# 3 Water Management Adaptations in Nonindustrial Complex Societies: An Archaeological Perspective

VERNON L. SCARBOROUGH

*Land management unites the household; water management units the community.*
*—Beardsley et al. 1959, p. 126*

Water management is the interruption and redirection of the natural movement or collection of water by society. It is a topic that most archaeologists are forced to address whether in the acquisition of field data or in the preparation of a broad theoretical treatise. The following presentation will review and assess the many ways in which water is manipulated by society. The chapter is organized into five parts: (1) physical properties, (2) water management techniques, (3) social costs of water management, (4) archaeological case studies, and (5) conclusions.

My purpose is to evaluate the significance of water management by examining salient aspects of several nonindustrial complex societies. This is not another attempt to critique Wittfogel's *Oriental Despotism*; it is, rather, a broad-based literature review canvassing old and new finds and interpretations associated with the manipulation of water. Generally the examples draw from primary state centers of sociopolitical development, though less complex cases are examined. The chapter provides a methodological framework for interpreting the variability in these water systems.

The presentation covers a range of human variability in the manipulation of water and emphasizes the various methodological and theoretical points developed in the "Social Cost" section and the "Archaeology Case Studies" section. In order to assess the environmental and social forces that facilitate adaptation, early techniques of water management are examined. The conditions under which complex water management schemes are developed, accepted, and used, regardless of their origin, receive considerable attention.

## Physical Properties

### *Characteristics of Water*

For organic matter, the presence of water is life itself. Humans require a minimum of 2 to 3 liters of water a day in a settled environment under normal living conditions (White et al. 1972:252). Clearly, this amount can vary with levels of work activity, physical differences in body type, and environmental conditions. In the dry sands of the Negev Desert, home of some of the earliest successful adaptations to severe aridity by the settled Nabataeans (Eadie and Oleson 1986; Oleson 1988), present-day nomadic families (six individuals, two camels, one donkey, two dogs, and ten sheep) survive on 18 $m^3$ of water a year (Evenari et al. 1971:150). This can be juxtaposed with the excessive consumption habits of the average U.S. citizen, who uses more than 225 liters of water daily (White et al. 1972:Table D).

Although water has several unusual physical properties, two of them are particularly important for any discussion of settled community life. *Fluidity* is that condition of a liquid which permits its ease of transport. Water does not usually require beasts of burden or wheeled vehicles for its immediate relocation, and thus its cost to the consumer is intrinsically low. *Gravity flow* is the characteristic of a fluid to move from higher to lower elevations via a path of least resistance. It is the cardinal principle in the manipulation of water within a canal scheme, but the primary obstacle to water control in rugged areas.

The properties of fluidity and gravity flow are responsible for two additional conditions imposed by human managers. The first involves the many mechanical problems associated with lifting water vertically. Its bulk and unwieldy dimensions require sealed containers for this movement. Prior to the widespread use of hand pumps, siphon tubes, and Archimedes' screw, stagnant water was pulled upward by hand or with the use of a simple manual device called a *shaduf*. Still used widely today in the Middle East and in antiquity in pharaonic Egypt, the *shaduf* takes advantage of a counterweighted lever or pole with a dipping line and bucket attached at the far end. Another device of Persian origin and dating from before 300 B.C. is the noria or current wheel (Glick 1970; cf. Hsu 1980:275). This animal-powered device with attached buckets moves water from a lower point to a higher point. Lifting techniques used by early states, then, were simple and labor costly.

A second condition imposed by fluidity and gravity flow is the ability to divert or abruptly cut the supply of water to a consumer. Diversion dams and conventional reservoirs with sluice gates permit individuals or a small group of users to treat water as a commodity in negotiating with other users. Unlike many other commodities, water is frequently a single-source medium. The initial investment in controlling water, particularly apparent in irrigation schemes, is to localize points of distribution through sluice gates and related features.

### *Climate and Geomorphology*

Water use is partially conditioned by the natural environment. Although most environments can be transformed into agricultural settings, given significant technological and labor investments associated with water manipulation (Ferdon's "agricultural potential"; Ferdon 1959), regional differences in climate and geomorphology dictate the amount of work necessary. Tolerable climatic conditions for agriculture are based on precipitation rates and temperature (i.e., evaporation and transpiration rates). By scheduling around seasonal fluctuations in these variables, water can be manipulated to an agricultural end within an otherwise inhospitable natural setting. Geomorphology is more difficult to modify and represents the principal obstacle to water control in a climatically acceptable environment. The primary geomorphological variables conditioning water management are topography and soil permeability (the latter measured by rates of seepage). Complicated geomorphological structure is sometimes the impetus for hydraulic innovation when population demands reach a threshold.

A dichotomy exists between the natural environments in which early complex societies emerged. Complicated experiments in water management occurred in arid regions with both rugged and low relief, as well as in humid settings with gentle topographic contours.

*Arid regions.* In the New World, the most celebrated early centers of complicated, regionwide water management appeared in coastal Peru (and later in highland Peru, Ecuador, and northern Bolivia), highland Mexico, and the American Southwest (Donkin 1979; Price 1971). In the first two areas, the topography is precipitous and associated with relatively small, less consequential drainages, especially when compared with Old World civilizations. In Peru and to a degree in highland Mexico, water management systems utilized the topography as an advantage in tapping rapidly moving water over steep gradients. Terraces, dams, aqueducts, and canal networks took on a valley-limited drainage focus knit together by empires.

The seats of primary state development in the Old World were Egypt (Butzer 1976), Iraq (R. M. Adams 1981), southern Pakistan (Allchin and Allchin 1982), and west-central China (cf. Hsu 1980). In each instance, a major river meandered through these arid territories. Although sometimes associated with unanticipated flood levels, these rivers represent not only permanent sources of water but also abundant stores. The topographic relief associated with them in proximity to the early state is gentle, particularly when compared with New World examples. This condition allowed extensive canalization in most cases, restricted only by the breadth of the floodplains defining these old, slow-moving drainages. Although elaborate diversion dams were clearly perfected, conventional dams with reservoirs or sophisticated terracing systems (characteristic of the Peruvians) were little deployed (Tigris-Euphrates notwithstanding; see below). Civilization was in part defined by the course of these great rivers.

*Humid regions.* The Maya lowlands is the principal humid region in the New World where complex water systems evolved. In a zone of limited relief and abundant though seasonal rainfall, the Maya pioneered intensive swamp agriculture (Adams et al. 1981; Scarborough 1983a; Turner and Harrison 1981) as well as terrace systems (Healy et al. 1984; Turner 1974). Well-designed dams for the deliberate entrapment of water within naturally low-lying areas permitted the drainage of excess water during the wet season and its judicious distribution during the dry. Other secondary societies adopting potentially similar techniques may have been the Woodland and Mississippian chiefdoms of the southeastern United States (Sears 1982; cf. B. D. Smith 1978) as well as the groups associated with the intermediate area of northern South America (Denevan 1970; cf. Steward and Faron 1959). These latter societies took advantage of major riverine settings, generally unlike the Maya.

In the Old World, early tropical intensive water systems are poorly reported from sub-Saharan Africa, though West Africa may be expected to yield some evidence of intensive water manipulation as a later state-development locus (McIntosh and McIntosh 1983; Wolf 1982). The best evidence comes from Southeast Asia, principally from Sri Lanka, Cambodia, and Java. Here, rainfall rates are comparable with those recorded in the Maya lowlands with similar topographic aspects. A clear comparative study by Bronson (1978) examines the ecological underpinnings of these early states in both Southeast Asia and the Maya lowlands. None of the principal early state centers commanded a major riverine arterial.

Given these apparent environmental divisions, a focused investigation of four of these regions, two in the New World and two in the Old World, is warranted. Highland Mexico will be compared with the Maya lowlands, and southern Pakistan will be juxtaposed with Sri Lanka. Within their respective hemispheres, the New World examples and those in the Old World are in relative proximity and may have cross-fertilized one another's development. Further, each hemisphere allows the study of an arid setting and a humid one. This range of variability captures the complexity of ancient water management and permits a cross-cultural comparison of hydraulic adaptations among early states. In addition, one secondary zone influenced by a neighboring primary arid-lands civilization has been included. An impressive literature treating water control has been amassed for the American Southwest. This region provides a case study of a society occupying an extremely harsh environment that successfully manipulated its setting in developing a complex social organization, although it was less sociopolitically stratified than those previously mentioned.

Before distinguishing these regions, several less environmentally determined issues influencing water manipulation will be examined.

## Water Management Techniques

### *Symbolic Statements*

Symbolic water management statements among the elites of society are static investments that yield little economic return.

Material metaphors indicate to a constituency that those in power have not only the authority to construct such works (a statement made by most monumental structures) but also the privilege of lavishly consuming this precious resource. Such elite displays cultivate a clear sense of social distance between a constituency and the aristocracy. Conspicuous consumption has been shown to be a major lever in the control of others (Veblen 1934; cf. Schneider 1974).

Unlike other public architecture associated with complex societies, symbolic water management facilities usually require great planning to construct and maintain. Although built as static and permanent fixtures and as an index of elite control—a quality of civic architecture generally (Price 1982:731)—water monuments require a careful layout to accommodate the physical properties of fluidity and gravity flow. Because of this condition, many hydraulic features were built in their entirety over a short period. This is opposed to the temporal uncertainty associated with other types of civic construction that may have been built over longer periods. This characteristic of water management systems makes them a better measure of an elite's power and control than lofty pyramids that may reflect many generations of labor (cf. Kaplan 1963).

