	–
drought	18	9, 18	4, 9, 10	4, 9, 10	9

Key: A dash indicates lack of available information.

1. *Canal hydraulic controls*: canal inlet blockage from rivers to regulate canal intake flow rate; use of canal overflow weirs (downhill water spillage from canals) triggered by El Niño-induced canal flow rates exceeding design capacity, *i.e.*, excessive rainfall-induced canal flows activate supercritical chokes causing side overflow weirs to activate to release excess flows; stream-wise alteration of canal slope, wall roughness, and cross-section shaping to alter flow height and velocity; dividing canal flow into two separate streams at different slopes and velocities, then recombining to induce a hydraulic jump in a single channel used as an energy dissipation method to slow flow velocity; coupling of intra- to inter-valley canals as a

means of reactivating dessicating intra-valley canals. They redirected water in excess of that required for available arable land, directing flow from large rivers to adjacent valleys of political importance to increase the latter's agricultural footprints and increase local sources of food. Examples present in Chimu Chicama-Moche Inter-valley, Lambayeque-Supe-Leche Inter-valley, and Chillón-Rimac-Lurin (Lima) Inter-valley complexes (Kosok 1965: map page 24, map page 86 figure 8 page 90, map page 146; Ortloff 1993: 345, 347-351, 356, 2009; Ortloff *et al.* 1982:581, 583-588, 591-593, Ortloff *et al.* 1985).

2. *Flood diversion channels*: used mainly in the Tiwanaku and Lukurmata areas of the Bolivian altiplano to intercept and shunt excessive

rainfall runoff from adjacent hill slopes directly into Lake Titicaca (Kolata and Ortloff 1996: 115, 121, 147, 149-50; Ortloff 1996) in order to modulate ground water level with respect to planting surfaces. Some application to Moquegua Valley mountain region terraces (in Wari and Tiwanaku colonies) to divert excessive rainfall runoff in terrace supply canals into downhill spillage channels draining into quebradas. Use of Pre-Moche or Moche Great Trenches for flood water diversion (Ortloff 2009).

3. *Ground water recharging*: north coast Moche and Chimu sunken gardens (*wachaques*) and Chan Chan compound wells (Ortloff 1993) activated by canal water seepage from field systems; Tiwanaku and Pampa Koani use of spring-fed canals to deliver water to local raised field water troughs to alter local water table height and chemical nutrient composition (Ortloff 2009).

4. *Springs, wells, and minor sunken gardens*: Moche Valley *pukio* (spring) systems; north coast Chimu wells in Chan Chan (Ortloff 1993: 343, 356, 364) and use by earlier north and south coast cultures; minor sunken garden systems (*cochas*) in late to post-Tiwanaku (Kolata and Ortloff 1996:134). Use of perpetual *pukio*-sourced canals for valley bottom agriculture at Caral and other sites in the Supe Valley (Ortloff 2009).

5. *Runoff interception and river canal shunts to modulate groundwater levels*: Tiwanaku and Pampa Koani raised field systems (Ortloff 1996: 156, 157, 159, 166; Kolata and Ortloff 1996: 128, 134-137, 148-151) laced with main canals having elevated weir structures that activate at high water to drain excessive runoff water directly to Lake Titicaca; possible Chiripa antecedents; Chimu canal systems near Farfán (Jequetepeque Valley) with trenches uphill of canal systems to intercept rainfall runoff from

mountainous terrain (Ortloff 2009) diverted into quebradas to limit inflow damage to major canals.

6. *Terrace agriculture*: post-Tiwanaku V, highland Wari, Inca polities, planting surfaces moved to higher elevations during low average rainfall periods. Use of high elevation canals supplied by snowmelt channeled water to irrigate terrace systems (Ortloff 2009).

7. *Sunken gardens (cochas)*: used by late and post-Tiwanaku V altiplano cultures to supplement pastoralism-derived food supplies. Chimu coastal *wachaques* near Chan Chan (Moseley and Deeds 1982:31, 33, 35).

8. *Lake Titicaca raised field agricultural zone shifts to incorporate the optimum raised field moisture levels for subsiding or increasing lake and rainfall level*: optimization method applied to field systems on Pampa Koani (Ortloff 2009).

9. *Underground galleries and channels collecting groundwater for surface field agriculture*: (south coast Nasca galleries (Schreiber and Lancho 1995; 2006).

10. *Canal and river seepage utilization*: north coast Chimu (Chan Chan wells, aquifer recharge from field system seepage; Ortloff 1993:356, 363); Moquegua Valley Chirabaya coastal ground seep agriculture (Clement and Moseley 1991:430, 434-435, 441); north coast valley mouth agriculture at Casma, Virú, and Moche Valleys.

11. *High and mid-sierra reservoir and lagoon water storage and transport to coastal valleys*: Chimu, lower Jequetepeque and Lambayeque Valley systems; also Moche Nepeña and San José reservoirs and use in mid-sierra farming. Probable water delivery by geological fault (or canals) to the Supe Valley to maintain high water table and springs to support Caral agricultural base (Villafana 1986; Ortloff 2009).

12. *Canal collection and diversion of runoff to modify ground water profiles*: Pampa Koani Tiwanaku systems area on the Taraco peninsula (Ortloff 1996).

13. *Snow-melt water collection channels directed to mountainside terraces*: Upper highlands Moquegua Valley drainage, post-Tiwanaku V, Estuqueña and Wari terraces—technique used in elevated temperature periods to provide water in the highlands.

14. *Shift to terrace agriculture when Lake Titicaca completely covers raised fields*: Late post-Tiwanaku, possible reuse of early Tiwanaku terraces in Inca times.

15. *Multi-valley transport/distribution canals*: Chicama-Moche Inter-valley canal, Motupe-Leche-Lambayeque inter-valley canals, Lima complex (Chillón-Rimac-Lurín inter-valley canals) used as possible drought remediation measure based on redistribution of excess water beyond that needed for valley agriculture, to large land areas in adjacent valleys with small, intermittent rivers (Kosok 1965: map page 34, figure 8, map page 146).

16. *Hydraulic efficiency improvements in canal design by cross-section, slope, and wall roughness changes*: (Ortloff 1993:345, 347-351, 356, 2009; Ortloff *et al.* 1982, 1985); canal hydraulic design changes to maximize low canal flow rates during droughts. Improvements also include canal spatial relocations related to river down-cutting and inlet stranding.

17. *Lomas farming*: fog condensation agriculture in coastal, natural surface field—yields amplified during wet periods (Moseley 1992a:41).

18. *Adaptions toward a marine resource base*: For drought affected land regions with access to marine resources this shift can provide an addi-

tional protein source (Moseley 1992b:5, 7, 10-12, 16, 22, 33).

19. *Adaptions toward sierra pastoralism*: As a drought response, the shift from land agriculture to high sierra animal herding can provide additional food resources.

The adaptive strategies set out in Table 1 indicate conscious efforts to control water supplies by a variety of technologies specific to different geographical areas and agricultural systems. While many of these strategies are related to observation of long-term climate trends (3, 4, 6, 7, 8, 9, 11, 13, 14, 17, 18, 19) others provided specific defenses against short-term El Niño related flooding (1, 2, 3, 5, 12, 14), and drought events (1, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19). Table 1 indicates a library of agro-engineering responses to both long and short term climate variations over many time periods and demonstrates that observation of climate over time and related technological innovations and controls were important factors in system design and operation.

