El Niño floods and culture change: A late Holocene flood history for the Rio Moquegua, southern Peru

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ABSTRACT

The 1997–1998 El Niño generated large floods throughout southern Peru, especially in inland locations along Rio Moquegua. Using remote sensing, hydraulic modeling, field surveying, and stratigraphic analyses, we estimate the magnitude and frequency of this flood and determine a late Holocene flood history for main-stem and tributary sections. Modeling indicates a peak discharge of 450 m^3/s for the 1998 flood, with an estimated recurrence interval between 50 and 100 yr. Flood deposits for two large events, dated to A.D. 690 and A.D. 1300, respectively, exist in a small tributary system. Tiwanaku site abandonment (ca. A.D. 1000) predates the younger flood, indicating that stratigraphically recognizable El Niño–driven floods were not a causal mechanism for abandonment. Although possessing three flood units, main-stem alluvium is considerably younger ($<$320 ^{14}C yr B.P.) than tributary alluvium, evidencing the major channel widening and lateral reworking of the main stem.

Keywords: El Niño, floods, climate change, Andean archaeology.

INTRODUCTION

Considerable research over the past several years has attempted to determine the causes, extent, and occurrence of El Niño–Southern Oscillation (ENSO) events in coastal South America. The history of ENSOs has broad climatological, hydrological, and cultural significance because it signals the development of the modern postglacial oceanic circulation and the regional hydroclimatology of the subtropical South Pacific. Understanding ENSOs may also help explain the timing and pattern of human settlement and site abandonment. In the Andean region, where cultural response to climatic events may affect the relationship of highland, middle altitude, and coastal regions, extreme ENSO events have profoundly influenced human migration, colonization, and exchange (cf. Seltzer and Hastorf, 1990; Binford et al., 1997; Grosjean et al., 1997; Keefer et al., 1998).

In the south-central Andes, recent analyses of environment and culture change have focused on the effects of floods and droughts on settlement and agricultural systems. This perspective has favored catastrophic interpretations for human responses to drastic climate events, such as the 14th century decline of the Chiribaya culture following the Miraflores flood dated to ca. A.D. 1330 (Wells, 1990; Clement and Moseley, 1991; Satterlee et al., 2000). Some of the sharpest controversy has focused on the effect of climate change on the Tiwanaku culture, one of the Americas' first expansive state societies, which flourished between A.D. 500 and 1000. Long-term climate trends have been cited in the highland Tiwanaku civilization's rise during wet periods from A.D. 610 to 650 and from A.D. 760 to 1040, whereas decreasing rainfall after A.D. 1040 and severe drought from A.D. 1245 to 1310 have been implicated as the proximate cause of the Tiwanaku society's collapse (Kolata and Ortloff, 1996; Kolata et al., 2000). Tiwanaku site abandonment may not coincide with the onset of this drought, however, and this environmentally determined collapse hypothesis may overestimate social consciousness of long-term climate trends and underestimate Andean peoples' ability to respond to short-term climatic stress (Erickson, 1999).

Our research documents the modern and late Holocene flood history for the mid-valley of the Rio Moquegua (also known as Rio Osmore, 17°S, 71°W) and one of its intermittent tributaries, which we call Rio Muerto. The study area is a hyperarid region in the northern fringes of the Atacama Desert, where precipitation totals $<$100 mm/yr. Our goals are to establish the magnitude, geomorphic impacts, and regional extent of the 1998 El Niño flood; to relate this episode to late Holocene stratigraphic evidence of large floods; and to put these large floods into the context of archeological settlement history, notably the colonization of lowland valleys by the highland Tiwanaku culture. Our stratigraphic and postflood analyses of the 1998 event indicate that large precipitation-driven floods have affected both the main stem and its tributaries and, at least mechanistically, could have affected Tiwanaku settlement history throughout the main valley of the Rio Moquegua.

METHODS

Because there are no stream gauges in the study area, we used postflood field surveys, remote-sensing techniques, and hydraulic modeling to document the size and regional extent of this flood. We combined this modern analysis with stratigraphic evidence from the main stem and its tributaries to embed these results within a broader temporal and archaeological framework.