The history of public bath use in ancient Rome among the governing elite is well known (Herschel 1899). However, civic architecture dedicated to bathing dates nearly three millennia earlier in ancient Pakistan. At Mohenjo-daro (2500–1700 B.C.), the Great Bath was located upon the elevated reaches of the Citadel and probably drew from the canalization of surface runoff as well as from well water (Wheeler 1968). More important than the technology involved or the capacity of the Great Bath was its location atop the access-controlled Citadel. Given the importance of ritualized cleansing by many groups on the South Asian subcontinent, the significance of this feature in association with the seat of administrative and ceremonial activity cannot be understated. In this case, access to ritualized bathing in part conferred status on an elite.

Palace gardens associated with fountain construction probably have an antiquity associated with initial experiments in statehood. Nevertheless, few references are readily available. By the third century B.C., the Greek (and later Roman) atrium was an established architectural design within elite houses (Glick 1970). Persian Persepolis also suggests the importance of enclosed private garden space among the aristocracy. The palace garden concept was disseminated widely by the Islamic jihad (cf. Wilber 1979) and reintroduced into thirteenth-century Europe in a spectacular manner within the walls of the Alhambra at Granada. In the late seventeenth century, Louis XIV commissioned the palace gardens and fountains at Versailles. The Moguls of South Asia (sixteenth–eighteenth centuries) made some of the most extravagant and imposing architectural statements.

A focused attempt was made by the Mogul nobility to create an earthly paradise through the private and public use of water. Most renowned for his commissioning of the Taj Mahal, Shah Jehan was the architect–king of the period. Elaborate terracing and enclosed gardens had been introduced two centuries before the Shalimar Gardens of Lahore were built at the order of Shah Jehan in the seventeenth century. Three receding terraces embraced a rectangular area of over 16 ha enclosed by a high wall. More than four hundred symmetrically placed fountains graced the lavish setting, and marble pavilions and causeways connected the tiers. A canal is said to have brought water from a pure source more than 160 km away (Rehman 1981; Taylor 1965).

At a comparable period in the New World, the Aztecs created splendidly altered landscapes through the manipulation of water. At the palace of Tetzcutzingo (Texcoco), King Netzahualcoyotl is credited with building a resort involving a significant investment in canals, aqueducts, and terraces (Palerm 1955:36; Wolf and Palerm 1955). On the island city of Tenochtitlan, Moctezuma Ilhuicamina established an aqueduct bringing water from the springs at Chapultepec. He is further credited with the construction of botanical and zoological gardens (Weaver 1981:424).

For the Lowland Maya, little evidence remains of their manipulation of baths or palace water systems. A vaulted aqueduct may have channeled water into the central precinct at Palenque (Weaver 1981:315), and a crude plumbing system seems apparent in the architecture of a single elite structure (Structure 4) at Becan (Potter 1977:44), but no sources refer to palace gardens. However, elaborate sweathouses have been identified throughout the Maya area within the central precincts of the largest cities. Although ritualized sweatbaths were a widespread Native American practice, the Maya appear to have been the first to formalize the institution architecturally. At Tikal (Coe 1967), Piedras Negras (Cresson 1938; Satterthwaite 1936), and Chichen Itza (Ruppert 1952) steam appears to have been directed into sealed masonry rooms.

In each of the above examples, elites have, through architectural manipulation and lavish consumption of water, further established a social distance between groups within the early state.

*Functional Statements*

The vast majority of anthropological research examining water management systems has been conducted in agricultural systems affecting the immediate needs of a greater population governed by an elite. Although these systems are influenced and manipulated by powerful elites, their success or failure is less conditioned by symbolic displays of control and more affected by satisfactory scheduling and technology. Four principal landscaping techniques comprise most water manipulations among early states. Wells, reservoirs, dams, and canals represent major earth-moving investments demanding significant labor, exact timing, and precision in both construction and maintenance.

*Wells.* Wells are vertical shafts excavated to a buried water table. Frequently an aquifer is tapped and made available by means of a well. Numerous variations exist, depending upon the local geomorphology and technology. Conventional wells are apparent in nearly every society and require limited resources to construct when the water table is elevated. They can be enlarged and deepened with fluctuations in the water table. In some settings, such as the Valley of Oaxaca, Mexico, shallow wells provide an abundant source of water for agriculture, both today and in the pre-Hispanic past. Here, "pot irrigation" entails individual plants that are watered from gallon jars in proximity to the many wells (Flannery et al. 1967). At the eighth-century Maya community of Quirigua, shallow wells were found to be lined ceramic shafts (Ashmore 1984), presumably to prevent the walls from collapsing.

More elaborate wells consist of large subterranean reservoirs permitting foot access to the source. One of the more complex examples of a "walk-in well" away from the heartland of a civilization is in thirteenth-century Casas Grandes, northern Mexico. Di Peso et al. (1974) indicate that a stepped entranceway descended 12 vertical m from the surface before reaching water. On the Yucatan Peninsula, walk-in wells were enormous. Because of the depth of many of the subterranean water channels and the natural formation of solution cavities (cenotes) that contacted these underground streams, exaggerated caverns were sometimes formed (Mercer 1975). The soft limestone was frequently carved to accommodate foot access (Matheny 1978; Stephens 1843:96).

By far the most complex well systems are the *karez, qanat,* or *foggara* reported chiefly in the Middle East but found along a narrow belt ranging from south-central China to Mediterranean North Africa and Spain (Cressey 1958). The *karez* system was probably invented by the Persians (the word is a Persian term), although the Arabic word *qanat* is used in most Middle Eastern countries where the technique is still practiced. Sixth-century B.C. Persepolis documents a clearly defined *karez* system (Cressey 1958; English 1966). Its introduction to Spain by the Moors appears to account for its later presence in Mexico as well as in Peru and northern Chile (Woodbury and Neely 1972).

The *karez* can be viewed as a horizontal well consisting of an underground tunnel allowing the channeling of water from an elevated aquifer to a low-lying oasis. Such aquifers are usually at the juncture of elevated bedrock associated with an exposed mountain range and an overlying alluvium. The amount of water available to the *karez* system is conditioned by the amount of precipitation and the size of the rainfall catchment recharging the aquifer. Access to the hand-dug tunnels is given by a series of vertical shafts each separated by 30–50 m. The depth of a shaft is dependent on the original "mother well" or the depth of the initial and most elevated shaft, as well as on the surface contours under which the tunnel courses. Most shafts are excavated in the range of 20 m to a maximum of 100 m (English 1966). The gradient of the tunnel cannot be significantly altered, and for a short *karez,* a maximum slope can be little greater than 1:1,500. If the gradient is too sharp, the *karez* may excite erosion and impede or block the flow of water. On the other hand, if the gradient is not steep enough, water will issue too far from the village and fields it is intended to reach. Evaporation and seepage loss accelerate under these conditions.

Springs or artesian wells occur naturally and involve little excavation. A surface catchment reservoir is sometimes constructed to permit the ready use of the discharge; and in arid regions, canal systems can issue from these more permanent water sources. Pre-Hispanic spring and canal systems are at Casas Grandes (Di Peso et al. 1974), Creeping Dunes Spring (Sharrock et al. 1961), and Hopi Mesas (Hack

1942) in the American Southwest. At Hierva de Agua in Oaxaca, Mexico, channeled spring water dates to the origins of canal construction in the New World (ca. 300 B.C.) (Flannery et al. 1967).

Functioning in a manner similar to a shallow well are the excavated field depressions or "sunken gardens" of Peru (Parsons and Psuty 1975; R. T. Smith 1979; West 1979). Employed today, these ancient fields were dug down to a zone immediately above the water table. Directly dependent on neither precipitation nor irrigation (though there is some suggestion that the seepage associated with widespread irrigation raised the water table), these fields took advantage of an abundant water source to feed, in part, such great cities as Chan Chan near the north coast (ca. A.D. 1000). Moseley (1983) has shown that tectonic activity, perhaps coupled with the overexploitation of the sunken field water table, forced the downward excavation of the garden plots over time. Near the core of the community, fields descended 5–7 m before they were abandoned (Parsons 1968).

*Reservoirs and dams.* Reservoirs are open catchment basins designed to hold intermittent surface runoff or water from more permanent canalized sources. Storage dams are frequently associated with reservoir construction; diversion weirs or dams are employed by canal users. Dams associated with reservoirs function to slow the velocity of intake waters (especially during flash flood conditions) as well as to raise water levels by permitting monitored gravity flow into issuing canals. Generally, reservoirs are constructed in regions without dependable riverine water sources.

Reservoir and dam construction has an ancient past. However, many small, deliberate ponding areas have probably gone unnoticed as a consequence of rapid sedimentation immediately following their disuse. In the New World, Middle Formative salt-producing evaporation basins have been identified at the spring head at Hierva de Agua (Hewitt et al. 1987). Dating to a comparable period (700 B.C.) is the dam and reservoir system revealed in the Tehuacan Valley (Woodbury and Neely 1972). Although diminutive at this early moment, by the Early Classic period (A.D. 100–300) the Purron Dam was 100 m by 400 m and reached a height of 18 m. Representing one of the most impressive hydraulic works in highland Mexico, the Purron Dam was located in an area relatively peripheral to centralizing developments elsewhere. In fact, it appears to have fallen into disrepair by A.D. 200–300, a period of accelerated growth in the nearby

Basin of Mexico. In addition to the major storage dam, the Purron reservoir contained a substantial cofferdam, probably constructed to entrap sediment (permitting its removal before it could enter the main body of the reservoir) as well as to allow the diversion of water during periods of reservoir dredging or dam maintenance.