MODELING DROUGHT STRESS: KEY COMPONENT FACTORS IN HIGHLAND/LOWLAND RUN-OFF RATIO (R)

During drought, coastal farmland that normally supports an abundance of crop types can sustain only a reduced number of types with low water demands. Crop yields are reduced in response to lower water supplies. Sierra rangeland, in contrast, may support pastoralism and some form of agriculture due to elevated rainfall amounts at higher altitudes (but which, during drought periods, are lower than normal). One reason for the difference between coastal and highland agriculture under drought is related to the soil types that influence rainfall infiltration, runoff, and transport rates, given highland rainfall sources. Highland soils retain water within their porous structure until saturation is

reached. Past this level runoff occurs. Channeled runoff is further subject to evaporation, seepage, and subsurface porous medium retention effects through a different set of nonlinear relationships than the storage/saturation effect, resulting in imbalances in the rainfall/runoff delivery rate.

To illustrate the effect of drought stress and the hydrological relationships between rainfall, soils, runoff, and flow losses, an illustration from the Moquegua Basin is useful. The Moquegua Basin lies on the Pacific watershed to the west of Lake Titicaca. This river system is 139 km in length, with headwaters reaching slightly above 5,100 masl. Along the Moquegua coast precipitation is negligible, but it increases gradually in the interior with altitude. However, the quantity of rainwater only exceeds (saturated) retention values in the 19 percent of the basin that is above 3900 masl. Between 3900 and 4500 m, average rainfall is about 360 mm/yr, of which 260 mm is absorbed at saturation and 100 mm is available as runoff (Perú, ONERN 1976). In this zone, a 10 percent, or 36 mm, decline in rainfall to 324 mm decreases runoff by 36 percent from 100 mm to 64 mm. Given a specific soil type with a given retention capability, the soil always retains the same amount of water, so a 15 percent decrease in rainfall results in a 54 percent decrease in runoff. In the elevation zone between 4500 and 4900 masl, rainfall averages 480 mm/yr and a 10 percent or 15 percent rainfall reduction results in runoff reductions of 21.8 percent and 32.7 percent respectively. Thus the asymmetric disparity between rainfall and runoff reduction diminishes as precipitation increases. Comprising less than 3 percent of the Moquegua Basin, precipitation in the zone of alpine tundra above 4900 masl is principally in the form of snow and ice (Perú, ONERN 1976). The runoff contribution is not known because an unknown amount of this moisture is retained in glaciers and snow-fields. Nonetheless, for the upper river basin as a whole, rainfall declines of

10 to 15 percent result in runoff reductions of 25 to 40 percent or more. Significantly, the asymmetric relationship between rainfall and runoff also works in reverse. Increased precipitation rapidly saturates the soil which then discards water and amplifies runoff. This effect was prevalent in the first two centuries C.E. when precipitation rose by 20 to 25 percent and the runoff by 72 to 90 percent.

Drought stress is exacerbated by the fact that once rainfall saturates the soil and excess water is released, some surface runoff is lost to evaporation and seepage. Due to these factors, the Moquegua River loses about 4 percent of its flow per kilometer in the arid sierra at elevations around 2250 masl. Other than during spring floods, the river channel does not normally carry surface flow at elevations below 1200 m. Farming in the coastal section of the drainage depends on springs fed by subsurface groundwater flows originating high in the river basin. The relationship between highland rainfall and coastal spring flow is highly asymmetrical because subsurface water flows through porous geological strata. Similar to soils, porous deposits have different hydraulic conductivity and saturation values. Although these values are poorly known, there are indirect indications that coastal spring flow may have dropped by 80 percent during the 1100 C.E. drought (Ortloff 1989:457-477). These calculations are approximations for the Moquegua Basin. Other soil adsorption and precipitation values characterize other drainages. Nonetheless, relationships between rainfall and runoff are always nonlinear, so drought always exerts asymmetrically greater stress on runoff farming than on rainfall farming.

The runoff not directly channeled into rivers is diminished en route to coastal zones by further infiltration into increasingly porous soils (adding to the local water table profile) as well as by evaporation losses. The resulting coastal

river hydrographs track the availability of coastal irrigation water over time. Of course, the details will vary between coastal valleys as functions of local soil geomorphology, topography, evapotranspiration, agricultural productivity potential, and temperature and humidity history. The net effect is one of a nonlinear, but generally similar, relationship between unit amounts of input rainwater at different altitudes and times, and net deliverable water to coastal irrigation systems with time lags. From this discussion, it may be concluded that in dry periods rain at high altitudes may sustain some form of agriculture in these zones, but coastal agriculture derived from runoff into rivers from the same watershed will experience a severe deficit of irrigation water. In terms of quantifying the runoff effect, the Runoff Ratio (R) is defined as the average net runoff rate from an area divided by the average rainfall delivery rate to the same area. Here $R=0$ denotes zero runoff and $R=1$ denotes that all delivered rainfall to an area converts to runoff, implying a total saturation condition.

VULNERABILITY INDEX (1-V)

Figure 4 shows a plot of the main agricultural strategies practiced by Andean civilizations. A vulnerability index is defined relative to available rainfall levels. The first entry, raised field agriculture (Index 1), was widely practiced by MH Tiwanaku III-V around the southern and western periphery of Lake Titicaca. Tiwanaku groundwater based agricultural systems are largely invulnerable to short-term drought due to the continuous arrival of subsurface water from earlier rainfall in the immense collection zone around the lake. Because groundwater transport velocities are on the order of a few centimeters per month, groundwater from distant collection basins may have originated as infiltrated rain that occurred many years earlier. The groundwater based systems are likewise relatively invulnerable to seasonal excessive

rainfall because elaborate field drainage systems shunt water directly into the lake, thus limiting infiltration into the water table (Table 1). Because the collection basin rainfall rates and Lake Titicaca height vary with seasonal and climate-related rainfall/runoff fluctuations (Binford and Kolata 1996:37-38), the raised field water table height sufficient to maintain agriculture shifts vertically and laterally within the extensive lacustrine field systems (Ortloff 1996; Kolata *et al.* 1996:205), and productive farming zones can likewise be shifted. This indicates that not all of the raised fields in the Lukurmata area north of Tiwanaku were farmed simultaneously, but only those areas with water trough zones supplied by spring water and elevated groundwater profiles at the correct height for agriculture were utilized, with remaining areas allowed to fallow.

Prolonged drought over many years can destroy the special heat storage features that provided frost damage protection under diurnal and seasonal temperature variations (Kolata and Ortloff 1996:130) and decrease the height of the water table in raised field troughs necessary to sustain agriculture. The raised field systems can, nevertheless, be optimized to highland climate conditions and cycles to produce high crop yields through interventions shown in Table 1, and as demonstrated by modern resurrection and use of these systems (Kolata 1996:203, 206-207, 226, 228-230).

