A Formal Study of Applied Ancient Water Management Techniques In the Present Water Crisis

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A FORMAL STUDY OF APPLIED ANCIENT WATER MANAGEMENT TECHNIQUES IN THE PRESENT WATER CRISIS

by

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An undergraduate thesis submitted in fulfillment of the requirements
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ABSTRACT

Many areas of the world are experiencing the effects of the water crisis. The water crisis is a widespread phenomenon whereby many regions are experiencing a shortage of water, lacking access to clean potable water. This study uses existing literature to examine the ways in which the ecological knowledge of ancient civilizations can be applied to modern water management in attempt to address the current water crisis. The literature reviewed for this study, stemming from notable books and peer reviewed journals, were published between 1882 and the present year. As part of a purposive sample, the following civilizations were chosen: Tenochtitlan (presently Mexico City), Angkor, and Petra. Past and present water management in the three locations are examined, as well as their impact on industry and social systems. Findings within the literature indicate that ancient methods of water management are able to provide water for populations of equal or greater size than their modern counterparts. Similarly, some studies have determined that modern water systems are problematic in their production of waste by-products, and inefficiency in water collection and distribution. The implications determined from the results of this study are discussed, as well as the limitations that arose throughout the review. The study seeks to fill the gap in literature connecting ancient water management techniques to modern practices, helping establish suggestions for reforms to address the current water crisis in the process.
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INTRODUCTION

Living species are metaphorically drowning in pursuit of water. Water management has been a millennia long concern, culminating in the present water crisis. Water management is defined as the societal manipulation of the natural flow and accumulation of water (Scarborough 1991). According to the Food and Agriculture Organization, “by 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world’s population could be living under water stressed conditions” (UN Water 2012). Modern solutions include, but are not limited to, dams, and desalinization plants, and while these are temporarily efficient, they often give rise to additional issues such as desiccation, high expense in maintenance, and toxic outputs. The question underlying this research is what concepts can be taken from ancient water management for application to the present water crisis? Ancient cultures, with an expansive knowledge of the landscape, created successful water management systems that were not dependent on modern technology such as electricity. The study of these ancient systems can provide a foundation for innovative blends of modern and past management practices to address the current water crisis.

Many studies have been conducted on the construction and use of ancient water systems. The scope is broad in both time and location, ranging from Mesoamerica to Sri Lanka and from prehistoric to medieval times. The relevance of these systems to today’s water problems and the potential incorporation of the resulting knowledge in design is underrepresented in academic literature.

The objective of this thesis is to discern what ancient implementations can be extracted and used in a modern context to create long-term sustainability of water as an essential resource,
and durable management systems. To provide a more holistic view of the bridge connecting the past and present, the study will focus on three different realms of water management. They are as follows:

1. Physical water management systems – This section outlines both modern and ancient water systems, as well as comparisons of factors such as durability, efficiency, and cost. This is the main focus of the thesis, and will be covered extensively.

2. Industry – Agriculture, amongst other industries, are major contributors to dwindling water availability. As such, these industries will be discussed in short, covering their role in the crisis, and ways they are addressed in both the past and present.

3. Social systems – Control over water is another major contributor to the water crisis. Politics governing water in the past and present are examined, and the resulting effects on local communities.

Water management is not a subject concerning solely environmental and infrastructural concepts, but rather part of a larger network that involves policy, economy, and cultural systems. The interconnectivity of these systems and their effect on the water industry calls for an analysis under Systems Theory. General Systems Theory, as delineated by Kenneth Boulding (1956), states that there are multiple levels of involvement in any system arranged in a way such that a hierarchy of complexity results. Although used widely in archaeology, systems theory is used cross-disciplinarily and calls for an analysis of interlinked subsystems making it an apt choice for this study.

General Systems Theory stresses the organization, interaction and interrelation of systems in the creation of a hierarchical complexity (Boulding 1956). Stemming from Ludwig
Von Bertalanffy’s work on General Systems theory, Boulding demonstrates that hierarchical complexity, in a system made of various subsystems, indicates a hierarchy will form under which certain subsystems take precedence over others when decisions are made. In the case of water management, the decisions for sustainable practice are occasionally overridden by things like agriculture and its economic importance. As a result, the weight of the varying components (cultural, economic, and political) on water management decisions are rarely in equilibrium, and yet are continuously affecting one another, further perpetuating the complexity of the hierarchy.

Figure 1 articulates the hierarchy of complexity regarding water management. Thus, the inclusion of various systems and their transformation throughout time is critical in gaining a more holistic view on water management. David Clarke takes one step further in arguing for the variability of these systems both spatially and temporally (Plog 1975), meaning that although societies share concepts such as water management they may not do so in the same form. Clarke, as a spatial archaeologist, focused on four theories to explain archaeological variabilities. Ronald Rood elaborates on these four theories. First, the Economic Spatial Theory indicates that humans are rational creatures and will attempt to maximize returns while minimizing costs in every decision.
Distinct environments require different approaches in water management to address the varying costs and benefits. The Social Physics Theory states that large groups tend to act in similar ways (Rood 1982), hence a similarity in larger concepts such as water collection in water management. Anthropological Spatial Theory (AST) declares that behavioral patterns create non-random distributions of archaeological remains that can provide evidence for or against hypotheses (Rood 1982). AST highlights human agency in a quantifiable way, which can be used when deciphering artificial water routes and the potential reasoning behind them. Lastly, Statistical Mechanics Theory aims to explain macroscopic systems such as water management by looking at the properties and measurable qualities of the more microscopic elements (Rood 1982) such as pond layouts. Understanding the basis for Clarke’s approach creates a foundation upon which the examination of water management systems can be made. Information regarding the analyzed water systems, and the tangential systems (government, economy, and culture) are extracted from previous publications on site studies from the three locations.
RESEARCH DESIGN & METHODOLOGY

Mexico City, Angkor and Petra were selected as a purposive sample after inclusion and exclusion criteria were used to narrow down the potential list of sites to be studied. Purposive sampling is “intentionally selecting specific participants due to their traits” (Robergs 2006). Thus, the sites chosen, situated in different countries, and across different time periods (to provide geographic and climactic variability), were selected for their historical status as centers of major civilizations with prominent water management features. The use of major civilizations is essential in understanding the hierarchy of complexity within water management decisions because major civilizations have established cultures, politics, and economies. The inclusion criteria, or the “attributes of subjects that are essential for their selection to participate” (Robergs 2010) included the following: a developed water management system, a large population, and significant changes made to the water management system over time. These criteria are crucial to the study as they provide comparative material of the water systems in the selected area across a span of time. The exclusion criteria, or the attributes “of the subjects which require their removal” (Robergs 2006), were: had similar topographic environments, and had little to no publications regarding the water management practices of the past and present. For this study to be useful different environments had to be analyzed because water management systems are constructed based on the surrounding environment and the variability provided would yield more alternatives in present innovative design. Likewise, due to the large scale of the study the research would not yield firm results without significant publications to review.