Several additional reservoirs have been identified in the American Southwest (Crown 1987a; Scarborough 1988a). At Casas Grandes, northern Mexico, an elaborate reservoir system has been reported (Di Peso et al. 1974). Two centrally located reservoirs were identified along with a large water retention basin and a stone-lined settling tank. In the water-precious Hohokam area, reservoirs were canal fed and sometimes dug to a depth of over 4 m (Raab 1975). At Mesa Verde, Mummy Lake represents a masonry-lined reservoir with a silting tank (Rohn 1963). In neither case is downstream canalization considered of principal importance.

Reservoirs in the Maya area were of several varieties. The *chultun*, large, bell-shaped cisterns of the dry northern Yucatan Peninsula, were designed to catch rainfall from a prepared platform surface (Brainerd 1958; McAnany 1990). Similar to cisterns in Nabatea (Evenari et al. 1971), these containers had highly constricted orifices to curb evaporation. Reservoirs were also the result of monumental building activities, although natural drainage gradients were utilized. At the Late Preclassic community of Cerros, Belize (ca. 200 B.C.–A.D. 150), volumes of construction fill used in the built structures were comparable with those removed from the extensively quarried canal and reservoir depressions. Through the manipulation of dams and sills, water was conserved in "basin canals" during the dry season while the core area of the community was drained during the wet season (Scarborough 1983a). At the much larger Late Preclassic site of Edzna, Campeche, the Maya used a system of linear canal reservoirs for potable water as well as for transportation (Matheny 1976). Elsewhere in the Maya lowlands, large depressions (*aguadas*) were frequently modified from the naturally low-lying terrain (Matheny 1978). Even the *bajos* (internally drained swamps) covering extensive tracts of the Maya area today are hypothesized to have been altered in establishing predictable water levels for supporting raised-field agriculture (Harrison 1977).

In both the Maya area (Dahlin 1984; Matheny 1980) and the five-lake region of the Basin of Mexico (Armillas 1971; Palerm 1955; Sanders et al. 1979), land transportation routes through swamp margins were maintained by causeways or roads. Functioning as dams, these features reduced the salinity of the water surrounding the island metropolis of Tenochtitlan during the Aztec period in the Basin of Mexico. The bulk of Lake Texcoco received the highly mineralized runoff from the surrounding terrain, but the dike system enclosing the Aztec capital allowed only sweet spring water to enter the city (see below).

In South Asia, reservoir construction had few parallels elsewhere in the ancient world. At the Harappan port city of Lothal in the state of Gujarat, India, a man-made basin 219 m by 37 m, was constructed with sunken sidewalls dropping 4.5 m below. The feature dates to the late first millennium. Early interpretations of the basin suggested that it functioned as an elaborate docking facility connected by canals to the nearby estuary. More recent examinations indicate that the basin was an attempt to capture fresh water from an elevated watershed and isolate it from the brackish waters of the estuary (Allchin and Allchin 1982).

The celebrated tank systems of western and southern India as well as northern Sri Lanka represent the largest non-Western reservoirs known. At Bhojpur near Bhopal, Madhya Pradesh, the king of Dhara built a huge tank in the mid-eleventh century. The embankment supporting the reservoir, breached in the fifteenth century by the Moguls, is estimated to have impounded more than 650 $km^2$ of water (Basham 1968:195). Constructed in a similar manner, the grand temple tanks of Anuradhapura, Sri Lanka, covered an area of 2,500 ha and permitted the controlled movement of nearly 90,000,000 $m^3$ of water (Murphey 1957:185) by canal over a distance of 90 km (Leach 1959:9). Gunawardana (1971, 1978) indicates that reservoirs of the dimensions identified in Sri Lanka were not possible until the appearance of the "cistern sluice." Introduced by at least A.D. 200, it controlled the outflow from a reservoir without damaging the catchment weir or dam.

Large reservoirs are also apparent in the Sahel of northern Sudan. The *hafir* system within the expansive Butana grassland appears to have permitted the long-term colonization of this zone by large, well-organized Meroitic communities (350 B.C.–A.D. 350) away from the Nile (Crowfoot and Griffith 1911; Shinnie 1967). Canals have not been associated with these reservoirs. A pastoral symbiosis may have attracted this settled agricultural state.

Functioning as reservoirs and huge silt traps were the large, shallow basins seasonally inundated along the ancient floodplain of the Lower Nile. Managed through a series of short canals and well-designed embankments, these basins became the planting surfaces for pharaonic Egypt (Butzer 1976; Hamdan 1961). However, except for the regulation of lake levels within the Faiyum Depression by the Middle Kingdom (2040 B.C.), little evidence exists for centralized management of Nilotic floodwaters (Butzer 1976).

The diminutive "pond-fields" of protohistoric Hawaii also acted as reservoirs and silt traps. Terraced hillsides irrigated from permanent sources allowed the intensification of taro agriculture by these sociopolitically complex islanders (Earle 1978; Tuggle 1979).

*Canals.* Complicated canal systems have been specified as one of the major material correlates in the identification of complex community organization (Wittfogel 1957). The descriptive literature examining canalization is enormous. Physically, canal systems are strongly affected by gradient and seepage rates. Once canals are established, their use and maintenance influence the distribution of settlement along their length, with head (upstream) communities having an advantage over their tail (downstream) neighbors except, perhaps, during times of severe flooding.

Canal systems are fed by one of two principal water sources: (1) systems replenished by springs, reservoirs, or intermittent stream flow, or (2) systems associated with permanent streams. Most New World examples are a result of less predictable water sources. In the heartland of the American Southwest, Hohokam groups along the Gila-Salt drainage system constructed over 500 km of major canals and another 1,600 km of feeder canals (Masse 1981). Further south, Woodbury and Neely (1972) have identified extensive canalization in the Tehuacan Valley of highland Mexico dating to at least A.D. 700. The earliest empirical evidence for canalization in the New World, however, comes from the Basin of Mexico (700 B.C.) (Nichols 1982), although older water systems are implied in coastal Peru (Lumbreras 1974).

The Lowland Maya introduced a "still water" canalization technique across their low-relief landscape (Scarborough 1983a, 1983b) as well as "flow water" channels in association with permanent slow-moving rivers (Turner and Harrison 1981). The former technique was controlled by runoff manipulation and its seasonally timed release from annually replenished reservoirs into internally drained environments. The latter represents a water system with an external riverine drainage outlet. At Pulltrouser Swamp, Belize, the water levels of a huge backwash zone immediately adjacent to the New River may have been controlled during the Classic period by sluice gates leading away from the river (Harrison and Turner 1983).

Peru provides extensive data on canal schemes (Farrington 1980; Moseley 1974, 1983; Ortloff et al. 1982), some associated with the widespread terracing of the Andean landscape (Donkin 1979). Guillet (1987) has shown that Peruvian terracing is as much an attempt to control limited water supplies as it is to create cultivable land. Today, in the semiarid setting of Arequipa, terracing provides the gradient necessary for the careful distribution of water downslope. Although terracing retards soil erosion on precipitous slopes, it is the skillful manipulation of water along terrace end-wall canals that permits agriculture. Both the pre-Hispanic Mochica and their subsequent Inka lords further managed water systems by sometimes lining their main canals with stones to reduce seepage rates (Ortloff 1988; Sherbondy 1982).

In the Old World many ancient canalization projects developed in association with large permanent rivers. Along the lower Nile (Butzer 1976; Hamdan 1961), the Huangho and Yangtze (Hsu 1980), and possibly the Indus (see below), canals helped direct seasonal floodwaters across extensive floodplains in association with early state developments. However, it was along the Tigris and Euphrates that canalization may have been most widely utilized at an early date.

The best evidence for the earliest experiment in canalization comes from Choga Mami (Mandali), Iraq (Oates and Oates 1976). Resting on the outer slope of the foothills near the limits of dry farming, Choga Mami was positioned on a triangle of land flanked by two streams. Canal segments dating to the sixth millennium portend in miniature later developments in southern Mesopotamia (Oates 1972, 1973). Further, Helbaek (1969, 1972) indicates that irrigation was necessary at other Samarran communities beyond the range of dry farming. His evidence is based on the moisture requirements of domesticated plants identified from these ancient arid settings.

The great attempts at dam and reservoir construction along the Tigris and the Euphrates extend back to neo-Babylonian times (625–537 B.C.), but the most massive earth-moving operations are associated with the Sassanians (A.D. 226–637) (R. M. Adams 1981). At one time, the Euphrates was entirely diverted in an attempt to force out recalcitrant farmers farther downstream (Fernea 1970). Unlike other great river systems associated with civilization, this latter drainage generated floodwaters during an April peak, too late for winter crops and too early for summer planting. Because of a steep gradient and low-lying floodplain, as well as overall irregularities in annual discharge rates, the Tigris and the Euphrates required the skillful use of dams and reservoirs in directing water through a canal system.

The extensive canalization systems of Sri Lanka were based on the collection of water in large tanks. Replenished from seasonal sources, these tanks released water into canals immediately below the dam or bund supporting the reservoir. Similar systems are suggested for Cambodia and Java (Bronson 1978).