The next least vulnerable agricultural system to rainfall fluctuations is a variant of raised field systems—sunken gardens (Index 2). These systems are pits excavated to the phreatic zone and are mostly found as a last resort drought response system used when the water table has declined out of reach of plant root systems. While sunken gardens are common in the 1100 C.E. post-collapse settlements around Tiwanaku, similar *wachaques* are also found in Peruvian north coastal valleys in response to the

pan-Andean LIP drought. Being primarily a drought remediation measure, these systems have no defense against excessive rainfall and groundwater level rises, because simple drainage paths usually do not exist.

At the next level of vulnerability are the terraces widely used by Inca, Wari, and post-Tiwanaku highland civilizations (Index 3). Terraces are mostly supplied by rainfall and provide a well-drained agricultural system that is effective during rainy seasons. Other variants are supplied by snow-melt and channel water during periods of low rainfall and elevated temperature (particularly in the upland Moquegua area). As rainfall diminishes, these systems generally become marginal for production unless supplied by channeled water.

Next in increasing order of vulnerability (Index 4) is canal-fed irrigation as practiced primarily by north and south coast civilizations. Figure 4 indicates that such systems are only viable in the presence of highland rainfall exceeding saturation conditions. As such, if coastal agriculture flourishes, then highland agriculture has an excess of water supplies due to the nonlinear input/delivery R relationship. The highlands appear to always have demonstrated less vulnerability to agricultural stress regardless of the level of rainfall, provided the technology to use the available water is adequately developed in each ecological zone, and drainage technology to control the water table height is in place.

Generally, long canals are more vulnerable (Index 5) than short canals due to greater seepage and evaporation losses, tectonic/seismic distortions, and higher technological demands for design, low-angle surveying (Ortloff 1995:60, 70-71), and construction. Yet more vulnerable (Index 6) are the coastal seeps that supply agriculture, mainly in northern Chile and in the Ilo area of the Moquegua Valley (Ortloff 1989:

471-472). Such systems rely on groundwater seepage to coastal bluffs over long underground distances, and thus are only marginally productive compared to other delivery systems.

Survival of the more vulnerable agricultural systems is questionable past a critical level (line DD, Figure 4) and extinction of highly vulnerable systems is inevitable whenever reconfiguration to lower vulnerability systems is impossible. In the presence of yearly rainfall and runoff variations, high vulnerability systems must have superior technology, innovation, and modification features to maintain agricultural production. Figure 4 plots a Vulnerability Index (1-V) such that the largest values of the index denote the least vulnerable agricultural systems.

TECHNOLOGY AND TECHNOLOGICAL CHANGE UNDER CLIMATIC DURESS

Andean agricultural systems have a long history of evolution and improvement over time. A sample of agricultural strategies (Figure 3) is shown for modified and unmodified water and land surface variables. An initial choice of an agricultural system fitting local ecological conditions is made by early inhabitants. System evolution proceeds through observation of agro-production changes in response to field system design changes. Key requirements are the preservation of the system and its efficient functioning under seasonal weather fluctuations, as well as those arising from large-scale climate fluctuations. Therefore, the ability to modify an agricultural system to maintain sustainability in anticipation of climate-related changes in water supply is part of the original concept of the system as shown by the interventions listed in Table 1. The agro-system modifications must be performed more rapidly than the climate variation effect unfolds, *e.g.*, system modifications are effective when long-term climate changes are initially observed and system modifications are carried out in anticipation of a long-term trend.

Therefore, the Vulnerability Index (1-V) of an agricultural system depends upon the sustainability of an initial design choice in the face of weather and climate variations, as well as the ability to modify technology (T) in time (t), denoted as (dT/dt) , faster than the climate-induced creation/evolution rate of a climate related disaster (dD/dt) .

AGRICULTURAL SUSTAINABILITY MODEL

Several key factors influencing agricultural sustainability have been discussed from the viewpoint of agricultural systems strategies. These factors, and others, are next combined to produce a trend equation where increases or decreases in each term imply a net increase or decrease in the agricultural sustainability (Q) of a society. The quantities in the equation (Q, R, S, P, V, Y, dT/dt and dD/dt) are non-dimensional values normalized to the maximum reference state for each variable. A large value of Q connotes agricultural sustainability, while a small value denotes the opposite. From the foundation of the above discussion, a simplified model equation, *based upon agricultural parameters only* (i.e., excluding implied or induced social, political, economic, and/or governmental system effects) can be postulated as:

$$Q = S + Y \cdot A \cdot R + (1-V) + P'(2-P') (dT/dt)/(dD/dt)$$

where R is the Runoff Ratio ($0 < R < 1$), S the agricultural storage capacity ($0 < S < 1$) normalized to S_{mx} where $S=0$ represents zero crop storage and $S=1$ represents total storage of all unconsumed crops. The quantity $Y \cdot A \cdot R$ represents the main comestible crop yield per land unit area times the total land area times the available water supply to the area normalized so that $0 < Y \cdot A \cdot R < 1$. Here the zero limit is a trend toward poor crop yield over a small land area with poor water supplies, while the unity limit indicates the best crop selection over the largest possible agricultural area sustained by

irrigation. The term, $P' = P/P_{mx}$ is defined as the population density ratio where P_{mx} is the maximum population sustainable by the in-place agrosystem. If $P'=1$, then $P'(2-P')=1$ at the maximum population level balanced with the food supply. If $P'=0$, then $P'(2-P') = 0$, indicating that a very small population exists (such as may occur after a natural or man-made disaster). Thus:
 $0 < P'(2-P') < 1$.

As before, (1-V) is the agricultural Vulnerability Index ($0 < V < 1$) for the agricultural system involved as shown in Figure 4. For the remaining terms, $0 < dT/dt < 1$ represents the time rate of technology (T) change to surmount a long term climate effect (excessive rainfall, drought) on agricultural production. Here the maximum dT/dt value is assumed to be unity to represent a technology growth rate typical of most advanced agriculture based societies. Here dT/dt can be large due to technical innovations listed in Table 1. The dD/dt maximum value may be typically very large for rapidly evolving disasters such as El Niño events (reducing Q dramatically in a short period). The $1 < dD/dt < \infty$ term is representative of the time rate of change of disaster-producing climate factors. Therefore, if $dT/dt \div dD/dt = dT/dD \geq 1$, the rate of development of technology to defend against climate-induced changes in water supply exceeds the rate of disaster evolution on the same time scale, then a positive effect on agricultural sustainability Q exists. If a sudden El Niño flood event occurs beyond the defense mechanisms' ability to protect, then $dT/dD \div dD/dt$ is a small number indicating no contribution to agricultural sustainability, Q. If, however, a climate related disaster evolved at the same rate as a defensive technology, then $dT/dt \div dD/dt \geq 1$, and then Q shows increased sustainability.