Below is a brief description of the geography and topography of each.
**Mexico City**

Tenochtitlan came into being with the beginning of the Aztec empire in 1325 (Hamnett 2006). Tenochtitlan, located in the Valley of Mexico and surrounded by a mountainous range with volcanic craters on all sides, was at an altitude of approximately 2,200 m with a temperate climate (Hamnett 2006). These mountains slope downwards forming a basin that was once covered by many lakes. The volcanic soil allows for the absorption of water into the aquifers, ensuring they stay stocked. Many years after the Spanish Conquest in 1519, Tenochtitlan would be transformed, turning into Mexico City. Mexico City today is considered a mega city, or a metropolitan area home to more than 20 million people (Tortajada 2008). The area presently holds less water than its ancient counterpart due to changes in water management. It is one of the few metropolitan areas in Mexico that does not run directly adjacent to or near a river, thus the lakes were crucial to water as a resource.

**Angkor**

Angkor was the center of the Khmer dynasty (800 -mid 1500 A.D.). The Angkor Basin is located in Siem Reap province within northwest Cambodia, running at an altitude of 2 m above sea level at its lowest to 490 m above sea level at its highest on the peak of the Kulen hills (Kummu 2009). Puok, Siem Reap, and Rolous are three rivers within Angkor which flow into Tonle Sape Lake, at the southern border of Angkor (Gaughan 2006). Tonle Sap Lake is the largest freshwater lake in Southeast Asia (Gaughan 2006). The slope of the land between Kulen hills to the north and Tonle Sap Lake is at an average gradient of 0.1% (Kummu 2009). The amount of rainfall varies geographically across the region, though averaging 1050-1800 mm a year (Gaughan 2006). This precipitation usually occurs during the monsoon season, which can
last upwards of five months, followed by extensive droughts in the dry season the remainder of the year. Many individuals in the present, as in the past, rely on the monsoons to provide enough water for agriculture.

**Petra**

The Nabateans first created Petra around 200 B.C. in the arid southwestern region of Jordan (Urban et al. n/d). Dubbed a desert metropolis, the Nabateans created hydraulic networks to bring in and distribute water at an altitude of nearly 1000 m (Lingis 2002). South of Petra lies the Siq, a fissure resulting from an Earthquake many millennia ago (Lingis 2002). Occasionally flash floods ripple through the Siq from the nearby Wadi Mousa and rip into Petra (Lingis 2006). It is water sources such as these floods that were manipulated by the Nabateans to provide water for their people. These floods still occur but are not being utilized in the same fashion as in the past.

The overall arching question remains what concepts from ancient water management can be incorporated into the present water crisis? There are, however, other questions to be addressed within the overlying question. Questions sought to be answered throughout the project include: What type of water management was used in each ancient city? Why and how was the system changed? How were decisions about ancient water management made? What has been the impact on the surrounding communities? The water management systems of these civilizations were studied in their entirety from construction to transformation and their impact on the living. To provide a thorough understanding, each system is described both in function and significance within the context of the culture where it is found. From there the scope broadens and a
discussion forms around the concept of applicability to the present and the urgency in the study’s significance.
PROPERTIES OF WATER AND OTHER DETERMINANTS

Statistically, the Earth is comprised of 71% water (USGS 2016), and water is cyclic in nature in the sense that it will evaporate and precipitate, never truly disappearing. In that regard, how is it possible that water has become a scarce resource? First, consider that freshwater, necessary for the survival of humans and most agricultural products which feed humans, consists of only a small sliver of that 71%; in fact only 2.5% of the Earth’s water is suitable for humans. Perhaps if that were available in its entirety the magnitude of today’s issue would be different. Only 1.2% of that is truly within reach, excluding ground water (USGS 2016). This means that the actual water content available to humans for use is miniscule in comparison to the total amount of water on Earth.

Water management is no easy feat in the sense that it is comprised of many underlying and humanly uncontrollable factors such as the climate of the region, elevation, and precipitation levels. The ease with which water is managed lies in its physical properties. Water has two crucial properties that assist in the manipulation process: fluidity and gravitational flow (Scarborough 1991). Fluidity is the component that allows for water to move easily, and fill any given container – making transport easier. Gravity flow is the concept whereby water travels from an area with a higher elevation to one with a lower elevation – as gravity pulls the liquid downward. This has proven to be extremely useful in the movement of water (consider canals), but also detrimental in less sloped terrains (Scarborough 1991). As such, for water management engineers, the issue of gravity flow presents itself as a challenge to produce a method of lifting the water, or moving water upwards. Likewise, gravity flow and fluidity permit the pliable nature of the control of water as a resource, or commodity. These constituents give rise to the decisions
that foster the chosen water management system for any given area, and thus directly affect both the industry and social systems.

A water management site is reflective of the surrounding environment. For example, it would be unlikely for a drainage system to be implemented at the top of a hill because water naturally drains downhill due to gravity flow, making the high altitude drain ineffective. Ideally, models that yield the highest amount of potable water with the least amount of costs (consider the term costs representative of things like energy, finances, and evaporation) are the most sought. When designing an effective water management plan, the surrounding environment must be taken into account. Other factors to be considered in this line of thought are soil permeability, and transpiration. To fully gauge an understanding of water management in both the past and the present, the conditions of the environment must be discussed.

The current water crisis can be divided into three separate, more approachable components; namely, water availability, water distribution, and water quality (McDonald et al. 2011). Water availability is the water that is accessible for use. Water distribution is how water that is accessible is dispersed throughout a given region. Water quality is the condition of the water in relation to its usability. It must be noted that without availability there is no distribution or quality at play, placing the matter of availability at the forefront. These components are further affected by factors such as growing populations, climate change and global warming, pollution, availability to other resources, all indirectly linked to politics, and economics. Industry, and social systems have accrued a large responsibility in the expanse of the present water crisis (Nelson et al. 2015), and will be discussed within each component.
WATER AVAILABILITY

Groundwater is a resource that takes substantial time to regenerate, collected from water that seeps deep into the ground when it is not used by plants and other wildlife. Due to the necessity of time, any considerable usage of groundwater depletes its capacity as a reusable resource. In Mexico City, the groundwater levels are subsiding by an average of about 40 cm a year for reasons of overuse (Carrera Hernandez and Gaskin 2007). This is water that is being removed faster than it is being replenished by natural processes, in part because the priority has been placed on supply rather than sustainable management (Sosa-Rodriguez 2010).