## Social Costs of Water Management

The manipulation of water toward an agricultural end involves short-term and long-term investments. In an important article, Hunt and Hunt (1976) have articulated some of these differences. Short-term investments are usually routine tasks or assignments conducted over the course of an agricultural year. They include decisions about water allocation, intragroup conflict resolution, and maintenance of functional features. Long-term investments occur much less frequently and usually require more uninterrupted time, labor, and planning. Construction projects, major repairs, and external conflict resolution are the domain of long-term community investments. The significance of social costs is best addressed by studies examining historic and contemporary peoples.

### *Short-Term Costs*

Water allocation is the principal source of conflict among all water users, from small-scale, community-oriented systems to complex, bureaucratically managed ones (Chambers 1980). Decisions must be made about the area of land to be irrigated, the time of water delivery, and amounts of water. Ethnographic groups have *traditional formulas* for this allocation, which vary with the ecological and technological constraints of their environments. Nevertheless, an impartial watchman or "ditch master" is routinely charged in most societies with the daily task of equitable water distribution. Further, as a result of unexpected drought conditions or severe flood damage, certain individuals or groups of community elders may become responsible for allocations during periods of acute stress.

Intragroup conflict generally arises as a consequence of differences concerning water allocation. Violations of the *traditional allocation formulas* by individual users or excesses associated with the interpretations of a ditch master lead rapidly to heightened tensions. Emotions can be especially volatile during periods of drought. Most water management infractions are quickly settled by an impartial ditch master who speaks in behalf of the community. However, if conflict goes unchecked or escalates, a greater jural body will eventually intercede. The latter condition is usually associated with long-term and infrequent water management costs (Hunt and Hunt 1976).

In addition to water allocation decisions, conflict can result from negligence in the maintenance of the water system. Small private construction projects without the support of the community are especially disruptive. The unannounced construction of a canal can have a significant impact on the entirety of a group (cf. Vandermeer 1971), with changes in water volumes throughout the irrigation scheme altering sedimentation as well as discharge rates (cf. Glick 1970).

Maintenance of the system is a periodic task dictated by tradition and sanctioned by a governing body. Varying with landscape, maintenance is a communitywide requirement of every canal user; stiff fines are levied against abusers, although a user can sometimes pay to have the service performed by another. In the Tehuacan Valley, it is necessary to remove the solidifying calcium carbonate accumulation annually from canal walls and floors in order to maintain the proper volume and gradient of water required for irrigation (Woodbury and Neely 1972). The swampy tail end of the medieval Valencia system not only required more work to remove the accumulation of sediments carried down from the head end of the canal system, it also harbored a greater incidence of disease (Glick 1970).

### *Long-Term Costs*

Short-term costs represent static or normative conditions in the anthropological record. They seldom offer a window into how agricultural systems grow, change, or decline. Long-term costs are apt to trigger lasting changes in a water system, and may significantly impact the course of other human institutions. Nevertheless, each society manifests a different level of tolerance to change, depending on its social structure and the magnitude and quality of the changes.

Corporate construction projects involving the reclamation of previously destroyed functional features or the initiation of new features requires energy and forethought. Construction often takes place during periods of perceived mismanagement and is done by the community at large. In this sense, construction is a form of repair in the understood water needs of a group. Generally, it comes at a time when material resources are at their highest premium. The building of a dam in San Juan, Oaxaca, may have been precipitated by inefficiency and a critical shortage of water to the community (Hunt and Hunt 1976), but its ultimate construction was delayed until local resources were entirely consumed or an external governmental agency intervened. In medieval Valencia, drought was the stimulus for canal building; adequate stores of water seldom stimulated public works projects (Glick 1970). This condition of construction costs establishes it as a major determinant of organizational change beyond the simple investment in the functional feature itself. Such costs minimally allow an evaluation of the decision-making process for a group and may promote an individual or group into a more powerful role in governing the rights of others.

Repairing an old water system following a natural catastrophe, such as unprecedented flooding or extended drought, represents an attempt to maintain the status quo during a period of resource stress. Again, the repair investment may force lasting organizational change if the disaster is of a monumental scale. Generally, however, repairs salvage not only damaged features but also the social organizational system. Most water management systems have *traditional formulas* for drawing upon laborers to repair water damage during times of natural disaster.

Long-term social costs also arise from uncontrollable, internecine feuding as well as from external conflicts (Hunt and Hunt 1976). Sometimes chronic short-term intragroup fighting can escalate as a consequence of poor institutional management. If the formulas are incapable of resolving the conflict, major institutional changes are predictable. For example, the uncontrollable conflict in the Teotihuacan Valley of Mexico has led to disorganization among water users (Millon et al. 1962). It has been catalyzed by a rapidly growing immigrant population without the corresponding traditional formulas for coordinating the new arrivals. Until an organizing principle is introduced, the water system will remain chaotic.

### *Growth Systems*

Both long-term and short-term social costs are dependent on whether the hydraulic system is expanding or contracting in scale and complexity. The expansion of a water system can result from a slow-growth process in which community organization, ecological constraints, and technology accommodate population increases. Slow growth generally develops within the original social and technological parameters of the water system. Significant institutional changes can sometimes evolve if the original water system is "pre-adapted" to accommodate change. Among agricultural systems, intensification can be triggered by further employing a growing labor pool (Boserup 1965).

Rapid or "radical" growth in the hydraulic system occurs during the establishment of long-term costs. They can be stimulated by accelerated population growth, technological innovation, the introduction of a new crop, or the more effective marketing of an old crop. Long-term costs are precipitated by an immediate and critical need caused by a hopelessly inadequate water system (as perceived by the users). Although a small community may maintain an inefficient water system to preserve its traditional formulas and the autonomy they allow, a point is reached where change must occur.

### *Declining Systems*

Contracting water systems are frequently victims of climatic or geological deterioration, although unresolved social conflict may also reduce a hydraulic system. Generally, ecological deterioration manifests itself through a "radical" decline in the water system in two ways: (1) the natural elements incite a catastrophic change or (2) early states find it difficult to correct the slow, extended effects of human-induced environmental deterioration that culminate in a rapid abandonment of a landscape.

The principal climatic variable affecting catastrophic change is clearly precipitation. Although some societies appear capable of accommodating extended periods of cyclic drought (perhaps best illustrated by aboriginal groups in the American Southwest) or periodic flooding (pharaonic Egypt typifies this condition), there is a threshold beyond which no group can continue. The primary geological variable influencing radical hydraulic change is tectonic. The postulated uplift along the lower Indus may have drastically altered the gradient and the hydraulic adaptations made at Mohenjo-daro (Raikes 1964, 1965, 1984; see Possehl 1967 for an alternative view). Along the northern Peruvian coast, Moseley (1983) and colleagues (Ortloff et al. 1982, 1985) have demonstrated that a tectonic event reversed the gradient of the Chicama-Moche intervalley canal system and severely disrupted the huge Chimu capital of Chan Chan (see Farrington 1983; Pozorski and Pozorski 1982 for alternative views).

The influence of human-induced deterioration results from too much water as well as too little. In arid and semiarid zones with extensive canalization or sizable reservoirs, the water table under an irrigated area rises. Swamplike conditions can occur without proper drainage, promoting root rot of some cultigens and the appearance of otherwise unfamiliar plant and human disease (cf. Glick 1970). An elevated water table also produces salinization in areas with mineralized runoff. This condition may have been most acute along the Tigris-Euphrates, where little occupation is possible even today in areas near the great Babylonian and Sassanian ruins (R. M. Adams 1981; Fernea 1970; Gibson 1974; Jacobsen and Adams 1958).

Poor management of a canal or reservoir system will increase the amount of sediment accumulation. However, a significant rise in the water table accompanied by poor management may result in rapid siltation rates and changes in the gravity flow gradient. This condition may have affected Mohenjo-daro (Dales 1965; Raikes 1965, 1984) as well as the Terminal Classic Maya (Harrison 1977).

Too little water, a condition influencing most early states, is exacerbated by climatic fluctuations. A dropping water table, whether induced by human mismanagement or a consequence of changes in rainfall patterns, will cripple a dependent population. Flood damage can produce erosion, and long-term gradient changes in a dropping water table will promote erosive cutting of a field area. Left unchecked, erosion will destroy a hydraulic system, as is well documented in the American Southwest (Dean et al. 1985; Vivian 1974: 109; Worster 1985).

In addition to the above influences, overly intensified agriculture can lead to decline. Agricultural systems in Southeast Asia have been described as "involuted" (Geertz 1963) or characterized as having more labor than is efficient, given the quantity of food produced (Hanks 1972). If more land or water or better techniques are not acquired, severe shortages of food will result. This intensification of the labor force within the traditional allocation formulas will eventually lead to collapse or to new formulas embedded in a different social organization.

### *Allocation*

Water allocation is as much a natural source of cooperation as of social conflict. Because water is a shared community resource and each member of a group has a daily need for it, the rules by which water is distributed reveal aspects of social, economic, and political behavior. Chambers (1980) has drawn attention to the differences between an analysis of water management through the eyes of an elite (the "top down" view) and an analysis through the eyes of the agriculturalist (the "bottom up" view). The elite perspective results from dichotomizing the hydraulic system into private and public sectors. Private water schemes include symbolic systems (baths, gardens, etc.) but may also involve the exploitation of water resources from a public domain. Control and manipulation of private water sources usually impinge on the public or community hydraulic system, causing shortages when water is at a premium.