If $P' < 1$, then the labor force to make rapid dT/dt corrections is not available and Q de-

creases. If $P' \approx 1$ in the presence of a declining agricultural supply, the agricultural resources are inadequate to feed a large workforce over time to ensure rapid dT/dt changes to increase Q . Thus, only a population balanced with agricultural supply (including storage) promotes large sustainability Q values. The relative value of Q ($0.2 < Q < 4$) (increasing or decreasing) applied to highland and coastal societies at different time intervals then gives indication of some underlying factors behind the relative agricultural sustainability of one society over another—at least based on agricultural parameters in different time intervals. Overall, from the Q equation, sustainability is enhanced when the runoff ratio/water supply (R), land area (A) in cultivation and crop storage (S) are all high, a stable population is balanced with agricultural output ($P' = 1$), the system vulnerability is low, the technology innovation rate exceeds or equals that of the disaster evolution rate, and soil productivity (Y)/unit of water input is high. In general, high Q indicates a successful, well-managed society with foresight to maintain a sustainable agricultural base despite weather and climate variations. Low Q indicates gaps in the perception of threats that will cause an agricultural system to fail or operate in a marginal manner. Of course, for extreme, long-lasting negative climate variations such as long-term drought, Q must ultimately drift to smaller and smaller values indicating that sustainability is no longer possible. We now use the Q equation to analyze historical patterns,

ANDEAN HISTORICAL PATTERNS

In the Uhle-Rowe chronological sequence, each period is characterized by a dominant polity (or polities) with distinct societal, political, and economic structures, governmental systems, architectural and settlement patterns, ceramic and religious iconography, and agro-engineering practices. Frequently, one dominant trait characterizes the period. During horizons,

one society exerts overarching influence over vast territories. During intermediate periods, dominant regional states may exert control primarily through branching government structures capable of integrating adjacent territories into the same ideological and political template. Although some revision regarding Formative and Preceramic societies such as Caral, 24 km inland in the Supe Valley (Figure 1), will undoubtedly alter previous understanding about origins of coastal society development, too little is known about climate effects in that period (3000-2100 B.C.E.) to warrant incorporation into the present discussion.

The Early Horizon is characterized by highland Chavín influence diffused into Peruvian north and central coast radiation centers showing similar, but locally interpreted, artistic traditions in iconographic, ceramic, and textile traits. The expansion of Chavín influence from highland sources appears to have been religion-based. Minor south coastal societies (Paracas Cavernas) arose at this time and had regional influence.

During the EIP major coastal architectural and agricultural complexes were begun by the Moche who were dominant on the Peruvian north coast. Lima cultures were preeminent on the central coast, and the Paracas and later Nasca polities were established on the south coast. All were characterized by some form of limited centralized administrative control. The minor north highlands Recuay culture and the Huarpa society of the central highlands arose in this period, but had only local extent and influence and built only minor irrigation works compared to the major coastal and highland polities.

During the MH there was a shift back to highland dominance with the late Tiwanaku (Phases IV and V) and Wari states dominating much of the southern and central Andean

coastal and highland regions through their political, economic, military, and religious influences. Large agricultural complexes in the form of raised fields, in the case of Tiwanaku, and terraces, in the case of Wari, were constructed in conjunction with secondary administrative centers such as the Tiwanaku centers of Omo, Pajchiri, Lukurmata, and Wankarani and the Wari centers of Pikillaqta, Cajamarquilla, Viracocha Pampa, Cerro Baúl, and Wari Willka.

The subsequent LIP is characterized by a shift back to prominence of coastal societies with the Chimú ultimately occupying a north coast zone from the Chancay Valley to the Lambayeque Valley. The Chimú incorporated a complex of new administrative centers (*e.g.*, Farfán, Manchan, Purgatorio) with older ceremonial centers (Pacatnamú, Chotuna) in north coast valleys adjacent to the Moche Valley where their capital of Chan Chan was positioned. The idea of centrally administered, multi-valley agro-engineering complexes directed by satellite administrative centers sharing common political, social, and religious practices appears to be a central feature of this period. Ica culture is dominant in the south-central coastal areas at this time, with the minor intermediate-highland Recuay and Cajamarca societies having only regional influence.

Military conquest and complete dominance of highland and coastal polities by the Inca state occurs in the LH. It appears coincidentally that the EH-EIP-MH-LIP-LH chronological sequence somewhat corresponds to a geographic alteration of prominence between highland and coastal polities. Because the effects of climate on agricultural systems had some role in the sustainability of Andean civilizations, these effects are next discussed in terms of the Q equation.

HORIZON AND INTERMEDIATE PERIOD SUSTAINABILITY CYCLES IN TERMS OF THE Q EQUATION

The climate change history reflected in the Quelccaya, Huascarán, and Titicaca cores indicates a drought in the late EIP. This drought seems to have had a role in the decline of the coastal Moche and Nasca polities at their traditional sites, while the highland Tiwanaku and Wari polities began their rise to the prominence observed later in the MH. A drought-induced lower Runoff Ratio (R) affected coastal zones disproportionately. Coastal canal-based irrigation systems have high vulnerability (low 1-V) because they are runoff-dependent. Known coastal agricultural storage facilities are minimal and population apparently was in balance with pre-drought agricultural resources (*i.e.*, balance is taken to mean that agricultural resources are adequate to sustain the given population size). Yields for irrigation-based agriculture are high, provided R is high. While technology (Table 1) to modify and defend agricultural systems was limited in early EIP times, and a slowly evolving drought crisis developed, $dT/dt \div dD/dt < 1$ resulted because technical innovations alone could not overcome extreme long-term drought, even at sites with high soil productivity. The net EIP result is a Q decline of coastal polities (Figure 5).

While large populations can provide labor resources, unless a technology is present (or can be rapidly developed) to utilize these labor resources, then large populations adapted to food supply levels developed during wet periods suddenly become liabilities when drought onset is rapid. With reference to the Q equation, drought then reduces the agricultural sustainability compared to pre-drought periods, *e.g.*, Q decreases during droughts for Vulnerability Index 4 and 5 systems characteristic of the north and south coast EIP, where low R and S prevailed. Some migration of the Moche to

northern coastal valleys and the creation of new centers such as Pampa Grande occurred in late EIP and early MH times, indicative of the need to restore Q to higher levels, primarily by utilizing high agro-technology levels (dT/dt) in combination with the canal-interconnected, higher flow rate (R large) rivers (such as the Leche, Chicama, and Lambayeque Rivers) with vast, fertile land areas (large $Y \bullet A \bullet R$).

Highland Tiwanaku and Wari cultures achieved high levels of sustainability Q during late EIP and MH times due to elevated highland rainfall rates. Because of their design features that imply large dT/dt , the low vulnerability Tiwanaku raised field systems and Wari terrace systems flourished under both high rainfall and intermediate-term drought conditions (Table 1). The highland systems have high R , S , Y , $1-V$, with balanced P' . Highland civilizations' sustainability Q continued high through the MH and apparently led to the diffusion of highland iconography and architectural patterns to the north coast polities, although the exact processes supporting this diffusion are still the subject of active research. Highland rainfall was apparently adequate during the late part of the EIP, so that Wari terrace agriculture flourished. However, towards the end of the MH diminishing rainfall levels undermined the productivity of these systems as sustained drought took hold after 1100 C.E.

With respect to the Q equation, highland Tiwanaku in the late EIP and early MH was characterized by low vulnerability (V) raised field systems (Table 1), large storage facilities (S), high yields from raised field agriculture ($Y \bullet A \bullet R$ large), large water supply, high dT/dt but slowly increasing dD/dt as drought began to reduce rainfall levels by 5 to 10 percent from previous norms, and a large population that could be utilized to modify the location of the agriculturally productive raised field zones in the Lake Titicaca area. The net result is a high Q

value that indicates good sustainability through the MH until the deepening drought that starts in the early LIP.