Several AVHRR (advanced very high resolution radiometer) multispectral optical images were obtained from the National Oceanic and Atmospheric Administration (NOAA) interactive satellite archive for the March 1998 orbits. The AVHRR scenes were first geocoded by using ground-control points; final geocoding was accomplished by registration to permanent drainage features. The imagery was exported to a geographic information system (GIS) data layer where inundation limits and flood watershed boundaries (and area) could be determined. Field surveys were conducted in the mid-valley section (elevations of ~1040 m above sea level [asl]), where numerous high-water marks of the 1998 flood exist. Two cross sections were surveyed perpendicular to the channel, and these data were subsequently input into a hydraulic model (HEC-RAS) to determine the magnitude and hydraulic characteristics of this event. HEC-RAS calculates discharge and other hydraulic variables from field-derived channel data by using a standard-step iterative process to reconstruct water surface profiles (cf. Hoggan, 1989).

We used a regional curve established by Waylen and Caviedes (1987) to estimate the return frequency of this flood. Their regional curve relates mean annual discharge to drainage area for 25 basins in coastal and inland Peru. The Holocene flood history was derived from exposures along the main stem of the Rio Moquegua, between the cross sections used for the hydraulic analyses, and was combined with stratigraphic evidence from alluvial exposures along the Rio Muerto tributary, ~1 km upstream of the archaeological site (site M70). Two small channels join to form the Rio Muerto, and we examined flood deposits along 50 m reaches for its northern (spring channel site) and southern (geoprofile site) tributaries. Ongoing excavations at Rio Muerto site M70, regional settlement pattern survey, and prior excavations at other

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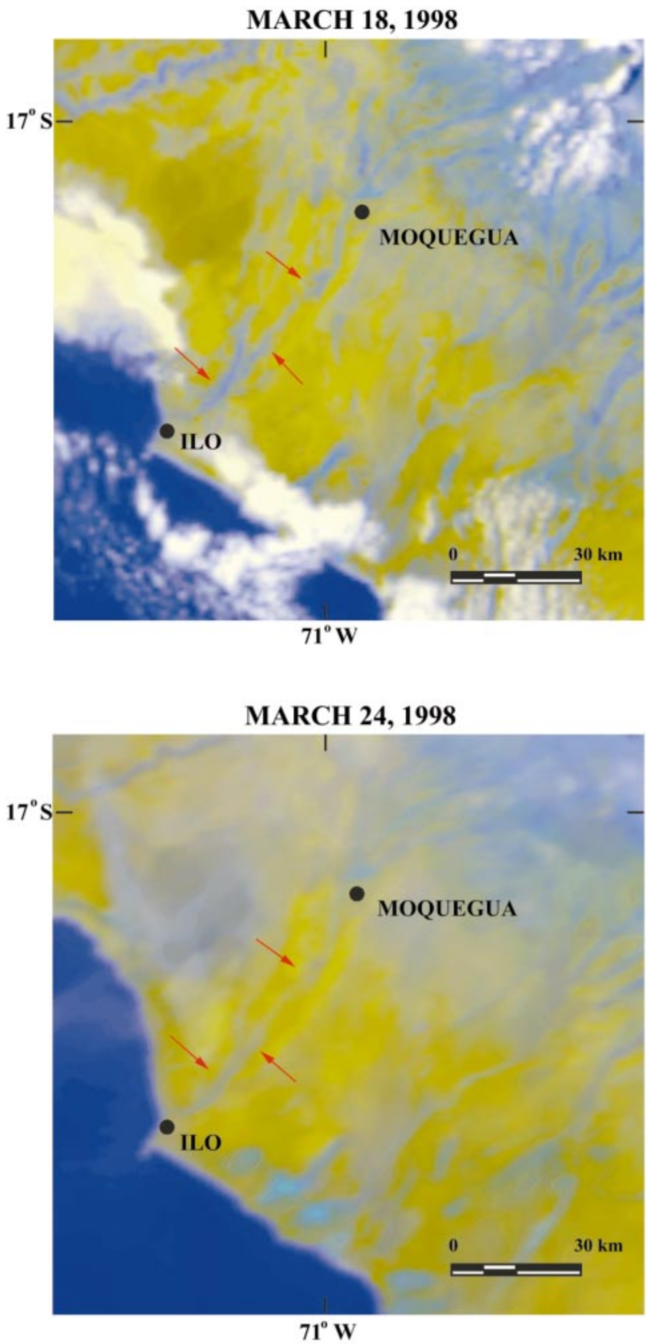