One form of addressing availability, without tapping into the groundwater resource, is storage. The Netzahualcoyotl dyke in Aztec Tenochtitlan was built shortly after 1449 to aid in the collection of clean water, apart from the salty run-off in its counterpart, the Lake of Mexico (Sosa Rodriguez 2010). This dyke, created during the reign of Moctezuma Ilhuicamina, was engineered by his nephew Netzahualcoyotl, King of Texcoco (De Garay 1882). The dyke, built with a combination of rubble-stone and masonry, traversed 8 miles, splitting a large lake in half (De Garay 1882). The west half, the Lake of Mexico, would collect water from the nearby southern lakes of Chalco and Xochimilco, thereby forming a current through the sluicegate of the dyke and into the eastern half, Lake Texcoco (De Garay 1882). This current in the western half kept the water fresh while pushing salts and other minerals into Lake Texcoco, as well as preventing local inundation. Figure 2-(left) displays the appearance of Mexico City prior to the lake drainage employed by the Spaniards.
The Aztecs kept Tenochtitlan on elevated ground, farmed with chinampas, and used the water as an ally against the enemy (Sosa-Rodriguez 2010). Chinampas are flooded fields used for agriculture. The fields were able to provide food for a large population. Tenochtitlan was estimated to have held at least 200,000 people (Cartwright 2014). It has been suggested, by Alejandro Tortolero, that policies with severe punishment were implemented to discourage waste disposal into the lakes (Sosa-Rodriguez 2010). The development of Tenochtitlan as an urban center for the Aztec is a display of their understanding of the surrounding environment. Unfortunately, the dyke was abandoned after the Spanish Conquest and it fell to ruins. The Spanish increased deforestation on the slopes to heighten visibility along the mountainside and used the resulting cedar-wood for construction (De Garay 1882). The removal of this vegetation
led to erosion from rain that carried sediment and soil down to the lakes – adding to the salinity and raising the floor of the lakes as the sediment settled (De Garay 1882). As such, the lakes expanded outward due to the decreased depth, making the new villages more susceptible to flooding. In reaction, the Spaniards built many additional dykes that aided in controlling the water but created stagnant pools of non-potable water with an extremely high salinity. Thus began the trials that Mexico City would face as a result of altering a functional water management system.

Although the dykes aided in controlling the water, the Spaniards continued to fear inundation. The only logical solution to finally rid themselves of this menace seemed clear: they needed to drain the lakes. Enrico Martinez, a practitioner of cosmography, came ready for the job with plans in hand to drain all the lakes (De Garay 1882). The junta, or congress, rejected his ambition and gave him the smaller task of draining Lake Zumpango (De Garay 1882). A dyke had previously blocked off Lake Zumpango from the lower lakes of Xaltocan and San Cristobal, turning them into salty marshes that dried out the surrounding soil. In 1608, after just 11 months of work, a 6 mile long tunnel opened to begin the drainage of Lake Zumpango (De Garay 1882). Shortly thereafter, Martinez was imprisoned when a flood blocked the tunnel, filled the lakes, surpassed the dykes and carried into the city. The city would remain flooded for four years, until an earthquake caused the water to subside (De Garay 1882). The tunnel was disregarded for a new project that involved cutting into the landscape, creating the Tajo (cut) of Nochistongo (Ober 1884). While the canal drained Zumpango, it also stopped any overflow feeding into Lake Texcoco, which, in addition to evaporation, has led to the shrinkage of the lake (Ober 1884). One
after another, projects, including the Grand Canal, fostered hope of a solution to the flooding dilemma.

With flooding at the forefront of the focus for Mexico City’s water management, past engineers hardly imagined their actions would leave them with the contrary – not enough water. Figure 2-(right) shows the extent of the drainage over time. The city cannot provide sufficient drinking water for its 20 million plus inhabitants. Mexico City is in dire need of an innovative solution. The continued pull from the groundwater of the aquifers means Mexico City has begun to sink from the subsidence of the dry contracting soil (Zambrano et al 2017). The volcanic soil contraction in turn contributes to more flooding in the sunken areas. The subsidence affects the current infrastructure – as the Grand Canal is only able to function at a 30% capacity rate (Kimmelman 2017). In 2007, a pump was built in Ecatepec along the canal just to lift the water for the canal to function as intended (Kimmelman 2017). Areas that are largely affected by this include the metropolitan center of Mexico City, where architecture and infrastructures such as roadways are susceptible to dangers like cracking, occasionally leaving civilians in peril as they are swallowed by the Earth (Kimmelman 2017). Urban sprawl, in part, is to blame. The city, once 30 square miles, has grown to approximately 3,000 square miles within a span of 60 years (Kimmelman 2017). This has created extreme pressures on the environment with an increase in carbon emissions, waste by-products, and an overall decrease in the soil available for infiltration. When water cannot infiltrate the soil, the aquifers cannot be replenished, and the water has no means of an exit, adding to the potential of flooding. Figure 3 provides an example of the relation between infiltration and flooding, showing areas with the lowest water infiltration rate are also the areas with the highest flood risk.
Figure 3 Mexico City Infiltration & Flooding Model (Zambrano et al 2017)

“Current potential infiltration of Mexico City (A) and potential infiltration scenario with change in land use and climate change (B). Current flood risk areas (C) and flood risk scenario with change in land use and climate change (D).” (Zambrano et al 2017)

The Spaniards’ lack of understanding in conjunction with the construction of a series of tunnels led to the “sinking of Mexico City”, as well as exposure to water-born illnesses, and low
water quality (Sosa-Rodriguez 2010). The difference between then and now is that due to the drainage, Mexico City must now import a resource that was once abundant to them with usage of ancient water management techniques. In addition to importation, the fluctuation between droughts and floods has lowered the soil fertility, inadvertently affecting agricultural production (Sosa-Rodriguez 2010). The resulting effect on agriculture presents the dependency of this industry on successful water management. The vulnerability of the agricultural industry demonstrates how changing water management systems without consideration of the consequences for water availability, and distribution subsequently affect other sectors such as the economy, and community health (through food security).

In all that has been done, no efforts have succeeded in stopping the flooding. What has been achieved is the wipe-out of the region’s water resources. Taking that into consideration, one must ask what can be done? In the case of Mexico City it is unclear as their local resources have been exhausted perhaps to the point leading to future abandonment. However, Mexico City should serve as a model to other places experiencing metropolitan growth and infrastructural changes to the environment. The environment, as the Aztecs displayed with the Netzahualcoyotl dyke and the chinampas, should be used to one’s advantage. The importance of learning the function of the environment and then maintaining the devices implemented is stressed historically in this region. Unlike the Aztecs, modern Mexico City has no method of massive water collection or water recycling and must thus import around 40% of its water (Kimmelman 2017). Of this percentage, 40% is lost in leakages and people who do not pay for it (Kimmelman 2017). Understanding the state of Mexico City’s condition should equate with investment to mediate the current water crisis within the area – however, funding is going into projects such as
the new local airport (Zambrano et al 2017), done to substantiate the urban growth and the movement to and from the city. In looking at the appropriation of local funds, one can discern that the level of immediacy in handling the water crisis is not shared amongst everyone. The current government is aware that it is no longer capable of providing enough water to feed the high demand (De Alba 2017). Chalco, a town within Mexico City, has faced 10 waste-water floods within the past eleven years (De Alba 2017). Some of the floods were due to negligence in maintenance of the nearby canal (De Alba 2017). The government response has been to declare the problem as irremediable or to excuse human error (De Alba 2017). The Mexican government has given up trying to find a solution. Adding to the urban sprawl through the incorporation of a new airport will only deepen the problem.