The "bottom-up" view evaluates a water supply in terms of costs, adequacy, convenience, and reliability (Chambers 1980:32). Although these factors are clear considerations in a "top down" view, they figure less importantly because of the elite's power to coerce work from a disenfranchised labor pool. Social costs are somewhat assumed in a "top down" view. Nevertheless, the "bottom up" view represents the underpinnings of an equitable communitywide allocation system. Even under a coercive elite, the "bottom up" view evaluates the distribution of a reduced water supply in terms of traditional allocation formulas and equitable allocations to the greater community.

As early as Hammurabi's code of laws (1850 B.C.), the concept of proportional distribution and collective responsibility to a greater irrigation community has existed (Glick 1970). Although less concerned with irrigation and clearly having a greater antiquity, Roman water law defined the basic doctrine of riparian rights. An individual living on the banks of a water source had the right to divert water as long as it did not harm those below. From this code evolved the notion of water "turns" (Glick 1970).

Water allocations in a simple irrigation system involve (1) the size of the area to be affected, (2) the amount and timing of the release and (3) the established rules and traditional formulas affecting distribution. In every case in which water is a scarce resource, a degree of risk is involved. Although the immediate decisions affecting the allocation of water across an individual's plot are the responsibility of each agriculturalist, the amount and timing of the release will be the responsibility of the community. This task is usually delegated to the ditch master.

In communities little influenced by privately controlled water sources or the force of coercive elites, ditch master tends to be a rotated position with little economic attractiveness (cf. Gray 1963; Hunt and Hunt 1974). Since the post takes time away from one's own fieldwork, access to additional land or water may be allowed to compensate for the loss. In less equitable situations in which land and water are not distributed equally, the role of the ditch master is compromised. He must give the appearance of representing the greater community while supporting the demands of the larger landowners or landlords.

Two convenient divisions have been made for assessing the forces influencing allocation (after Glick 1970). The Syrian model suggests that the quantity of water available to each user is directly proportional to the amount of land under cultivation. This ideal system demands that an agriculturalist at the head end of a canal receive the same amount of water as his neighbor at the tail end, given that both cultivate the same acreage. The Yemenite model argues that water distribution is not tied directly to one's acreage, but allocated on fixed time bases and open to elite control through the sale of water.

One of the greatest individual advantages in any moving water system is the positioning of one's plot at the source of the system. In both south India and Sri Lanka (Chambers 1980; Leach 1959) as well as the Philippines (Coward 1979), an individual's cultivable land is parceled equally between the head end and the tail end of the canal system. This ingenious distribution of land, sanctioned by tradition, permits the maintenance of the Syrian model. Water allocation abuses are considerably more difficult if access to the head end of the canal is shared equitably.

A similar adaptation is apparent in southern Peru. Guillet (1987) indicates that the allocation of water over the terrace system of the Colca Valley is usually controlled in vertical strips. Water is released from an elevated main canal above each of the vertical strips sequentially. The individual terraces within a strip are usually owned by a family, an attempt being made to keep strip holdings intact. This land use/water use adaptation or traditional formula makes the same individuals securing access to the head end of the main canal accountable for losses to tail-end plots. The South Asian, Filipino, and Peruvian examples clearly represent Chambers's "bottom-up" view of water distribution, in which indigenous custom and community sanctions direct the water needs of the greater community.

In the classic Yemenite scheme, a tail-end user is penalized by the conveyance loss associated with his distance from the main canal. Evaporation and seepage can severely diminish an initial allotment made by a time-controlled rationing arrangement. During periods of extreme drought, a tail-end user is unlikely to receive water.

Under any allocation model, extended drought is especially difficult for the small plot agriculturalist. Even under the equitable Syrian design, an allotment of water proportional to the amount of land that a small agriculturalist may have under cultivation would be so reduced as to make cultivation untenable. Add to this any tendency by larger and better-positioned head-end users to extract "just a little more" during periods of sparse water availability, and tail-end users are completely ruined. The Yemenite model probably results during periods of natural calamity, even when an earlier Syrian adaptation may have been in place.

In the Cuicatec as well as the Teotihuacan regions, Hunt and Hunt (1974, 1976) and Millon et al. (1962), respectively, indicate that a Yemenite model was operative in the private sector, while state lands (*ejido*) were governed by a Syrian model. Nevertheless, during periods of extended drought, a Yemenite allocation model prevailed on state-supported lands. As will be discussed in the next section, sociopolitical control can be taken by a few users at this time of vulnerability, and dependency relationships rapidly develop.

### *Sociopolitical Organization*

The influence of water management on sociopolitical organization has been hotly debated. Wittfogel (1957) and Steward (1955) champion a deterministic view in which early state development and complex bureaucratic organization were triggered by controlled irrigation schemes. Several scholars have taken this position to task (Hunt and Hunt 1976; Leach 1959; Millon 1962; Mitchell 1973; Service 1975). Although the voluminous support offered by Wittfogel for his position has been challenged, his thesis has forced a timely reflection on the impact water manipulation has had on early state development.

The cooperative bond established by water users sharing an irrigation system appears to stimulate a territorial alliance among them. Strong group associations develop, although intragroup conflict may continue to follow clan or lineage lines. Among closed corporate communities such as the Sonjo (Gray 1963), the Pul Eliya (Leach 1961), the Zanjera Danum (Coward 1979), and the Quinua (Mitchell 1976), associations are clearly defined. In conflict-ridden regions such as Cuicatec (Hunt and Hunt 1974, 1976) and Teotihuacan (Millon et al. 1962), immigration and lack of well-developed traditional formulas for water allocation have worked against associations.

Intervillage irrigation systems at a regional scale usually maintain intervillage territorial alliances. In medieval Valencia (Glick 1970), Peru (Mitchell 1976), Japan (Beardsley et al. 1959), and Bali (Geertz 1973; Lansing 1987), well-established ritual, coupled with periodic marketing events, helped to bind the associated communities and stem conflict.

Wittfogel (1957) has examined regional systems at the largest scale. Despotic bureaucracies are argued to be a consequence of large-scale irrigation schemes within regions where water is channeled from some distant source. Irrigation is posited to centralize resource control and trigger a "pecking order" of managers and users, resulting in rigidly defined social stratification. Wittfogel's earliest successful "hydraulic societies" were southern Mesopotamia, Egypt, and the Indus Valley, with Classic China representing the paradigm of "Oriental despotism." More recently, Wittfogel has argued that the pre-Hispanic states of the New World developed along similar lines (Wittfogel 1972).

Despite the many problems associated with the "hydraulic society" model, most early states did develop sophisticated water management schemes. Wittfogel's approach to understanding water manipulation is akin to the "top down" view mentioned earlier. Viewed by the agriculturalist in the field, state interference and control represent meddling with a community's traditional formulas for resolving water problems (cf. Flannery 1972). Although state control can provide the capital necessary for long-term construction, restoration, and conflict resolution, it introduces the element of domination and potential coercion. If long-term, regionwide state investments are initiated, considerable risk to an individual community can develop. The construction of a dam may be advantageous for the residents of greater Mexico City, but its immediate impact on the water supply of farmers in the Teotihuacan Valley may be disastrous (Millon et al. 1962).

State-level control attempts to integrate complex social organizations. Bureaucracy is an order imposed on these complex social and political interactions. Control is the driving force behind an incipient bureaucracy and occurs at the expense of organizational efficiency. Many insular communities react against this "top down" view, preferring their own traditional formulas for water distribution. Clearly, early states realized this dilemma, and true despotic regimes could force communities into submission by controlling the sluice gates to their fields. The kind and degree of control used by early states differed markedly (see below).

One index used to assess the significance of water management and its influence on early states has been the degree of boundary concordance between the two (Hunt and Hunt 1976). Wittfogel's despotic state should have borders corresponding to the extent of the irrigation system, a condition apparent in Classic and medieval China (Wittfogel 1957). However, some states were not organized in this manner. Irrigation schemes can crosscut state boundaries, as does the *qanat* system in the Tehuacan Valley (Woodbury and Neely 1972).

The Bali example has received considerable attention in this regard. Millon (1962) argues that Bali was not a state, yet presents strong evidence for a sophisticated water manipulation system. Lansing (1987) argues that Bali may be a decentralized state (cf. Geertz 1963, 1973), but that the irrigation system on the island operates independent of state control. Nevertheless, the water system is isomorphic with the boundaries of the state. If Lansing is correct, then the significance of boundary concordance between the state and the water management scheme is further reduced.

## Archaeological Case Studies

The documentation of water management among contemporary or historic peoples provides synchronic detail not retrievable from the archaeological record. Attempting to understand water systems, however, requires temporal depth to identify long-term social costs. Archaeology permits longitudinal comparisons between water systems from well-defined centers of complex social organization. By examining the growth, maintenance, and decline of water systems from various parts of the world, ecological and cultural constraints can be identified. The Old and New World examples presented reveal the tension between hierarchically controlled water systems and those of the insular village. The juxtaposition between arid and humid settings further illustrates the variability and complexity of ancient water management systems.

### *Southern Maya Lowlands*

The environmental seat for Classic Maya civilization (A.D. 250–900) was the heavily vegetated limestone surface of the Yucatan Peninsula. In the southern Maya lowlands (the focus of state development), rainfall is seasonal with a three-month period of annual drought. Precipitation rates today range from 1,500 to 2,000 mm/year in the north-central Peten, Guatemala (Bronson 1978; Puleston 1973). Major surface drainage is lacking, although the Usumacintla on the west and the Rio Hondo on the east permit some riverine discharge from the ancient heartland of the Maya. Far from being desertlike, the setting is a semitropical forest area slightly on the dry side. The thin soils are fertile on the hills and better-drained flatlands (mollisols), but in the low-lying *bajos* thick, viscous clays (vertisols) obstruct utilization.