At the end of the MH, highland polities undergo very slow collapse due to effects of long term drought, while coastal polities (Chimu, Sicán, and Lambayeque) appear to flourish. This can be explained by observing that while R , S , and $1-V$ were low in coastal areas, dT/dD , Y , and P' were high, reflecting the development of advanced transport and distribution canal technology, sufficient labor to implement major agro-engineering projects that altered canal placement and design to accommodate drought effects (dT/dt large), and the availability of marine-based food supplies to supplement land food resources.

Coastal valley canal systems can be easily modified to manage reduced water supplies. This is evident with the reconfiguration of intra-valley canals (Ortloff *et al.* 1985) and the development of large, inter-valley canal systems (*e.g.*, the Chicama-Moche, Motupe-Leche-Lambayeque, and Chillón-Rimac-Lurín systems; Kosok 1965: map page 24, map page 86, figure 8 page 90, map page 146; Ortloff 1993; Ortloff *et al.* 1982) that redistribute available water over long distances between valleys to large field system complexes. While water supplies were adequate, low-slope surveying accuracies (large dT/dt) extended canals to larger cultivatable areas (Ortloff 1995). When water supplies declined due to drought, canal replacement and reshaping for hydraulic efficiency improvements provided an optimum strategy (increasing dT/dt further) to distribute available water supplies brought in by inter- and intra-valley networks. The potential to transfer main agricultural zones to higher flow rate north coast valleys may be thought of as another variant of "storage capability S " or simply an increase in R . Therefore, sustainability of coastal societies under declining water resources is aided by their ability to alter

irrigation systems (technology and placement), while highland raised field and terrace systems cannot be easily modified, and are thus also susceptible to long term drought extinction.

To illustrate this point, while the Tiwanaku raised field systems have high 1-V, and water table height and agricultural area movement was somewhat controllable (Table 1) in the presence of extended drought, an option to lower all 80 square kilometers of the Tiwanaku-Lukurmata raised field planting surfaces to accommodate the late MH drought-induced sinking water table would have required a vast labor input over many years to achieve marginal benefit. While a large Chimu labor force on the coast could have been productively employed in canal modification and inter-valley connection projects and expansion into large land areas, even the large highland labor force was not sufficient to modify 80 square kilometers of raised fields effectively in time to lower the levels of large enough areas to accommodate the declining water table levels induced by sustained drought, although lateral transfer to high water table areas provided some limited relief. Therefore, higher dT/dt is possible for coastal irrigation systems due to more easily modified canals, use of inter-valley canals that redistribute water, and relocation of agricultural production centers to water-rich valleys while highland systems are limited in design modifications to react to long term drought, but are highly resilient to short term drought. Although highland agriculture based upon terraces can move upslope in drought conditions, Y decreases due to poorer soils and decreasing farming area. The lower runoff R available to coastal zones can still be better utilized due to higher Y from fluvial-deposited soils, more effectively utilized labor resources, and high dT/dt from various strategies, despite the somewhat higher vulnerability index of canal systems.

Eventually, coastal systems had the potential for recovery as normal levels of rainfall resumed in the late LIP. The water supply advantage to highland systems (large Q , R , S , 1-V, $Y \bullet A$, P' , high dT/dt and low dD/dt) was again manifest in the LH to the advantage of the Inca. Their policy of population relocation to revitalize high and lowland agricultural centers, however, saw the end of many LIP polities operating in their previous political-economic and socio-political modes. A summary of Q equation results over time is shown in Figure 5 for the major polities discussed above.

SUMMARY

MH highland expansion/radiation appears to be associated with low vulnerability agricultural systems and adequate rainfall. The late EIP and mid-LIP are associated with steady but lower average rainfall levels with coastal polities somewhat maintaining their full population potential based upon large arable land areas and balanced populations. Coastal polities' choice of farming methods based on irrigation technology in extensive fertile valley areas together with superior irrigation management skills provided the basis for further expansion of these polities in time. In the presence of extended drought, however, the ability to modify canal systems and relocate population to different valley enclaves with better water supplies and the ability to supplement plant foods with marine resources extended sustainability of these coastal societies. For example, while the Chimu could direct the expansion of Chan Chan towards the coastline to intercept the declining water table with urban wells, construct sunken gardens, start construction of the massive Inter-valley Canal to direct Chicama River water to revitalize the desiccated Moche Valley intra-valley canal networks, and easily modify intra-valley canal systems, only small sunken gardens, limited use of distant raised field areas, and pastoralism were possible

as alternative highland urban center survival strategies.

In the Moche Valley at least 30 percent more terrain was farmed in the past than until recently. Agricultural systems bear widespread evidence of disastrous destruction and initial loss of land due to exceptionally severe flooding during a 1100 C.E. El Niño event during a long term drought in the 1100-1400 C.E. period that disrupted many northern valleys (Ortloff 1993:334-337, 339). The building of the Chicama-Moche Inter-valley Canal was a strategy to direct water from the larger flow rate Chicama River to the dysfunctional Moche Valley Vinchansao Canal to resupply the north side Moche Valley intra-valley irrigation system as a response to extended drought in the mid-to-late LIP. However, in the presence of such extended drought, neither the Inter-valley canal, nor the intra-valley distribution canals carried sufficient water to maintain the earlier field systems over time. As part of the Chimú strategy of dispersal of fields to water sources, feeder canals from the Inter-valley Canal to the Lescano fields south of the Chicama River, and to the Chicama Valley fields, helped sustain the Chimú Empire in this period. Ultimately, however, large land areas were lost as river runoff dwindled in the presence of sustained drought and tectonically-induced river down-cutting stranded inlets, forcing loss of arable land (Ortloff *et al.* 1985). Reclamation efforts in the Moche Valley shifted to low areas where sunken gardens could access ground water, but this strategy could not match the volume of past field production. Northward military thrusts to incorporate valleys from Jequetepeque to Lambayeque, with their higher flow rate rivers and potential for large agricultural domains proceeded in this period, most probably as a survival policy to maintain the Chimú empire.

The highland counterpart drought in the late MH involves extensive use of pastoral

resources to add to high productivity brought about by largely invulnerable agricultural systems—at least where short term, as opposed to long term, drought is concerned. Early Tiwanaku and Wari expansion is associated with adequate water supplies and low vulnerability systems tailored for optimum productivity in a highland weather/climate environment. Upon transition into an extended drought continuing beyond 1100 C.E., LIP coastal societies manifest at least transient sustainability due to high dT/dt levels, while the Tiwanaku state declined slowly due to the lack of possible modifications to their agricultural systems in the face of extended drought. Eventually, both highland and coastal polities underwent decline in the late MH and LIP and only the return of water resources to previous norms in the early LH reactivated elements of Andean society—albeit now under Inca military domination. Under higher rainfall conditions in the late MH and throughout the LH, terraces replaced previously abandoned fields in the Inca dominated highlands. Abandoned agricultural terrain in conquered territory was repopulated with groups from dissimilar territories. An overview of the historical record appears to show some shifts of major population centers over time, and shifts of dominant polities from coastal in the Formative, to highland in the EH, back to coastal in the EIP, to highland in MH, to coastal in LIP, then back to highland in the LH. In view of the previous discussion, this trend appears at least partially related to climate shifts and their effect upon the agricultural bases of different polities.