Since the arrival of the Spaniards, the focus of Mexico City has been solely linked to controlling supply. The supply-oriented approach has created a flawed system where, per a 2014 report by the government of Mexico City, “only 71% of water provision in Mexico City was of acceptable quality” (De Alba 2017). While 71% may seem like a sufficient amount to reach a great deal of people, the percentage is further diminished by politics. The government informally, as in organized by the state though not publicly recognized as such, created the system of tandeos and pipeo to service the poor (De Alba 2017). Tandeos are suspension of water services for an extended period. Pipeo is a system in which pipas, or trucks provided by an intermediary rather than the state, transport and sell water to areas that are extremely marginalized or physically inaccessible (De Alba 2017). More often than not, this is a form of political and economic manipulation. Throughout election campaigns, candidates may back the pipas to enter a particular area thus painting a picture of a savior, or provider of water and
encouraging votes. In some areas, the residents must demonstrate their voter ID to receive water (Kimmelman 2017). There was a 73% difference in voter participation between areas without water and intermediary help than those without water access but with pipas in the 2009 election (De Alba 2017). The pipas come with their own set of hassles – they arrive when they arrive which could be at twilight, a few days, or weeks and if one is not home when the pipa pulls up they can go even longer without water (Kimmelman 2017). The pipa also doesn’t always carry enough water and may run out, making the towns susceptible to violence, and the pipas susceptible to bribery (Kimmelman 2017). It is estimated that the people within these areas spend anywhere from 6-25% of their daily salary on water, thereby perpetuating their poverty as a means of survival (Garcia 2012). The affluent do not face these trials for water. This discrepancy amongst the different classes and their access to water demonstrates how water is intertwined with politics, and the economy.

The tandeo, pipeo, pumping stations along the canal – are all temporary fixes to an ongoing issue. Not only do they contribute to the problem at hand, but they give rise to other issues. For example, continued extraction from the aquifers without another means of water collection has led to the literal sinking of Mexico City which in turn will lead to the physical collapse of the urban sector. It cannot be said that the Aztec water management system was perfect. They relied on water transference to feed the Netzahualcoyotl dyke thereby straining distant water sources to suit their needs (Sosa-Rodriguez 2010). Whenever this dyke or a related part had to be repaired, the Aztec would face water shortages. However, The Aztecs understood that there must be a balance. While they pulled from a distance source, they also retained the lakes so that water would seep back into the aquifers. Although they faced shortages, it was done
in the name of providing continued access to clean water. Policies were implemented to keep the water unpolluted and they were respected.

Instead of implementing temporary solutions such as the pipeo, which can be manipulated for social gain, Mexico City should be focused on finding a solution. This would entail incredible amounts of reform – beginning with the prioritization of water management. Additionally, an arrangement must be developed to organize what should be addressed first within the water management system. The most prominent issue is the sinking of Mexico City which stems from the overuse of aquifers. If this cannot be further prevented, then any infrastructure built to address water management is liable to face destruction or loss of efficiency as with the Grand Canal. The next issue is water collection or processing. The aquifers are continuously tapped because Mexico City does not have a method to massively collect rainwater or process waste water. These are useful resources that are essentially wasted. The Aztecs modified the lakes rather than draining them because water meant survival, and as long as the water was present they would find a way to manage it and maintain it within safe proximity for use. The Spaniards drained the lakes without implementing a reciprocal method of collection, setting themselves up for water shortages. Lastly, but perhaps most crucial, the importance of maintenance of the water management systems must be stressed and retained in the forefront of all the decisions concerning budget. Many dykes, and canals have fallen into ill repair over the history of Mexico City, calling for the creation of new infrastructure. This proves to be costlier both financially and socially (many deaths are consequence of flooding due to the lack of maintenance of infrastructure) than a repair would have been. The Aztec system of water management was simple but effective in its use of the environment. Study of the Aztec water
management reveals the necessity to revert to methods of massive water collection, and understand and foster a balance between the environment and development to aid with things like infiltration rates. Modernity has offered many advances in the way of water management. It is the blend of the advances with the understanding of the natural environment that leads to successful water management.
WATER DISTRIBUTION

Mexico City is not the only place facing the intensity of the water crisis while sitting atop ruins of a highly successful water managing society. People of Angkor in Cambodia, specifically within the Tonle Sap Lake area, are in dire need of fresh water (Mithen 2010). From the 9th to the 15th c. Angkor served as the capital to the Khmer empire in Cambodia (Kummu 2009). Ninth and tenth century Angkor is known as the largest pre-industrial city with an estimated population of over one million (Mithen 2010). Considering the entire country of Cambodia is relatively the size of Oklahoma, this massive population estimate is quite astonishing (Irvine et al. 2000).

Dubbed the “Hydraulic City”, they constructed massive channels and embankment networks to address the monsoon rains, and irrigation needs (Mithen 2010). The nature of a monsoon season means that they also experienced extended droughts, through which they relied on the water of 3 rivers: Roluos, Siem Reap, and Puok (Kummu 2009).

Droughts created a necessity for the collection and long term storage of water while monsoons spurred floods and fostered a need for a controlled dispersal system. A great example of their feats in Angkor is the 11th century West Baray measuring about 8 km in length, 2 km in width, and the ability to withhold 50 million liters of water (Mithen 2010). A baray is akin to a reservoir (Day et al. 2012). Claims have been made that the West Baray may have been built as the East Baray had begun to be silted (Goodman 2000), represented by the numbers 4 and 5,
respectively, in Figure 4. These claims have yet to be proven but are interesting to note in understanding possible motivations for such large constructions. The West Baray is still in use today (Feneley et al 2016), though the others have been deemed unusable, possibly due to siltation or the suspension of fine mineral particles clouding water (Goodman 2000).

Angkor is most famously known for its temples and religious monuments like those found in Angkor Wat. Historically, Angkor has very few written records of the city throughout its existence apart from about 1200 inscriptions and one written account from a Chinese visitor named Chou Tan Kuan (Goodman 2000). Kuan’s recounting of the city leaves the impression of a massive water system utilized for the irrigation of 3-4 different rice crops per year (Goodman
Estimates indicate that this level of production would have been enough to sustain the population of over one million people with a potential irrigation scope of 19,000 ha or 190,000,000 square meters (Goodman 2000). Despite the built-in capacity for irrigation, Kuan notes that the agriculturalists would time their harvest with the flood of Tonle Sap Lake during the monsoon season to ensure proper hydration of their fields (Goodman 2000). These accounts, and the proximity of many of these monuments to water sources indicate the importance of water to Angkor and the extent to which they sought to ensure the reach of the resource.

“Water management in Angkor was based mainly on four sources of water: (1) natural rivers, (2) groundwater, (3) precipitation, and (4) Tonle Sap Lake.” (Kummu 2009). Figure 4 illustrates these features along the landscape. It appears Angkor implemented a three-tier system, beginning in the collection phase within the northern zone (consisting of the land and rivers north of the barays), making its way down to the central zone (comprised of the area around the barays) where it was fed into moats and reservoirs before getting further distributed for drinking and irrigation purposes (Mithen 2010). The channels within the north zone were constructed with numerous right angles for the water to hit as it travelled southward to the central zone. The right angles served to slow the speed of the water and decrease the possibility of erosion (Fletcher et al. 2007). The southern zone (the land south of the barays up to the floodplains) functioned for swift disposal of water through channels and embankments that were crucial during monsoon season (Kummu 2009). Analyzing how Angkor, once deemed the “hydraulic city”, becomes a place experiencing water shortages calls for a closer look at the differences between past and present water management practices and what can be utilized from each to aid in the current water crisis the locals are facing.
The Angkor plain contains notably high quantities of clay that was used to construct many of the channels and embankments used in ancient Angkor (Fletcher et al. 2007). These features were created to slow the water, redirect and in some cases, disperse it for collection or use in other areas (Fletcher et al. 2007). The channels were created with dual function as the raised edges of the banks allowed for usage as elevated roadways (Fletcher et al 2007). This creative design for multiple functionalities is a characteristic that remains to be admired. This combination means that the water management and transportation systems are complementary aspects and the maintenance of one would require the maintenance of the other.