In the past, the cultural landscape was considerably more complicated than it is today. Drawing on an earlier position taken by Cooke (1931) and Palerm and Wolf (1957), Harrison (1977) indicates that many of the internally draining *bajos* may have been lakes or huge modified reservoirs that have since silted in. Poorly coordinated slash-and-burn agricultural systems practiced on higher ground adjacent to the *bajos* have accelerated sedimentation into these depressed settings since their disuse over a millennium ago. Recent aerial imagery suggests that the margins of many of the ancient *bajos* were utilized for intensive agriculture (R.E.W. Adams 1980; R.E.W. Adams et al. 1981; Scarborough 1983b), and Culbert et al. (in press) has demonstrated *bajo* canalization through survey and excavation. Further, ground-truth survey and excavation have demonstrated drained-field agriculture in *bajo*-like settings in Quintana Roo (Gliessman et al. 1983; Harrison 1977, 1982; Harrison and Turner 1978) and northern Belize (Scarborough 1983a). Riverine raised-field agriculture associated with open or "flow" drainage systems has been well documented (Bloom et al. 1983, 1985; Hammond 1985; Hammond et al. 1987; Harrison and Turner 1983; Kirke 1980; Siemens and Puleston 1972).

In addition to the possibility of *bajo* "tanks," numerous reservoirs have been reported in more elevated settings in association with ancient communities of all sizes. Perhaps modified from natural depressions or limestone quarry sites, these basins could reach immense proportions. At the Campeche city of Edzna, Matheny (1976; Matheny et al. 1983) has identified several monumental canal basins dating as early as the Late Preclassic. Over 1.75 million $m^3$ of fill were removed in their construction (a figure well in excess of the volume of the Pyramid of the Sun at Teotihuacan).

Tikal represents the best-documented large community in the Maya lowlands (Coe 1967). At several elevated locations within and immediately outside the central precinct, reservoirs were formed behind well-defined causeways. Although these *sacbeob* (roads) connected various portions of the dispersed-compact temple core, they also functioned to dam water within a sizable catchment area (Carr and Hazard 1961). Although additional excavation is required, it seems likely that these nearly dry tanks held considerably more water in the past. The controlled release of water from elevated reservoirs to the downslope flanks and adjacent *bajo* margins would have permitted access to potable water as well as water for agriculture during the dry season. The physical appearance of the Tikal "tank system" is strikingly similar to the tanks of south India and Sri Lanka (see below).

Causeways functioning as dikes are not limited to Tikal. In one of the large lakes/reservoirs at the Classic period site of Coba, a dam or dike crossed the water-filled basin (Folan et al. 1983). At Late Formative period Cerros (Scarborough 1983a) and El Mirador (Dahlin 1984), *sacbeob* traverse low-lying *bajo*-like settings in proximity to the central precincts of these communities. The Cerros hydraulic system suggests that water was separated by an elevated road or dike into communitywide agricultural sources on one side and potable private household sources on the other (Scarborough 1983a). Canalization was well developed in the slow-moving, internally drained Cerros system (Scarborough 1991).

The social costs necessary to establish the water systems found in the Maya area may not have been as severe as in other parts of the world. The relative ease with which limestone was quarried in producing reservoirs and dams (causeways), as well as the apparent call for construction fill in erecting monumental architecture, permitted an approximately 1:1 relationship between reservoir volumes and temple/palace/house mound volumes in some communities (Scarborough 1983a). Further, the greater rainfall associated with a semitropical forest allowed small, insular communities to construct and maintain their own reservoir sources independent of larger cities.

The tank or reservoir systems of the Maya (excluding reclaimed *bajo* settings) probably functioned in a manner akin to those documented in south India and Sri Lanka (see below). Within the insular community, water was probably allocated following a Syrian model until resources were severely stressed. Although some meddling by the state would have occurred, most of the maintenance and internal conflict resolution associated with water distribution probably operated within the community.

If the *bajos* were lacustrine settings, however, salinity rates and lake levels would have been controlled by state regulators, as indicated in the lake basin of Aztec period highland Mexico. Raised fields, like the *chinampas* of the Aztecs, would have required a significant corporate investment for their establishment and maintenance. The early utilization of the *bajos*, as evidenced by the causeways into these depressions at the Late Preclassic city of El Mirador (Matheny 1980), the satellite imagery of canal systems reported near Seibal (R.E.W. Adams et al. 1983), and the aerial photographs of drained fields in southern Quintana Roo (Harrison 1978), suggest large tracts of agriculture regulated to a degree by controlled water levels. Recent foot survey and excavation in far northeastern Peten (Culbert et al. in press) and Quintana Roo (Gliessman et al. 1983) indicate that water levels today fluctuate seasonally within *bajos*, but that rainy-season drainage devices and dry-season conservation measures would have permitted at least two crops per year. Sizable diversion dams have been documented along the Rio Azul (R.E.W. Adams et al. 1984), and floodgates are postulated immediately off the New River (Harrison and Turner 1983). In these latter examples, water appears to have been diverted from a river to an adjacent floodplain/backwash setting for raised-field agriculture.

The water systems of the Maya allowed several different functional adaptations at once. The seasonality of the rainfall and the lack of significant external drainage allowed the control of water reserves at several sites. Tikal may have controlled several sizable tanks, providing an elite with additional authority. If water levels were further manipulated in the adjacent *bajos* for agricultural ends, Tikal's water bureaucracy clearly would have been a significant one. However, small autonomous communities were capable of constructing adequate reservoirs for domestic use. Because of the difficulty of controlling a dispersed population in a tropical rain forest (cf. Scarborough and Robertson 1986) and the relative ease with which a reservoir system could be constructed from the limestone relief, absolute control of the resource by an elite was never possible.

### *Highland Mexico*

The Basin of Mexico was the seat of great civilizations. Although canalization has been reported as early as 700 B.C. (Nichols 1982), clear associations between the state and the construction and maintenance of water systems are not apparent until the Aztec Postclassic period (A.D. 1350–1520). Like the Maya area, the basin was without significant external drainage. The closed system of five connected lakes, coupled with the expanded lake margins of the rainy season (the Lake of the Moon), covered an area comparable with the *bajo* and small lake system between Tikal and Rio Azul of northeastern Peten. Unlike the Maya lowlands, the rainfall in the basin is 700 mm/year with frosts severely affecting the agricultural year (Sanders et al. 1979). The soils in the basin are fertile, characterized as either chernozem or chestnut. Today, crops are particularly successful on the piedmont slopes above frost-damaged alluvial settings.

Extensive canal irrigation systems are suggested within central highland Mexico from a very early date (Fowler 1987; Nichols 1987; Sanders et al. 1979; Sanders and Price 1968; Sanders and Santley 1977; Woodbury and Neely 1972). In the basin, these irrigation communities were relatively small, although a single drainage might share its waters with several adjacent communities (cf. Millon et al. 1962). Unlike the Maya area, a mountainous watershed allowed some permanent streams that eventually issued into the closed five-lake depression. However, the rugged topography and the distances separating small drainages made state control of large tracts of the irrigation systems difficult.

Nevertheless, intensive agriculture supporting an early state is implied by the scale and complexity of a city the size of Teotihuacan. With a population in excess of 125,000 people living in an area of 23.5 $km^2$ (Millon 1970, 1973), Teotihuacan was the most influential city in Mesoamerica in A.D. 500. The hinterlands immediately surrounding the city, however, were sparsely occupied. Sanders et al. (1979) indicate that this would have been agricultural space, probably irrigated in part by the small stream now apparent at the site. If so, considerable landscaping and water manipulation would have been necessary, a condition for which we have little evidence.

Teotihuacan derived much of its political and economic power by controlling ancient obsidian trade inside as well as outside the basin (Sanders et al. 1979). Its geographical location away from the resource-abundant lake margins and near the principal obsidian quarries suggests this association. It is frequently argued that its distance from the lakes indicates that *chinampa*-type raised fields were not utilized at this early date. However, Palerm (1955:35), Coe (1964), and Armillas (1971) indicate the construction of *tlateles* (islands) thought to be ancient *chinampas* dating from as early as the initiation of Teotihuacan. Given the longevity of Teotihuacan (over 700 years), experimentation and adaptability seem clear. Several agricultural adaptations were made by Teotihuacanos to feed themselves and control their neighbors. To command the obsidian market, it was necessary to monitor the quarry source, perhaps the raison d'être for this location. Nevertheless, the productivity of a *chinampa* system coupled with canal irrigation would have allowed the necessary flexibility in the agricultural base to deal with an expanding population.

Although the precise inception of lakeshore *chinampa* agriculture is unclear, Palerm (1955) provides historic accounts demonstrating its widespread use during the Aztec period. Two factors severely limiting the potential of extensive *chinampa* agriculture were unstable lake levels and elevated salinity rates. Because of the closed nature of the basin, heavily mineralized sediments accumulated in the lakes, making the waters nitrous and harmful to plants and humans. Further, unchecked fluctuations in stream discharge rates, coupled with periodic droughts, could radically alter lake levels or, alternatively, flood or dry *chinampa* plots.