Highland and lowland environments offer different options for responding to drought. When highland rainfall declined by 5 to 15 percent from previous yearly norms during the 1100-1500 C.E. dry period, runoff reaching the littoral desert declined on the order of 30 to 50 percent or more. The amount of land under irrigation decreased proportionally, as did agrar-

ian yields. Long term corollary declines in population are documented in a number of northern and southern desert valleys (Owen 1993a: Appendix F, 1993b: 12; Willey 1953:19-37, 390-395; Wilson 1988:357-358). Although use of marine resources intensified, there were few means to mitigate farming shortfalls on the coast. Reconstructing canals to make water delivery more hydraulically efficient and lining channels with silt and clay to limit seepage was undertaken in the lower Moche Valley (Ortloff *et al.* 1985:85, 87, 88-90, 93, 95-96) as a defensive strategy to conserve precious water resources. Population centers clustered around available river resources in valleys under Chimú control. In the lower Moquegua Valley, farmers diversified plant foods to include drought tolerant domesticates and wild species. The most dramatic attempts to alleviate coastal food loss entailed the utilization of ground water *wachaqes* during 1100-1300 C.E. dry period as surface water sources diminished. Hydrological conditions conducive to agrarian and demographic recuperation did not return to the littoral valleys until the drought abated and above normal runoff and rainfall occurred in the Little Ice Age, post-1400 C.E. (LH). By this time, however, the highland Inca had conquered the drought-depressed coast and thereafter littoral populations were decimated by the convergent catastrophes of Old World pandemics and Spanish subjugation.

While drought can be a prime reason for change in the political and social context of different polities, other nature-derived effects in the form of collateral disasters involving earthquakes and El Niño events transpired during the centuries of drought and contributed to stress. One documented incident warrants brief review. When the 1100-1300 C.E. drought began in southern Peru, the Moquegua drainage was occupied by the post-Tiwanaku V Chiribaya culture. This society was mostly focused upon the coast but also extended into the lower arid

sierra. Exceptionally severe El Niño flooding decimated the cultural landscape around 1360 C.E., and the Chiribaya occupation was largely obliterated (Moseley *et al.* 1992; Satterlee 1993; Satterlee *et al.* 2000/2001). Demographic recuperation was minimal (Owen 1993a:535-537) and post-disaster population levels in the lower drainage remained some eighty percent below pre-flood levels. Poor recovery is attributable to continued drought. Calculations for one Chiribaya irrigation system suggest that water supplies and productivity had declined by at least eighty percent when dryness was at its peak (Clement and Moseley 1991: figure 9; Ortloff 1989:472-475). Thus, the collateral El Niño disaster struck a population that had minimal resources for recovery.

CONCLUSIONS

The Andes are a natural laboratory for investigating climate change and its dependent societal consequences because many proxy records of its past climate exist. These include, but are not limited to, lake sediments, glacial moraines, and mountain ice caps. All are sensitive to global climate change. As a center of ancient civilization, the Andean region offers a long record of response to environmental change as seen through analysis of the history of agricultural systems.

Upon examination, alterations between highland and coastal society sustainability patterns appear to bear some relation to some of the known climate cycle variations, although environmental determinism is not suggested as a prime cause, because many social, political, and economic changes can be induced by sustainability problems in the agricultural base. The reverse is also true; social, political, and economic factors influence the sustainability base. In terms of key variables R , P , Y , A , S , V , dT/dt , dD/dt , at least some of the underlying correlatives for the sustainability of different

societies with different agricultural systems that are subject to different climatic conditions, provide a partial basis for underlying factors that lead to changes in cultural patterns and agricultural sustainability.

Because only fragmentary details of Andean climate cycles are known from ice and lake core data, only an approximate hypothesis can be offered at present to explain the effects of changing climate upon socio-political structure and sustainability. For the present, however, some factors underlying the agricultural basis of societies have been discussed and preliminary arguments have been advanced which relate climate change to observed agricultural pattern changes. The coupling and feedback of these effects as they relate to the political, economic, religious, governmental, and social responses of societies remains an area for future investigations.

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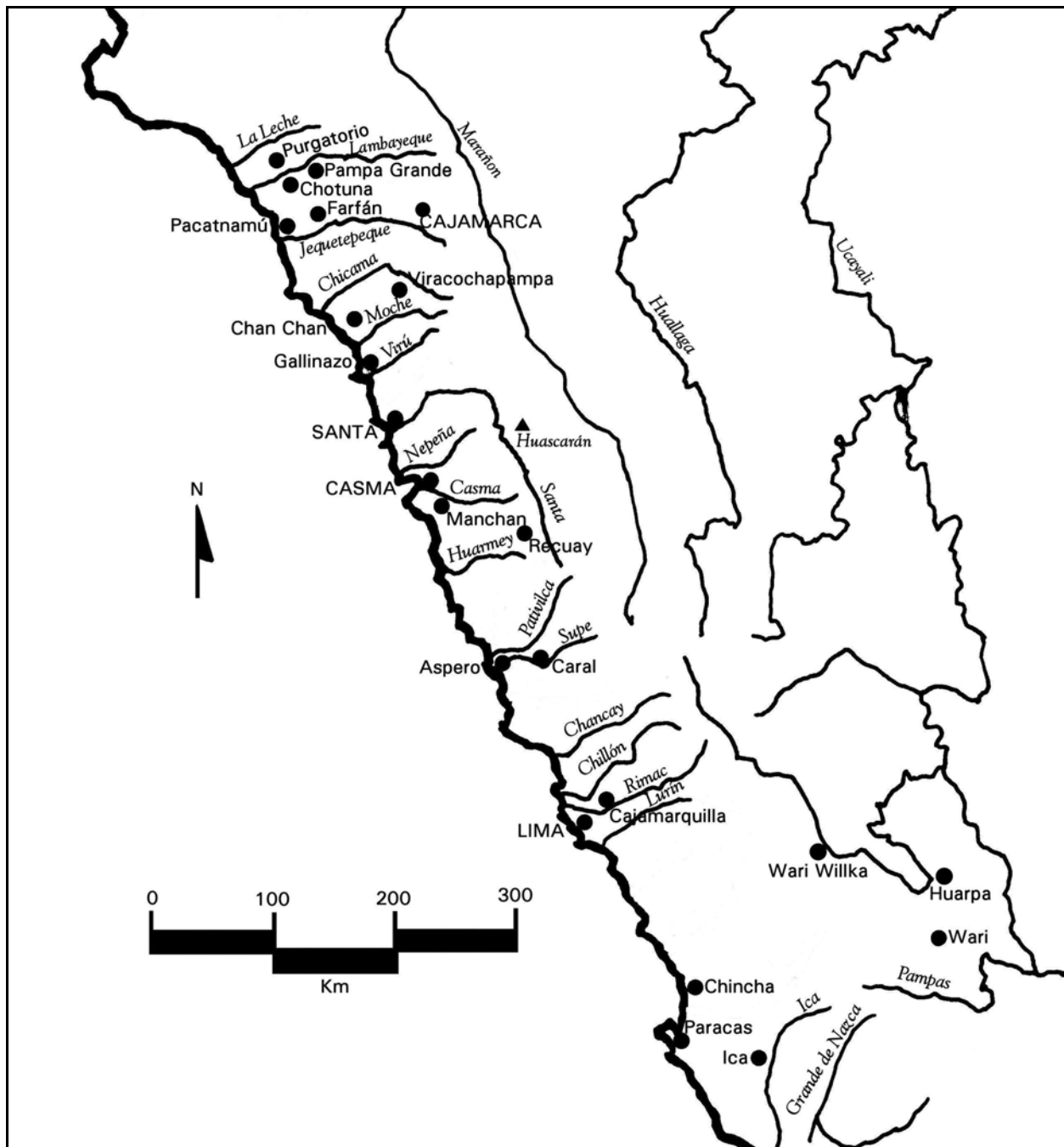


Figure 1: Map of Northern and Central Peru showing some of the geographic features (in italic type) and sites (in uncial type) mentioned in the text. The names of modern cities are written in all capitals.