The water distribution system in Angkor was delicate in that many parts of the system and their maintenance were crucial to its function due to the systematic usage of the small gradient of the land (Fletcher et al. 2007). On a small island within the West Baray, a statue of the god Visnu termed the West Mebon was found (Feneley 2016). Visnu is a Hindu god that is most commonly depicted with water (Feneley et al. 2016). Microscopic pollen from a lotus plant of the 11th century was found near the statue (Feneley et al. 2016). The presence of the lotus indicates that there would have been deep clear water available for the plant to grow in and speaks volumes for the clarity of the water at the time (Feneley et al. 2016). Control of water in Angkor was seen as a display of power and an appeasement to the gods (Feneley et al. 2016). Excavations reveal that certain channels may have been cut off for land usage for things such as the Ta Prohm temple which was built in the twelfth century (Fletcher et al. 2007). This not only opens the discussion up to the incorporation of religion and its points of intersection with water management but also highlights that the water system underwent plenty of changes throughout
history. These changes, in addition to the fragility of the system, may be considered a reason for the overall collapse.

Presently, apart from continued use of the West Baray, Angkor also taps into groundwater as a source for clean water. The aquifer under Angkor is considered fairly accessible as it sits anywhere from 0 m to 5 m under the ground surface (Kummu 2009). The people of the Khmer empire were aware of this and is noted in the distribution of the responsibility in the ancient water management. It can be argued that there were three levels of operation for water management in ancient Angkor: the household level, the village level, and the city level as seen in Figure 5 (Kummu 2009). The houses in ancient Angkor were built on mounds to avoid floods and created small depressions in which water could be collected either from the monsoon rains or the water table if dug deep enough (Kummu 2009). Although this is an individual use of water it is within
sustainable amounts and provides a method of water absorption back into the ground. At the village level, again connected with religion, water was associated with temples which were mostly built with surrounding moats and an associated trapeang or large pond (Kummu 2009). These moats and trapeang were used to collect groundwater or rainwater as well. The moats also served as spiritual and physical defense mechanisms for the temples (Moore 1989). The city level is where the barays and the other features such as the channels were incorporated. It is important to note that the distribution in collection led to widespread availability which cut back on the need for increased dispersal, therefore the focus on dispersal was a result of an awareness of the heightened danger of the monsoon rains.

The Angkor water management system is not flawless. “Hydrological alterations have been broadly defined as changes in the magnitude, frequency, duration, and predictability of river flows caused by human activities” (Dang et al. 2016). The natural course for dispersal was originally the Puok River and the Roluos River (Day et al. 2012). To increase the capacity of collection and dispersal, the Khmer split the Puok watershed in half, creating the Siem Reap River (Day et al. 2012). Thus, the Siem Reap River was made from a few off-take channels that aided in the dispersal of water (Kummu 2009). Figure 4 represents the rivers after this change was made but can still be utilized to imagine the magnitude of the alteration that took place. This, like all other hydrological alterations, has some negative consequences. The artificial off-take channels were constructed without the sinuous nature of rivers leading to increased erosion of the banks. Rerouting part of a river may also hurt vegetation along the original river due to decreased water levels, lowering the animal biodiversity by changing the nutrient flow and affecting migration patterns (Dang 2016). The Tonle Sap Lake, in conjunction with the Mekong
River, provide approximately 72% of the protein consumed by Cambodia (Dang et al. 2016). Seventy-four dams have been constructed since 1960 and another 135 are estimated to be constructed within the next ten years (Dang et al. 2016). Such a drastic level of hydrological alterations could have a heavy impact on the food supply and overall environmental health of this area in Cambodia.

The people of ancient Angkor relied heavily on the Tonle Sap Lake for food and transportation (Kummu 2009). Similarly, modern Cambodians rely on the lake for fish, with over a million people depending on Tonle Sap Lake for either food or irrigation purposes (Kummu 2009). Another way in which the modern population is like the ancient Khmer is in the use of groundwater. The difference in the modern use of the groundwater is that it is used abundantly without the replenishment. The tourism industry, which feeds off the history of Angkor primarily with places such as Angkor Wat, a famous temple, is the main abuser of groundwater (Doherty 2010). In 2007, Siem Reap saw more than 2 million visitors (Doherty 2010). With over 6,000 private pumps and additional wells, it is no surprise that some businesses are extracting at least 1 megaliter, or 264,172 gallons of water a day (Doherty 2010). This is individual use on a massive scale. Although the people of ancient Angkor practiced individual water extraction they did so at a much smaller scale with additional water to rely from the different levels of collection as represented in Figure 5. Modern Angkor does not have these additional levels of water collection to fall back on. In an area that suffers droughts, this is an entirely unsustainable practice.

Deforestation has increased because of the tourism industry as well. The wood is used as charcoal to fuel the tourism industry and the land is often converted to agricultural lands (Gaughan et al 2009). Generally, deforestation heightens evaporation rates by lowering ground
cover percentages. The conversion to agricultural lands creates an increase in the necessity of water to hydrate the land. The Cambodian government is concerned that this increased deforestation and the continuous groundwater extraction will lead to reduced availability of water (Gaughan et al. 2009). They have reached out to Japan in attempt to engineer a plan that can address the need for the amount of water the tourism industry demands while still supplying enough to keep the ancient temples from cracking or sinking into the ground (Doherty 2010). This proves to be a delicate situation because if the temples were to fall to ruin, so would the tourism industry which relies on them. In the scenario where history and the modern industry both fail, a disaster prevails where the past, the present and the future are doomed because of water.

There is eager investment in water infrastructure within the Mekong River Basin, where the Tonle Sap Lake resides (Arias et al. 2012). Access to electricity, particularly for the poor in Cambodia is low, with the country rating one of the lowest in rural electricity provision (Dang et al. 2016). The hydropower dam systems provide a means of generating electricity while aiding in the collection of water. While this may seem like a positive outcome, it does not go without ulterior motives outside of water conservation. The hydropower projects are expected to triple within the next several decades (Arias et al. 2012). The increase in the incorporation of hydropower is common in developing nations for the provision of electricity (Siciliano 2014). Currently, irrigation is the largest water consumer within the Mekong River Basin and it is projected, provided current development trends continue, that the overall irrigation area will grow 65% by the year 2060 (Arias et al. 2012). The increase in development could heighten urban sprawl, which would diminish the levels of water replenishment while pushing for an
expanded electrical grid. The location of the dam can cause the necessity for resettlement, meaning that residents are removed from the land to settle elsewhere (Dang et al. 2016). In addition, once built the dams may create other issues such as a dip in water quality due to natural ramifications like an increase in salt intrusion (Dang et al. 2016).