Figure 1. AVHRR images for 1998 El Niño flood. Upper image is during flood peak; blue pixels indicate inundated areas along major drainages. Bottom image, of same area one week later, shows lack of inundated places. Arrows point to Rio Moquegua. AVHRR data provided by NOAA. Images compiled by Dave Finnegan and Elaine Anderson at Dartmouth Flood Observatory and used with permission.

Tiwanaku sites within the mid-valley of the Rio Moquegua provided the archaeological information (Goldstein, 1989, 1993).

HYDRAULIC ANALYSES

Although current thinking suggests that El Niño floods largely affect only coastal reaches, with higher altitudes becoming drier during ENSO episodes (Caviedes, 1984; Fontugne et al., 1999), March 1998 precipitation generated significant flooding in the middle and higher elevations throughout southern Peru. The AVHRR image (Fig. 1) indicates that most large rivers were well out of bank for at least a week and that mid-elevations were significantly affected by this ENSO. Durations were relatively limited (Fig. 1), approximately one week, suggesting a relatively peaked hydrograph.

TABLE 1. HYDRAULIC OUTPUT FROM HEC-RAS ANALYSIS FOR THE 1998 EL NIÑO FLOOD

	Downstream cross section	Upstream cross section
Top width (m)	192.7	233.1
Maximum depth (m)	1.84	2.16
Velocity channel (m/s)	2.38	2.16
Channel shear stress (N/m^2)	273.9	223.2
Channel unit stream power (N/m s)	651.4	482.9
Energy grade line slope (m/m)	0.0189	0.0147
Discharge (m^3/s)	450	450

Note: Distance between cross sections = 206 m, and drainage area = 1590 km^2.

Hydraulic modeling estimates a peak discharge of ~450 m^3/s for the Rio Moquegua at the Tres Quebradas site (Table 1). Because of the relatively steep gradient in this section (~1.6%), energy expenditure generated along the bed was quite large, and shear stresses higher than 200 N/m^2 occurred. Common fresh gravel bars along the reach indicate considerable sediment transport. Significant lateral erosion and channel widening also occurred, as manifested by the newly eroded raw banks that extend for kilometers. The flood peak, however, failed to overtop the high late Holocene right-bank flood plain.

The estimated peak discharge of the 1998 flood was compared to a regional curve (Fig. 2) to ascertain the return frequency. The Rio Moquegua drains ~1600 km^2 at this point, indicating that its estimated mean annual runoff is ~100 m^3/s (Fig. 2). In comparison, the 1998 flood had a modeled peak runoff of 450 m^3/s, generating an event 4.5 times the mean annual runoff. Comparison with other basins in similar climates (Lewin, 1989) indicates that this ratio of 4.5 has a return frequency between 50 and 100 yr.

RECORD OF LATE HOLOCENE FLOODS

Tributary Stratigraphy

Two major flood deposits are exposed along Rio Muerto, a usually dry tributary of the Rio Moquegua, which heads in a spring at ~1200 m asl. The sedimentological characteristics of both gravel units indicate deposition by either a hyperconcentrated fluid flow or a debris flow