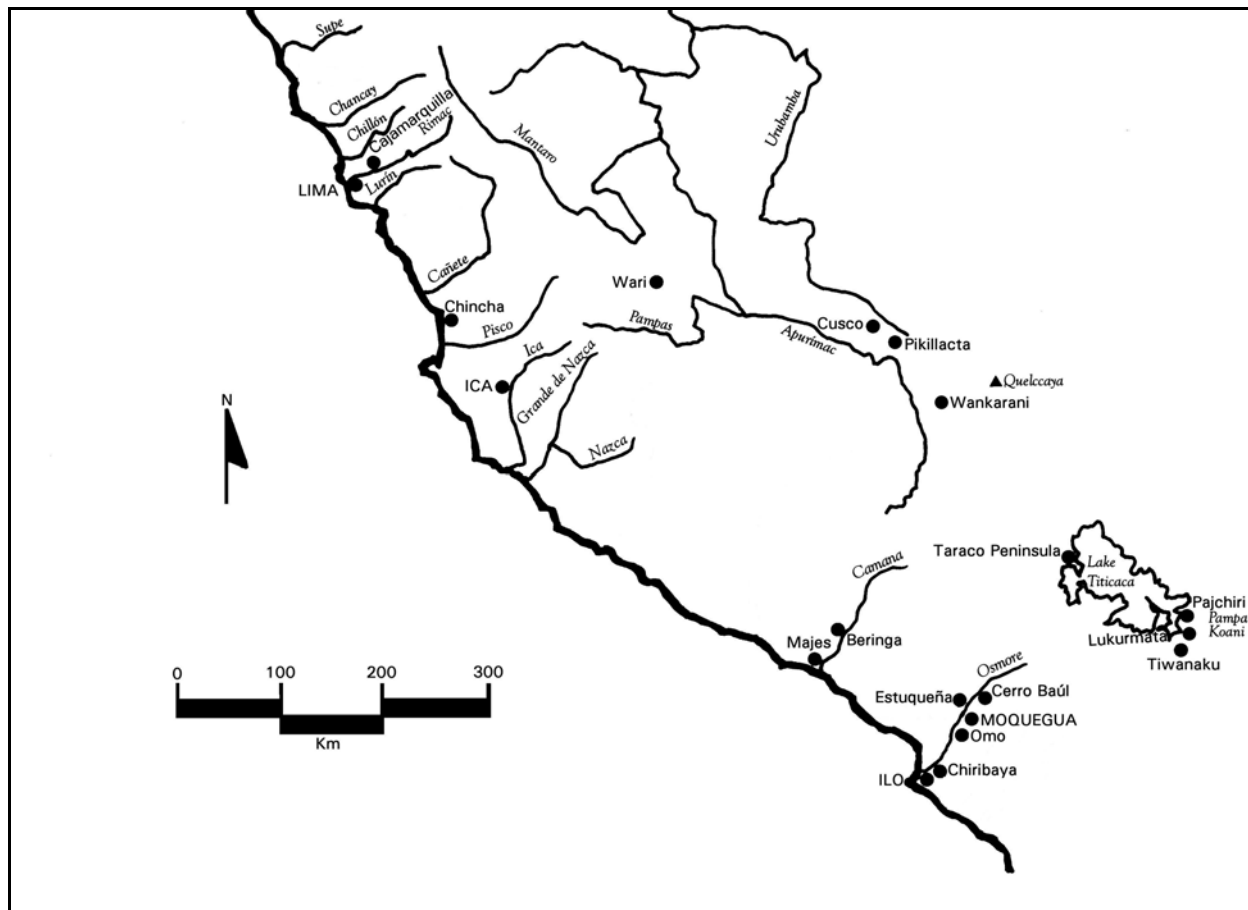


Figure 2: Map of Southern Peru and the Lake Titicaca Region of Bolivia showing some of the geographic features (in *italic type*) and sites (in *uncial type*) mentioned in the text.
The names of modern cities are written in all capitals.