Present day Cambodia faces a high mortality rate, partially due to waterborne diseases (Irvine et al. 2006). Currently, the country faces difficulties in monitoring both water quality and quantity on a regular basis due to obstacles such as inundated roadways, and broken equipment that cannot be readily repaired as quickly as it might be in a western country (Irvine et al. 2006). Inundation of roadways would decrease if the ancient dual-purpose design was implemented back into the landscape. By reverting to elevated roadways there is a simultaneous effort in revitalizing the expansive water collection that once existed in Angkor. Switching the focus back to controlled water dispersal and retention alleviates some of the pressures on groundwater usage.

Agriculture is the dominant economic sector in Cambodia, providing employment for about 80% of the workforce and bringing in 28% of the GDP in 2001 (Irvine et al. 2006). With agriculture representing such a large sector of the Cambodian economy, water management should be at the forefront of economic and political decisions. As a developing nation, Cambodia is experiencing a growth in urbanization as demonstrated by the increase in hydropower dams. If urbanization growth is not monitored, whether by the government or the business sector through people such as civil engineers, the water scarcity throughout Angkor and beyond will continue to grow. The growth of water scarcity can readily impact the nation’s agricultural sector, thereby affecting individual workers financially and physically in health, as well as the nation’s GDP.
With such a large dependency on agriculture as a means of subsistence, water is crucial to the livelihood of many individuals in Cambodia, and yet the proper measures are not being taken to ensure their safety and well-being. Their human right to clean water is a call for action. Like the multi-level water collection system in ancient Angkor, there must be an understanding of the multi-level responsibility in water management restriction and care. Change cannot happen at the government level alone. Change must also occur across business and individual practices to mitigate the issue of water scarcity. Restrictions and limitations on water usage should be placed and enforced at the individual and business level to aid in controlling the over usage and waste of water. Encouragement to cooperate can be ignited with the incorporation of public engagement through school programs and the use of media, including signage in places where electricity is not yet available. Educating the public of the severity of the water problem is the first step in creating a water conscious population. Widespread knowledge will change the attitude towards monsoon rains and emphasize the importance of harnessing the resulting water as did the people of Khmer. Ideas that should be inherited from ancient Angkor include creating a sense of widespread awareness and responsibility through multi-level collection, considering multi-tier systems meant to target distribution and awareness, and the encouragement of dual-purpose design in water management infrastructure.
WATER QUALITY

Petra, within the Jordan Valleys of the Middle East, was and continues to be presented with a unique water problem. The Nabateans, a once nomadic tribe, occupied Petra from 300 BCE to 300 CE (Ortloff 2014). Towards the beginning of the second century, Petra came under Roman rule, and was later abandoned for unknown reasons (Al-Farajat and Salameh 2010). The ancient Nabateans, though gurus for the understanding of producing water availability and distribution, also worked to ensure quality. Formed as a desert metropolis, Petra has always had low water availability with small seasonal rains (Ortloff 2014). Interestingly, though sparse, these rains have been liable to cause major floods (Ortloff 2014). In the early 1960’s, a flashflood within the Siq, which is a long narrow gorge walled by high cliffs leading into the city of Petra, killed a series of tourists (Akasheh 2002). The loss highlights the dangers of the brief downpours that have and still occur in the Jordan Valley. Ironically, the Government of Jordan’s response was to open an ancient tunnel of Petra to remedy the situation. These actions speak volumes about the durability of the ancient water system and its effectiveness. Nabateans used a variety of water management techniques such as wadis, dams, and even constructed features such as the Wadi Mataha Pipeline which is similar in design to those developed by contemporary western technology (Ortloff 2014). Figure 6 displays a map of the landscape of Petra, including features such as the Siq. Petra is a host to modern tourism as it is displayed in the Petra Archaeological Park (Pringle n.d.). However, the ancient city has been left undeveloped in modernity (Pringle n.d.). As such, this case study will examine the hydraulic system that was implemented in ancient Petra, its condition in the present, and modern water problems plaguing other areas in Jordan to see how the Nabatean system can influence other situations.
The Nabateans could reside in a dry environment for an extended period because of their ability to manipulate water with their ecological knowledge. In their understanding of fluid dynamics they were able to provide the local population of approximately 30,000 with a year round supply of water and a surplus to aid travelers as Petra became a trade hub in the first and second century CE (Pringle n.d.). Charles Ortloff conducted a plethora of research on Nabatean water management and concluded many of the following findings. They used terracotta pipelines constructed with sockets sealed by cement to carry water from nearby or far-off springs. The pipes would take the water from reservoir to reservoir, moving from high areas downward until ultimately reaching a fountain or holding basin usually created by dams. From there the water may continue to drainage, or be further dispersed to cisterns used by artisans, or other water basins used for storage for the dry season. The springs from which the pipes transported their water extended beyond the likes of Ain Ammon and Ain
Debdbeh. Wadi Mataha traverses the mountainside with a trough running 3.5 km (Orloff 2014). The construction of the trough was purposefully done with a 2 degree slope that has been proven through mathematical models using computational fluid dynamics to limit the possibility of pipe leakage (Orloff 2014). The thorough construction of this Wadi Mataha pipeline demonstrates the awareness of potential problems and an engineering plan meant to combat those for prolonged usage and durability.

The Nabateans demonstrated an impeccable ability to consistently provide water in an arid land. The hydraulic system they created functioned on the basis of providing water availability through extensive distribution. While this is true, all their efforts would have been futile had they not accounted for water quality and methods of its maintenance. The Nabateans selected their water sources carefully. “The natural water quality of the sources, even after recent urban and agricultural development, is still suitable for drinking purposes and there are no signs in these waters, which may cause chronic acute poisoning” (Al-Farajat & Salamah 2010). The fact that the water sources used by the ancient Nabateans are still potable to this day highlights the resilience of the water sources to maintain high water quality.

Other methods would have been utilized in conjunction with the natural quality to assure its drinking standard. Diodorus Siculus, who authored The Bibliotheca Historica, wrote of the Nabatean hydraulic system (Al-Farajat & Salameh 2010). Siculus mentions how the Nabateans would dig underground reservoirs that they would line with stucco prior to being filled with rainwater and closing off (Al-Farajat & Salameh 2010). Only a marker known to those from within the community would be left denoting the area with the small water cache (Al-Farajat & Salameh 2010). This process ensured that they had high quality water collected for periods of
drought by eliminating the potential for pollution or evaporation (Bedal 2002). This is further verified by archaeological evidence in the form of hydraulic features (Al-Farajat & Salameh 2010).