To prevent damage by floods or salt contamination, dikes or causeways were constructed across portions of the lakes. The spectacular island city of Tenochtitlan was established on the western embayment of the large central lake of Texcoco by controlling the floods of nitrous water. *Chinampa* cultivation and potable water supplies were established by constructing a dike that effectively separated the embayment from the greater body of the lake. Sweet water from Chapultepec and other springs on the mainland was carried by aqueduct into the cordoned-off embayment, in time diluting the saline concentration. In addition, the sluice gates of the dike were used to control water levels within the dammed area (Palerm 1955).

Among the civilizations that identified the Basin of Mexico as their seat of power, truly urban conditions prevailed. State planning and control dictated water manipulation in proximity to large cities. Tenochtitlan had its own *chinampas* within the island core (Calnek 1972). Clearly, *chinamperos* were at the service of the state bureaucracy, since only the state could control and regulate water levels. A statewide Syrian water allotment system would have been unavoidable, given the characteristics of lakeshore agriculture.

Nevertheless, canal irrigation in the basin probably operated within a less coordinated organizational system. Given the small size of the drainages feeding into the basin and the absence of conjoined interdrainage areas, little evidence suggests regional hydraulic control. It should be noted that Palerm (1955:40) does indicate that the river of Cuauhtitlan was dammed, diverted, and finally redirected into a newly widened channel 2 km long, nearly 3 m wide and about 3 m deep. Clearly, such focused energies required the actions of kings to mobilize the number of villages Palerm's figures suggest. However, in this enterprise the state is viewed as a temporary player called upon for long-term social costs that may or may not have been beneficial to the individual village (cf. Hunt and Hunt 1974). Generally speaking, organization of irrigation was villagewide and sometimes drainagewide. Less predictable quantities of water, induced by natural drought or increased numbers of consumers, probably resulted in considerable conflict. Under these conditions, a Yemenite allotment adaptation is suggested. Such conditions would have favored a local elite and triggered widespread tension during periods of severe shortage.

The Maya lowlands and the Basin of Mexico represent state levels of organization. The technology associated with closed-basin, raised-field agriculture and standard forms of canalization were probably shared by both as early as the Late Preclassic period. Canalization at the insular village level was elaborated in the basin, where at least some permanent streams were present. In the lowlands, without permanent sources of water but with greater precipitation, reservoir construction appears to have been the focus of the individual village. In either case, the potential for state control was limited to *bajo* or lakeshore hydraulic management. The more dispersed and autonomous village managed its own water needs, unless severe action was called for by the state.

*American Southwest*

Although the American Southwest developed complex social institutions, state levels of sociopolitical scale or integration cannot be argued. However, examining this region provides one example for comparing complex prestate water management systems with complex state systems. Some of the best evidence for pre-Hispanic canalization in the New World comes from the American Southwest. In the northern Sonora Desert of present-day Arizona, the Hohokam established extensive canal systems in proximity to the Gila and Salt rivers. Both of these streams are considered perennial, although segments of each may have carried little surface flow during drought cycles (Crown 1987b). The rainfall in the Salt-Gila Basin averages less than 25 mm/year. As noted previously, over 500 km of major canal have been identified (Masse 1981), tentatively dating from the Pioneer through the Classic periods (A.D. 150–1400) (Nicholas and Neitzel 1984). (It should be noted that controversy remains concerning the precise date of these pre-Hispanic canal systems [Schiffer, personal communication].)

In the Salt-Gila Basin, canalization cultivated intervillage cooperation in the construction and maintenance of the canal system (Wilcox 1979). Crown (1987b) has shown that the land along main canals issuing directly from the Gila River was settled by "irrigation communities" that may have included several platform-mound villages which interacted independently of neighboring single-main-canal irrigation communities. This autonomy appears similar to that of the insular villages noted in the Maya lowlands and Basin of Mexico.

Without a more predictable long-term water source, manipulation of the water supply by an encompassing centralized authority was less probable. Water storage in reservoirs during drought conditions was attempted throughout the Southwest (Scarborough 1988a), but sparse rainfall, high evaporation rates, and less dependable drainage sources prevented greater manipulation. However, it should be noted that Nicholas and Neitzel (1984) demonstrate that during the Classic period Salt River canal networks coalesced, allowing multiple main canals to service a single large platform-mound site. Such organization would have stimulated intercanal system coordination, but still would have fallen short of the scale and integration necessary for state institutions.

The irrigation community along a single main canal clearly was well integrated. The platform-mound site of Casa Grande was located at the tail end of its canal, though it was the largest town on the canal and had the most land in cultivation (Crown 1987b). In order for Casa Grande to have received the amount of water necessary to irrigate its fields, a controlling elite within a greater irrigation district would have had to enforce the equitable allocation of water to this "tail-ender." Given the clear geographical opportunities that smaller villages had to divert water, the size and needs of Casa Grande suggest a Syrian allocation model. Even during periods of drought, it seems unlikely that a Yemenite distributional model could be enforced. As the most powerful town on the canal, Casa Grande would have attempted to receive the lion's share of the resource; but without state sanctions, it is unlikely that it could prevent head-end villages from drawing a generous allotment.

The settlement pattern associated with the Hohokam during the Preclassic period (A.D. 150–1150) was a dispersed *rancheria* type. However, Wilcox (1979) indicates that a more aggregated village settlement evolved during the late Sedentary period (ca. A.D. 1100) at Snaketown, and room space aggregated behind compound walls at Casa Grande during the Classic period. Although canalization was identified by the Pioneer period (A.D. 150–600; see Wilcox and Shenk 1977), consolidation of shorter canal segments into major canal systems did not occur until A.D. 1150 (Nicholas and Neitzel 1984; Wilcox 1979). The coincidence between greater village aggregation and extensive irrigation systems probably indicates increased centralization of resources. A greater social investment in village solidarity was necessary along a shared canal length, resulting in village compaction. The defensive advantage gained by settlement compaction may also reflect heightened competition for well-watered resources.

The Hohokam example illustrates the limits to which water systems can be taken, even under the most severe environmental constraints. Nevertheless, major long-term corporate work projects were not initiated, and state levels of organization were unable to develop. Perhaps if the multiple main canals issuing from the Salt River into single platform-mound sites had continued, greater complexity and scale would eventually have emerged. Still, without techniques for increasing the availability of water, little lasting development would have been possible. It should be noted that there is no evidence in the American Southwest of the conspicuous consumption of water that is suggested by the Gardens of Netzahualcoyotl in the Basin of Mexico (Wolf and Palerm 1955) and the sweatbaths of the Maya. Perhaps the presence of such conspicuous consumption is an index of elite power and early statehood.

### *North-Central Sri Lanka*

The dry zone of ancient Ceylon harbored one of the world's great tropical civilizations. The capital city of Anuradhapura was occupied from approximately A.D. 400 to A.D. 1000, a time period and environment comparable with the Classic period Maya lowlands. Slightly drier than the north-central Peten (1,500 mm of rain per year), the dry zone is without navigable drainage. The soils are reddish brown earths that may be thin on the unirrigated uplands, but more fertile for rice production in the low-lying depressions of the island today (Bronson 1978; Panabokke 1976). Unlike other early states previously cited, ancient Ceylon was a secondary state. Colonization from south India by complex societies was initiated in the last half of the first millennium B.C. (Murphey 1957; Gunawardana 1981). However, Sinhala remains perhaps the oldest of the great tropical civilizations of Southeast Asia, having particularly elaborate water systems. It should be noted that a link may exist between the earlier Harappan civilization of Pakistan and the Dravidian stock of south India (cf. Parpola 1986). Although several centuries later, the colonization of ancient Ceylon by Dravidians may represent the one-way diffusion of ideas from a temperate (desert) state to this tropical civilization.

Today, as in the past, north-central Sri Lanka is a landscape of reservoirs. Most of the present tanks are ancient and reclaimed (Leach 1959:8). Because of a long dry season, sizable reservoirs were constructed, some fed by runoff from enormous catchment areas and others supplied by way of anicuts (diversion weirs) placed across small streams (Gunawardana 1971; Murphey 1957:184). In addition, the kings of Anuradhapura and neighboring Powlonaruwa were responsible for enormous masonry embankments or dams, some rising to heights of 27 m over a length of 14 km. Leach (1959:9) estimates the Kalawewa tank to have been nearly 65 km in circumference and the issuing canal system to have extended for nearly 90 km. Although Leach dismisses the amount of labor necessary to construct these public works as a consequence of centuries of earth-moving additions, they clearly represent statelike control systems comparable with anything discovered in the ancient Old or New World (cf. Gunawardana 1971). Repair was expensive, with flood damage and siltation accumulations necessitating periodic maintenance by a sizable work force. Moreover, these major reservoir schemes within or immediately outside the capital cities were symbols of power and the conspicuous consumption of the elite. The largest artificial lake, Parakrama Samudra (Sea of Parakrama), provided the water piped into several royal baths in the later capital of Powlonaruwa (Murphey 1957:193).

Tank and canal systems of this magnitude were designed, in part, to irrigate land that would not otherwise have been routinely cultivable. Within the sphere of control established by city-states such as Anuradhapura and Powlonaruwa, water allotments were state-managed in a manner not unlike the lake system of the Basin of Mexico or the postulated *bajo* settings of the Maya lowlands. However, insular village tank systems were made possible by the storage of seasonal rainfall in much smaller reservoirs. The manipulation of water away from the large cities was probably very similar to that described today by Leach (1961) and Chambers (1980). Here, villages are not interconnected by canal systems, but retain their autonomy by the singularity of their community tank. The villages rest immediately below the embankment between the tank and irrigated fields, with sluice works first leading into the residential community. The ancient settlement around these tanks is little known, but the adaptation made today is one of small-scale, dispersed compaction in proximity to the tank.