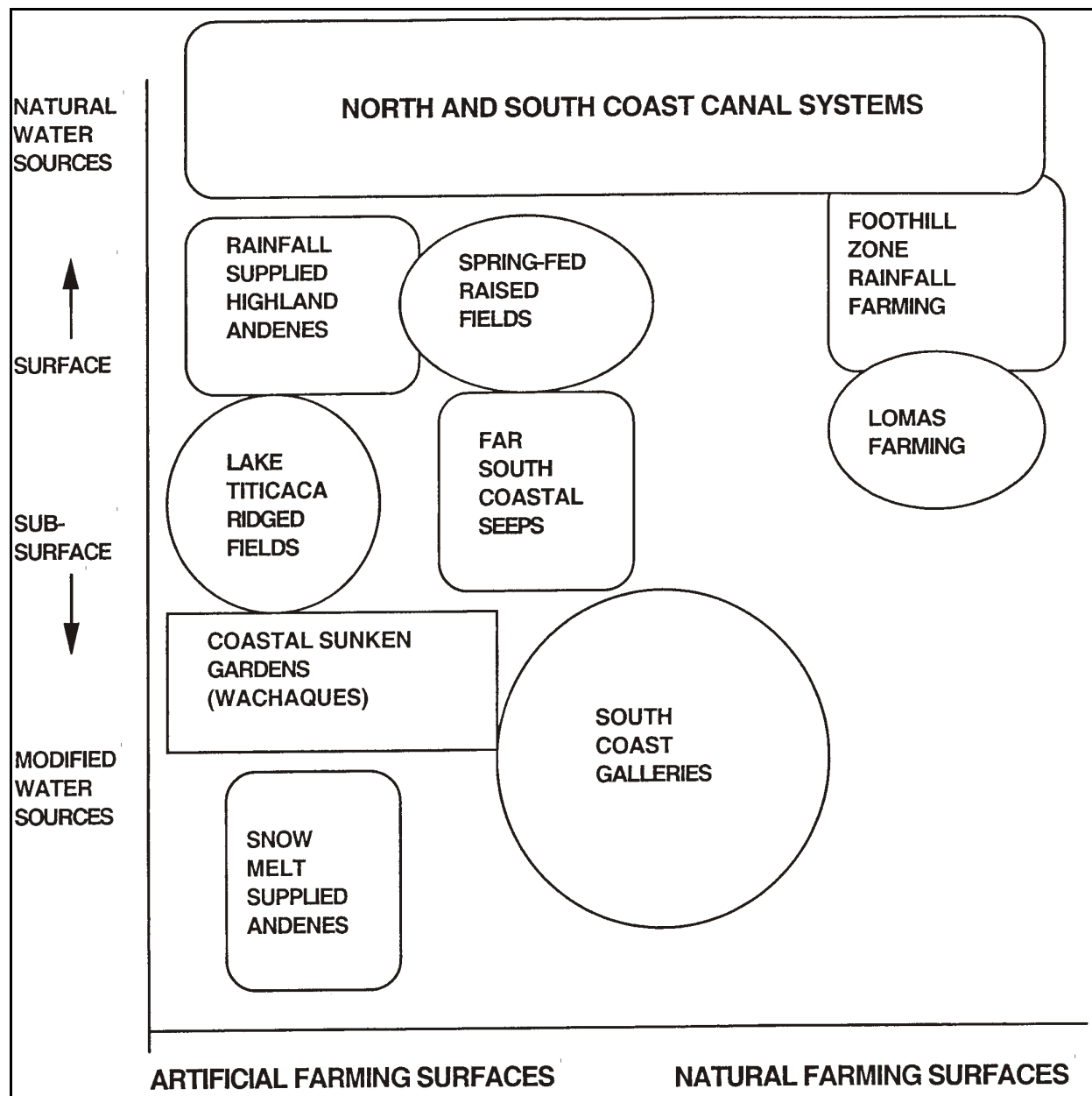


Figure 3. Agricultural strategies for artificial (modified) and natural planting surfaces for surface and subsurface water sources.

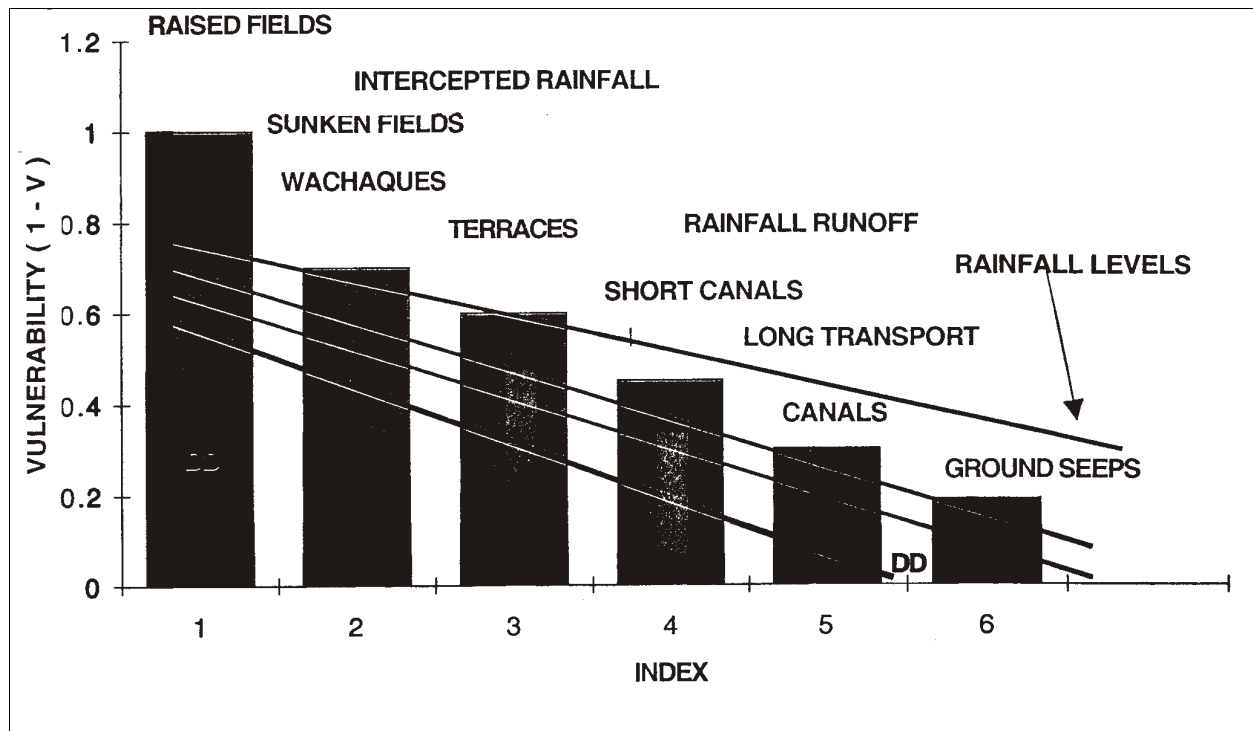


Figure 4. Vulnerability Index (1 - V) for different types of agricultural systems and water supply methodologies (rainfall intercepted and runoff) indexed by numbers 1-6.

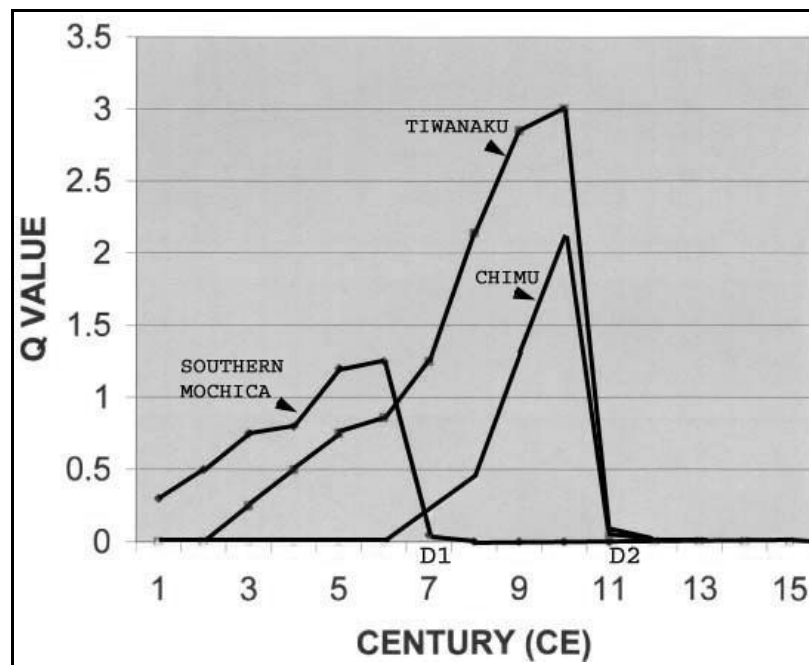


Figure 5: (best-estimate) application of the Q (agricultural sustainability) equation for Moche, Tiwanaku, and Chimu societies in their heartland areas. The D1 notation indicates the time of drought-related collapse of the (EIP) Moche V society in the Moche Valley area; the D2 notation denotes loss of agricultural sustainability due to a later drought period during the 12th Century CE affecting (MH) Tiwanaku and (LIP) Chimu societies. (The Chimu curve shown applies only to the Moche Valley capital area not for expansion period valley sites to the north.) The curves indicate that the drought-related decline in agricultural productivity most probably underwrote subsequent changes in societal structure and agricultural strategies of these societies as previously noted.