Additionally, two types of channels, open or closed were constructed in Petra to assist with the transportation of drinking water from the springs to the citizens (Al-Farajat & Salameh 2010). Closed pipes were typically made with ceramic and held within rock channels or inlaid in the rock and used to transport water to homes for drinking purposes (Al-Farajat & Salameh 2010). The enclosure of the pipe prevented any outside interference with the water quality. Open pipes might have been easily susceptible to pollutants such as insects, debris, algae, or waste (Bedal 2002). The open channels were used primarily for transport of water to agricultural areas. Even these hydraulic features accounted for quality, incorporating strainers throughout the descent from the spring (Al-Farajat & Salameh 2010). Leigh-ann Bedal studied water consumption in ancient Petra and interpreted the following information. Open pools, full of stagnant water, were rare due to the possibility of evaporation and other pollutants to submerge. Though used for more decorative purposes rather than storage for drinking water, the open pools did exist and were demonstrative of the surplus of water that was evident at the time. Some open-air pools were also placed on the outskirts of the city to provide water for the cattle of passing caravans. Pool complexes, remnants of large gardens, and waterfall features were discovered archaeologically within Petra and serve as evidence of the believed surplus that existed. The use of this surplus through these forms would convey a sense of grandeur and power to all of those who visited or heard of the hydraulic city in the desert (Bedal 2002).
Many of the springs have a rather quick recharge since there is little soil coverage across Petra (Al-Farajat & Salameh 2010). Therefore, when the rainfall hits, the groundwater can be replenished rather quickly. The soil along with the rock components create a self-purification process for the water to undergo (Al-Farajat & Salameh 2010). The use of the land as a tool for purification combined with the careful construction of hydraulic features ensured the Nabateans had access to clean water. Their success is a representation of their ecological knowledge and their direct utilization of that knowledge to create optimal results in a less than optimal environment.

To fully capture the impressive feats of the Nabateans, the nearby present area of Jordan must be examined in terms of their water management. Before modern day Jordan can focus on quality or distribution, the nation must focus on supply. Climate change has lowered the amount of rainfall that Jordan receives (Alqadi & Kumar 2013). Jordan is one of the highest-ranking countries in water scarcity globally (Zietlow et al. 2016) and has launched a conservation and water literacy program as a result. The program is meant to inform Jordanians of the severity of the issue, what can be done individually to assist with the situation and different technologies that can help; all presented through a cartoon character named Abu Tawfir (Zietlow et al 2016), shown in Figure 7. It is essential to inform and increase public awareness as much as possible if water illiteracy is going to be combatted. Jordan uses a high amount of fossil fuel, with more than 80% of their energy coming from oil (Perkovich et al. 2015). It
is estimated that by the year 2030, Jordan’s population will double (Perkovich et al. 2015). A tremendous strain on Jordan’s water and energy resources already exists with the current population. If changes are not implemented the future of Jordan will be dim. The next portion of the case study will provide similar information to what Abu Tawfir might have presented to familiarize the reader with the water situation in Jordan.

Jordan has shifted focus from internal provision and resources to external resources through use of foreign diplomacy. The rivers that feed Jordan’s water supply pass through Syria first, therefore any upstream actions directly affect Jordan (Alqadi & Kumar 2013). The aquifer that Jordan uses is shared with Israel and Palestine meaning that if the latter two states overdraw from the aquifer, areas in Jordan may run dry (Alqadi & Kumar 2013). Although resource sharing can be good for nations such as Jordan, which are overwhelmingly dry, to secure water access, it also has shared consequences. Climate change is expected to reduce river flow capacity by 23% within the present century. Considering that the neighboring countries are experiencing their own struggle with the water crisis, they will most likely use their resources, the rivers and aquifers respectively, to combat the resulting changes. Politicians feel as though internal resources have been exhausted (Alqadi & Kumar 2013) but it must be said that expanding the scope of Jordan’s water crisis is not the answer. Once water becomes overly scarce in neighboring regions as well, Jordan will be cut from the priority list. Jordanians need internal reform both in their infrastructure and their industry reliance on water. Jordan will be left navigating through the desert in search of water if the proper measures are not taken to ensure water security from within the borders.
In nearby Amman, though 98% of households are linked to the supply network for water, they have only been receiving water once a week due to intensive rationing implemented since 1987 (Darmame & Potter 2011). Many might think that this ration stems from the scarcity itself, however it has been proven to be associated with mismanagement associated with “unaccounted water” (Darmame & Potter 2011). Water that is lost to structural problems such as leakages is incorporated into the allotted amount available to the public, as well as illegal connections to the water network, unpaid bills, and the inaccurately read meters (Darmame & Potter 2011). The inclusion of these 4 factors into the water budget means that the public is getting less water than is truly supposed to be available to them. In 1999, a study was done which observed that the rate of unaccounted water was 54% and of that 30% was due to leakage (Darmame & Potter 2011). By 2010, the amount of water lost to leakages in pipes grew to 57% in some areas such as the Zarqa Governate (MCC 2010). In 2004, it was determined that Jordan had a supply of 817 cubic meters to provide, but a demand well over the supply at 1,297 cubic meters (Darmame & Potter 2011). Also in 2004, it was demonstrated that 64% of the available water supply was going into agriculture. These statistics indicate that Jordan does not have enough supply to start, is not maintaining infrastructure to remedy the losses, and is over-allocating a scarce resource to a single sector.

In Amman, these factors are further heightened by the fact that the city did not undergo a planned water management construction process (Darmame & Potter 2011). No reservoirs for water collection were placed uphill to aid in the dispersal through use of gravity flow and must thus have been pumped up hill, expending more energy (Darmame & Potter 2011). The water was originally pushed through metal pipes which were liable to rust and break in a short time
span and any water that was stored by residents was primarily on rooftops, exposed to elements such as evaporation (Darmame & Potter 2011). By 2008, a large project had been put into effect to change the pipe system to a more durable material called polythene, and construct more uphill reservoirs – two of the fifteen contracts have yet to be completed (Darmame & Potter 2016).

Despite these improvements, within Amman there are socio-economic differences that also affect the quality and availability of water (Darmame & Potter 2011). The inequality is presented through the presence or lack thereof of material items such as filters or underground cisterns, and behaviors such as meter sharing (Darmame & Potter 2011).

A few other investments are taking place. The Water Network Project, a multimillion dollar project ($102.57 million), is repairing secondary, and tertiary pipelines, reservoirs, and pumping stations (MCC 2010). This sum includes funds to regenerate the sewage systems, and storage systems within poorer communities as well. Another large project is the Wastewater Network Reinforcement and Expansion Project to expand sewer pipelines and improve those in place to harness the wastewater better than was previously being done (MCC 2010). The latter project was done in effort to aid the As-Samra Wastewater Treatment Plant Expansion Project. The current plant was at risk of being overloaded, thereby running the chance of impacting the agricultural sector which thrives off irrigation from processed wastewater (MCC 2010). This project will expand the plant so that a larger quantity of water can be processed. Unfortunately, these new plans estimate that the plant will only be effective until 2025 before being forced to face another expansion due to increased demand (MCC 2010).