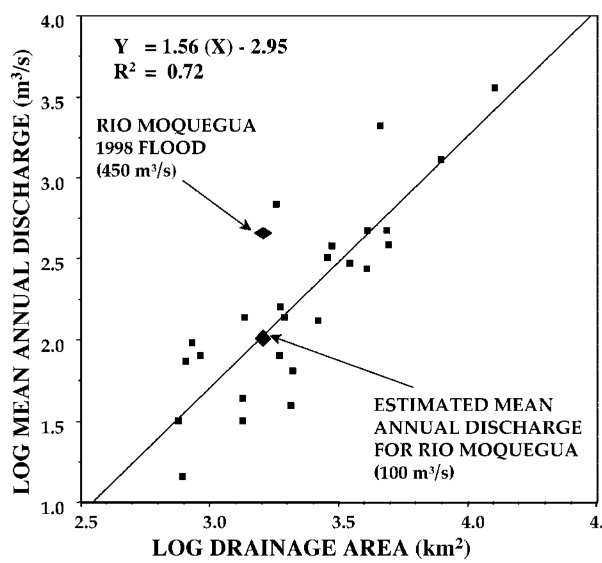

Figure 2. Regional relationship between mean annual runoff and drainage area (data from Waylen and Caviedes, 1987). Peak discharge for 1998 flood is also plotted.

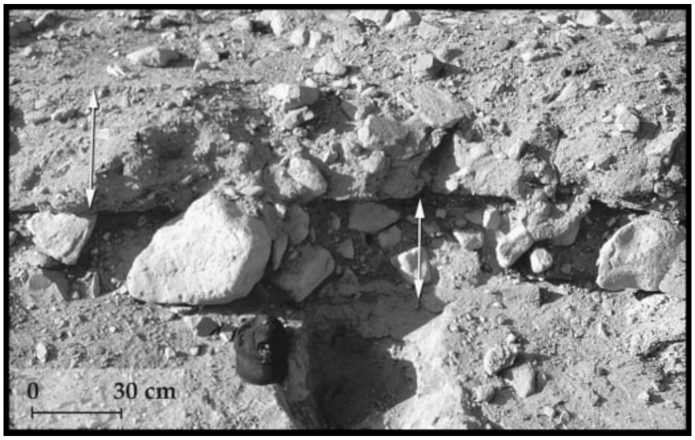

Figure 3. View of flood units along upper Rio Muerto. Arrows indicate flood unit thicknesses. Unit II results from Miraflores flood (A.D. 1300) and unit I dates to A.D. 690.

TABLE 2. RADIOCARBON DATES FOR FLOOD UNITS AND ARCHAEOLOGICAL MATERIAL

Sample	Conventional age (^{14}C yr B.P.)	Yr A.D. (1 σ)	Comments
A. Rio Muerto flood gravels			
Unit I (lower pink flood unit)			
Beta-124115	1290 ± 50	670–775	Spring channel site (wood)
AA-37978	1325 ± 42	660–763	Spring channel site (wood)
Unit II (upper gray flood unit)*			
Beta-124116	620 ± 40	1300–1400	Spring channel site (wood)
Beta-142835	730 ± 60	1255–1295	Spring channel site (wood)
Beta-142834	620 ± 70	1290–1410	Geoprofile site (wood)
Beta-133794	750 ± 60	1235–1290	Lower Rio Muerto flood gravels near site M70 (wood)
B. Rio Moquegua floodplain (near Tres Quebradas)			
Beta-122794	320 ± 50	1480–1650	Point bar gravels (charcoal)
C. Tiwanaku archaeological occupation at Rio Muerto			
AA-38031	1122 ± 44	888–982	M43 = 1067 (charcoal)
AA-38032	1132 ± 39	887–979	M70 = 1245 (charcoal)
Beta-129939	1160 ± 60	785–970	M70 = 1509 (wood post)

*Weighted mean date = A.D. 1300.