Access to dependable sources of water during periods of extended drought or mismanagement may have made the state hydraulic works, or the subjugation by an empowered elite, more acceptable. Unlike the raised field, lake-leveling adaptations made in Mesoamerica by the state, water was controlled through canals. Canal systems can be operated in an equitable Syrian distribution or a less equitable Yemenite manner. The turbulent history of Ceylon/Sri Lanka would suggest that water was manipulated by the state in Yemenite allotments much of the time (Gunawardana 1971). In the small villages, water may have been more fairly distributed, a situation that continues today. The presence of sizable "temple tanks," sometimes still maintained by the community, suggests the strong effect Buddhism has had on the Sinhalese, both now and in the distant past. Its tenets of equality in association with sometimes sizable temple tanks in small villages suggests an ancient Syrian allocation model. It is unlikely that the state could meddle successfully in most insular village water-management affairs.

### *Lower Indus Valley*

Harappan civilization (2500–1700 B.C.) was tethered to the Indus floodplain. As in other primary states of the Old World—Sumeria, Old Kingdom Egypt, and the Shang dynasty—civilization rose from the banks of a great river flowing through an otherwise arid environment. Today the Lower Indus Valley receives less than 200 mm of precipitation a year (Johnson 1979), even less than the American Southwest. Nevertheless, the Indus carries an abundance of water, as well as a heavy silt load, along a very shallow gradient following a precipitous plunge from the Himalayas. Before the British introduced the most extensive canal irrigation scheme known for any single river drainage, great annual floods blanketed the ancient floodplain. Although salinization and waterlogging of soils have severely altered the productivity of many areas formerly occupied by Harappan cities, pre-Aryan occupation tapped an extremely fertile, annually inundated setting.

The earliest evidence for water management in Pakistan comes west of the Indus in Baluchistan (Raikes 1965, 1984). Massive walls of uncut stone climb as high as 2 m across intermittent streambeds, forming diminutive dams, and along the parallel margins of these drainages, producing agricultural terraces. Called *gabarbands*, these features are associated with pre-Harappan materials but probably have a long, less interrupted use continuing into the present (Wheeler 1968).

Although water manipulation along the Indus may have a long history, it is not until the appearance of Harappan civilization that the complexity of the water system can be fully appreciated. Unlike the preserved remains of canals along the Tigris-Euphrates (R. M. Adams 1981), the single course of the Indus has buried any trace of ancient *gabarbands* or related agricultural water control. Except for the covered and brick-lined drainage channels within the great city of Mohenjo-daro, no evidence exists for extensive canalization (Allchin and Allchin 1982; Scarborough 1988b). Regardless, primitive floodwater farming without the aid of diversion technology would have allowed double-cropping of the fertile alluvium, as is apparent among present-day populations in the state of Sind (Lambrick 1964).

One of the blessings of the seasonally turgid Indus and the nutrient-rich sediment load it deposits is also its bane. At Mohenjo-daro, the water table has risen over 9 m since the initial occupation of the site. Some of this rise is a result of recent irrigation schemes and the saturation of the water table, clearly noticeable in the damage inflicted by salinization everywhere at the site. However, ancient fluvial deposits lie nearly 12 m below the present floodplain and appear to be associated with cultural occupation. Moreover, Wheeler (1968) indicates that a mud-brick embankment or bund over 13 m thick was placed outside at an early period in the citadel's history. Presumably constructed to hold back the floodwaters and their ever-encroaching sediment load, it is now entirely buried and featureless on the vast plain.

It should be noted that some students of ancient hydrology have suggested that catastrophic uplift immediately south of Mohenjo-daro and oscillations in recent worldwide sea level have significantly altered the sedimentation rate along the lower Indus during and since Harappan times (cf. Raikes 1965, 1984). Clearly, such eustatic imbalances would have had a tremendous effect on cities inextricably tied to the riverine resource. Unfortunately, much still remains conjecture about these environmental changes and the way they may have influenced the course of Harappan society (Miller 1985; Possehl 1967).

Harappan cities were nucleated communities. At Mohenjo-daro alone, the population has been estimated at over 40,000 (Fairservis 1975) within an urban area of approximately 2.5 $km^2$ (Wheeler 1968), an adaptation more similar to ancient highland Mexico than to tropical Sri Lanka. Nevertheless, little evidence can be marshaled for the presence of complicated irrigation systems (cf. Leshnik 1973). Hydraulic investments appear to have been made in functional and symbolic urban contexts, not in subsistence strategies. The apparent abundance of water from the Indus suggests a Syrian allocation model, both in the floodwater farming of fields as well as in the manipulation of water in urban settings.

At both Harappa and Mohenjo-daro, sizable public granaries were initially postulated near the summits of the main citadel (Wheeler 1968). Such implied surplus indicates that foodstuffs were controlled in part by the state. More recent interpretations, however, indicate little evidence for granary platforms at any Harappan site (Fentress 1978; Jansen 1979; Shaffer 1982). Direct control of surplus and the water system that allows it cannot be argued. On the other hand, a degree of state meddling in the affairs of the horticulturalist is suggested by the stratified character of the society. Inner-city water use may have been under greater control.

Nevertheless, the same resource abundance, by way of wells and runoff channelizing, probably prevented the "despotic state" suggested by Wittfogel. Unlike some other examples, Harappan water use does not appear to have promoted state control. The Great Bath at Mohenjo-daro and the elaborate reservoir at Lothal represent monuments to the elite responsible for their construction, ostentatious displays of power (see Miller 1985 for a dissenting view). The size and elaborate appearance of these features suggest that significant public architectural investments in water manipulation were necessary in attempting to associate the natural abundance provided by the river with the ability to control an aspect of the otherwise seasonally intractable Indus. The inherent difficulties in canalizing the Indus were not resolved until the 1850s when the British introduced gated barrages that managed the floodwater silt load and permitted the canalization of zones immediately outside the floodplain (Johnson 1979; Taylor 1965).

## Conclusions

Understanding water management in a comparative framework involves a representative range of case studies. Evidence from semitropical Maya and Sinhalese systems suggests that the use of reservoirs to control water sources was of primary importance. In the Indus Valley, the presence of a sediment-laden river precluded the need for intricate agricultural water management systems. Highland Mexico reveals that controlled lake levels rather than traditional canal maintenance stimulated state hydraulic control. The nonstate example from the American Southwest suggests the limits to which the environment will accommodate human use of the water resource.

In the New World the great water management systems were not associated with the great river drainages of the hemisphere. Reservoir storage and canal diversion schemes drew from small perennial drainages and seasonal runoff catchments. Of particular interest have been the resemblances noted between the water systems of highland and lowland Mesoamerica. Although a long history of theoretical disagreement exists, the potential similarities between state-maintained water systems suggested by lake or *bajo* water-level management indicate the utility of addressing a panregional Mesoamerican system. The role of the insular village or town in water control within the larger hierarchical framework also may be analogous between highland and lowland settings in the New World areas treated.

Old World examples appear more varied and in many ways less comparable with New World cases. Large rivers were generally the location for civilization. Canalization was most pronounced along the ancient course of the Tigris-Euphrates and in Classic China. However, the Sinhalese and Harappan case studies of South Asia present very different adaptations. Here an abundance of seasonal precipitation is juxtaposed with the abundance of a great river. The Indus Valley civilization developed highly nucleated settlements along the limited reaches of the river. Sri Lankan settlement was less restricted by the specific course of a river but was dependent on the ingenuity of its architects in locating and constructing reservoirs and dams. Sri Lankan populations appear to have been dispersed-compacted in a manner akin to those of the Maya lowlands.

In the desert American Southwest, the nucleating tendencies associated with the Gila-Salt River irrigation communities may have been influenced by the same sociopolitical vulnerability affecting Harappan cities: frequent exposure to less agriculturally secure neighbors. Unlike the vegetated tropical environments of the Maya or Sinhalese, in which communities could remain hidden and autonomous beneath jungle foliage, desert towns were visible and assailable by anyone drawn toward the fertility of the river.

Water management in complex societies can be seen from different perspectives: the state manager's and the individual consumer's. Most of the preserved remains of water manipulation associated with ancient civilization accent the state manager's view. The visibility of these features emphasizes elite control when compared with less definable water management vestiges recovered from the archaeological record. Although impressive monuments have been erected that incited Wittfogel's notion of hydraulic societies, many smaller-scale and autonomous water systems existed within the state bureaucracy. The tension created by this condition can stabilize or destabilize a society with equal ease.

Most complex societies or states made a significant investment in water management. Clearly, the initial outlay was at the community level. The time and energy channeled into the construction and maintenance of a local reservoir or canal system tethered a community to a territory. The social ties resulting from the investment in a water resource stimulated greater community cooperation or incited conflict, but in either event they aided in defining the meaning of "community." Rather than a commitment to the power of the state, local water control systems submitted in part to a water bureaucracy because of the people's initial investment in place (Gilman 1981). Even in Classic China, seat of many monumental canalization projects, the state was dependent on local landowners to provide sustained water management (Wolf 1982:53).

Cooperation between water users within a larger territory induced complex social, political, and economic relationships, whether produced by internal or external conditions. Water manipulation in the Old and New World significantly influenced the direction of complex social organizational schemes.

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