(Fig. 3). The lower flood gravel (unit I), dated to A.D. 690, is a pink unit of generally imbricated, rounded to subrounded coarse particles (mean particle size of 183 mm) that are irregularly clast and/or matrix supported. This layer, 20–25 cm thick, overlies 140 cm of massive, poorly sorted sands and gravels exposed down to the modern channel bed. Unit II is less matrix controlled and contains somewhat coarser, rounded to subrounded clasts that are more strongly imbricated (mean particle size = 224 mm). Unit II ranges in thickness from 50 to 80 cm and is subsequently overlain by a thin ash, the stratigraphic position of which associates it with the A.D. 1600 eruption of Huaynaputina at Omate (Thouret et al., 1999; Satterlee et al., 2000). A scattering of angular, locally derived gravels and cobbles overlies the ash.

Unit II, dated to A.D. 1300, was probably deposited during the Miraflores flood that has been stratigraphically recognized throughout coastal Peru (Wells, 1990; Satterlee et al., 2000). A slightly smaller, but still extreme, flood occurred ca. A.D. 690, depositing unit I (Table 2). Although direct comparison of peak discharges from these events to the 1998 ENSO is not possible, the fact that the extreme 1998 event had no effect on this tributary attests to the catastrophic scale of these two prehistoric events. Most indices of ENSO strength rank the 1997–1998 ENSO as one of the strongest and best developed ENSO events of the 20th century (Wolter and Timlin, 1998). Its lack of fluvial impact along Rio Muerto suggests that its areal coverage was too small to generate rain and floods in this region or that it was of insufficient magnitude to spawn any major geomorphic activity. AVHRR evidence (Fig. 1) indicates broad areal coverage of flooding, thus supporting the latter interpretation. The dominance of localized mass wasting hillslope deposits above unit II and the flood-plain ash suggest that large El Niño floods have not occurred in this tributary section since the Miraflores flood and that more arid conditions have prevailed since at least A.D 1600.

Main Valley Stratigraphy

Because of large-scale erosion during the 1998 flood, fresh alluvial exposures at least 3 m high are quite common along the Rio Moquegua main channel. The alluvial sedimentology is dominated by yellowish-brown coarse silts in the upper 160 cm, grading to silty fine sands from ~160 to 190 cm, and by grayish yellow-brown fine to medium sands with scattered fine to medium gravels from 190 to 225 cm. The lower unit overlies an undulating coarse-gravel bar surface that has a 2–3-cm-thick ash directly above the high point of the bar surface (the ash probably represents the A.D. 1600 event that is exposed near the surface of the Rio Muerto section). This overbank alluvial sequence includes three probable flood units: a cross-stratified sandy unit at ~70–80 cm, and two poorly sorted gravel units at 130 cm and 165 cm below the surface. There is no geomorphic record of these floods in tributary sections. Like the 1998 event, where geomorphic activity occurred on the main stem but not on the tributaries, this difference may result because precipitation was not sufficient in either magnitude or intensity to generate large floods in smaller tributaries. The lack of tributary response may also reflect differing causal mechanisms, whereby the floods preserved in the main-stem alluvium were generated by runoff processes occurring in the highlands that would not affect tributary sections.

Stratigraphic evidence in the mid-valley indicates much younger flood-plain sediments than exposed in the tributary sections (Table 2). A basal date of 320 ^{14}C yr B.P. was obtained directly above the gravel surface and immediately below the tephra. Maximum flood elevations during the 1998 flood were 1 m below most bank tops. Downcutting does not appear to be the causal mechanism, because gravel-bar tops exposed in the bank of this late Holocene surface appear to be at the same elevations as modern point-bar gravel surfaces. The lack of incision and the relatively young dates of the main-stem alluvium indicate that significant lateral reworking occurs along this section of the Rio Moquegua.

Regional Correlations

Paleoclimate comparisons are limited in this remote and arid region, where more continuous climate records derived from paleobotanical evidence, such as tree rings or fossil pollen, are rare. Most long-term climatic reconstructions for this region rely on proxy climate evidence preserved in the Andes, where ice cores from the Quelccaya ice cap (Thompson et al., 1985) or either lake cores or shorelines from Lake Titicaca (Martin et al., 1993) are used to develop longer term climate and ENSO histories. Because the climate of coastal and inland Peru is negatively correlated with the climate of the altiplano (Caviedes, 1984; Thompson et al., 1984), these records can be temporally correlated. The timing of large floods at Rio Muerto accords well with the Quelccaya ice cap record, where extreme dry periods in the altiplano occurred from A.D. 650 to 730 and from A.D. 1250 to 1310 (Thompson et al., 1985). Furthermore, unit I corresponds to a lake-level lowstand in Lake Titicaca dated to ca. A.D. 640 (Martin et al., 1993), and may correspond to an extreme wet period in the Sechura Desert of northern Peru (Martin et al., 1993). Extensions to the regional stratigraphic record work best for the Miraflores flood (unit II), which has been recognized throughout coastal and northern Peru (Wells, 1990; Satterlee et al., 2000). Although the timing of unit I at Rio

Muerto corresponds to climate conditions ripe for high coastal and inland precipitation, no dated regional stratigraphic comparison exists. Wells (1990), however, documented more than 18 flood deposits since 3 ka; three of these pre-date the Miraflores flood, and unit I may correlate with one of the two undated pre-Miraflores events presented by Wells (1990).

Relation of Archaeological Record to Flood History

Connecting flood history to recent archaeological research at the Rio Muerto site group may help explain the timing of Tiwanaku expansion. Excavations in 1998 at the M70 and M43 sites at Rio Muerto, one of the most marginal of the Moquegua Valley's Tiwanaku desert enclaves, found structures and domestic remains dating from ca. A.D. 790 to 828 (Table 2). Most radiocarbon dates for Tiwanaku settlements elsewhere in the Moquegua mid-valley (Goldstein, 1993) also postdate unit I. This result suggests that the densest Tiwanaku occupation and attempts to cultivate the most marginal areas of the Moquegua mid-valley followed the older flood, perhaps responding to increased water availability in the desert valleys and/or related drought events in the highlands. It is possible that ENSO events spurred Tiwanaku migration, colonization, or conquest.

Conversely, we find no correlation of the Tiwanaku abandonment of the Moquegua valley with either of the two extreme floods documented by this study. We cannot entirely rule out the disruptive effect of long-term drought on Moquegua Tiwanaku's agricultural systems suggested by Kolata and Ortloff (1996), nor can we discount the possibility of very strong ENSO floods that were of insufficient magnitude to register in the tributary stratigraphic record. Nonetheless, we concur with Erickson (1999) and previous reconstructions that the primary cause of Tiwanaku collapse was internal social instability (Goldstein, 1989).

CONCLUSIONS

Results from both modern and ancient analyses indicate that El Niño floods have occurred in the mid-valley of the Rio Moquegua and therefore must exist as a flood-producing mechanism in this region. The 1998 El Niño flood peak discharge of 450 m^3/s probably corresponds to a flood with a recurrence probability of 50–100 yr. AVHRR images indicate that most large inland drainages throughout southern Peru were flooded; inundation durations last about a week.

Flood plains of the main stem within the study reach are young, indicating major lateral reworking of flood plains followed by rapid aggradation in the past 300–350 yr. The inability of the 1998 flood to overtop banks further suggests major channel-bank erosion during large floods. The recent reworking of the main stem indicates that little prehistoric evidence of either artifacts or El Niño floods is likely to be present in the main valley.

Therefore, the prehistoric El Niño flood record is best preserved in tributary sections where the larger, Miraflores flood (unit II) and a slightly smaller, but still extreme, older event (unit I) are preserved. Both of these floods would have been immediately catastrophic for many human settlement and agricultural systems. At the same time, they may have encouraged colonial settlement in otherwise nonviable arid regions, owing to a perception of increased rainfall in their wake and potential recharge of groundwater aquifers for subsequent spring-fed agriculture (cf. Grosjean et al., 1997). Several other El Niño floods between A.D. 700 and 1400 have been reported throughout coastal and southern Peru (Wells, 1990). The lack of stratigraphic evidence of these other floods at our sites suggests that they have yet to be identified, that they were stripped, or that these southern, inland tributary locations only respond to extremely large El Niño floods.

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