Amman has the potential to learn a substantial amount regarding water management by looking to ancient Petra. The initial construction of the metal pipes for water transport in Amman
is baffling considering the well-known effects of water on metal objects. Water corrodes metal which, when used for pipe construction, can lead to leakage and water contamination. The Nabateans used materials such as terracotta to build their water transportation methods. Terracotta, as noted by the archaeological remains of the city of Petra, is a durable material even with heavy water contact. Building materials should be critically examined during the design process of any water management system to ensure durability and little to no chemical reaction to water over time, prior to financial cost analysis. Another concept to consider during design is the hydrodynamics. The Nabatean design of the Wadi Mataha displays an understanding of hydrodynamics in the effective use of slope to minimize leakages. If the ancient water system were mimicked in design, modern civil engineers could create water management systems less vulnerable to waste and pollution through preemptive design. Examinations of the design, including the building materials, prior to construction will lower the need for repairs and replacement thereby working to ensure water availability and quality.

To avoid the continuous necessity for renovation, Jordan should, like the Nabateans, focus on their natural strengths. Duckweed, or water lentil, has been found in multiple bodies of water in Jordan (Shammout & Zakaria 2015). Duckweeds are small, and quickly growing aquatic plants found on the surface of ponds, canals, ditches, etc. (Shammout & Zakaria 2015). The advantageous duckweed serves many purposes. It has been known to be a viable food source with a protein level up to 40%, similar in taste to spinach and commonly used in Chinese medicine (Shammout & Zakaria 2015). Duckweed has the ability to extract pollutants from water, making it a great purifier for wastewater and water treatment (Shammout & Zakaria 2015). The plant displays a rapid growth rate, easily grown, and prevents other plants such as
algae, that rely heavily on solar energy, from growing (Shammout & Zakaria 2015). Pilot projects in Latin America have tested the Duckweed and revealed it as a great water treatment source but even more so as a source for feed for the animals (Shammout & Zakaria 2015). This knowledge provides a way for the wastewater to be treated outside of the wastewater plant while providing an agricultural product simultaneously. Using the Duckweed, Jordan can manage to provide additional clean water for irrigation while having extensive amounts of duckweed that can be sold for human consumption, livestock, or even trade. Incorporating the Duckweed would be using the given environment to aid in the management of resources just like the Nabateans did in Ancient Petra. Elements from Nabatean water management that can be incorporated in the present are the use of durable materials, regular maintenance for optimal functionality, use of environmental concepts such as slope as advantages in quality and distribution control, and the use of resources such as mathematical models to ensure the effectiveness of a design in infrastructure.
THE EFFECT OF URBAN GROWTH

Many of the countries discussed have experienced a population boom. Population growth and urbanization are both placing extreme pressure on water resources today (Mithen 2010) – yet these same issues were overcome in the past. Part of the problem of modern urbanization is that economic and political priorities are being placed above the necessity of water management. Soil coverage is lowered by the spread of asphalt caused by urban growth, which in turn affects ground water recharge and natural soil drainage capabilities (Mithen 2010). Presently, water decisions are made under economic and political pressures – shifting the essential focus away from water. Looking further into the political spheres of influence concerning water regulation, and legislation can create a better understanding into why certain water management systems are used in place of others, and how the policies can be changed to reflect a more crisis directed approach. Urban growth has led to innovative water management systems unheard of in ancient times. Although contemporary methods can use a wider variety of water sources than in the past, they are problematic in other ways. For a deeper understanding of where ancient and modern water systems can intersect to address growing populations, modern water management systems must be analyzed.
MODERN WATER MANAGEMENT
Ancient water management systems did not have the advanced technology that exists today but they utilized ecological knowledge fully to address concerns stretching from urban growth to water availability. Modern water management has the tools necessary to achieve effective management but very often forgets to use the environment as an aid. To capture the strengths and weaknesses in comparison to ancient water management, modern water management techniques must also be examined.

Desalination
Desalination is the process through which salt is removed from seawater or salty groundwater (Richter 2014). The whole essence of desalination is that it takes unusable water and transforms it into a usable product, thereby defying the statistics of available water\(^1\). This can be done through two processes: reverse osmosis or distillation. Reverse osmosis involves pushing the saltwater through a semipermeable membrane that only accepts water molecules while distillation entails boiling the water so that the freshwater evaporates, leaving the salt behind, before it is cooled back into its liquid state away from its salty counterpart (Richter 2014). Reverse osmosis is the cheaper method of the two, though still one of the most expensive, and is growing in usage, although both forms are widely used to provide clean water (Richter 2014). Arguments have been made that Jordan should invest in natural energy sources such as wind or solar power, and desalinization plants. The Red Dead Sea Conveyor project is estimated at a cost of $3.8 billion (Qdais 2007). The saltwater reservoir from which the input into the desalinization plant would be extracted is the Red Sea, and the brine reservoir from which the

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\(^1\) Refer back to Page 7 for statistics on water availability
output of the plant would be released is the Dead Sea. See Figure 8 for clarity on the path of the water to and from the desalination plant in the Red Dead Sea Conveyor Project. “Salinity is 10 times higher than sea water in the Dead Sea (salt concentration is about 33 percent)” (Qdais 2007) primarily because of high evaporation levels with no exit, making it a salt repository. The idea was proposed due to the declining water levels within the Dead Sea (Qdais 2007). Using the Dead Sea for brine disposal would help to raise the water level, thereby “preserving” the Dead Sea.

The fact that this method uses saltwater or brackish water is useful in the sense that it allows for the preservation of inland resources like lake beds by diverting the source to otherwise unusable water sources. However, desalinization has its fair share of flaws. Desalinization requires an extensive amount of energy to operate, which if done through coal or oil powered electricity – produces considerable carbon emissions (Richter 2014). Carbon emissions are known to be a solid contributor to the rise of global warming and the production of it should be avoided if possible. In many cases, as with Jordan, to be more energy efficient it is encouraged to be paired with wind power plants (Perkovich 2015). Desalinization plants must also be located near a saltwater or brackish water source to function optimally, limiting this primarily
to coastal regions. Hence, Jordan is optimal because it is near both the Red Sea and the Dead Sea. In addition to this, the by-product of the leftover salt, brine, can be difficult and costly to dispose of due to its toxicity.

The leftover brine, depending on the technique used, can be up to 75% more than the original salinity of the source (Carretero et al. 2016). If proper disposal is not ensured, the biodiversity within the water can be harmed by the brine and chemicals infused with it such as coagulants (Carretero et al. 2016). Disposal methods are determined by the disposal area as it can differ between an ocean and estuary (Carretero et al. 2016). Most commonly a diffuser is used to slow the rate at which the water is dispersed and this allows for the mixing of the water via the current. The brine has the capacity of changing the light conditions in a body of water, and creating an anoxic environment (Martel et al. 2012). This is caused in large part by construction of facilities disturbing sediments and beach deposits which in turn cloud the water and oil spills from construction and maintenance (Qdais 2007). In the past, benthic communities, particularly amphipods which are shrimp-like in nature, have been negatively affected (Carretero et al. 2016). Sometimes marine life can be decreased throughout the intake of the water, being killed throughout the process (Qdais 2007). A decreased biodiversity can affect the entire eco-system. This stresses the importance of a proper disposal of the brine.

Studies have been done to test the possibility of utilizing a water diluted brine mix to grow hydroponic lettuce heads. The yield demonstrated that depending on the stage of growth of the plant, the salinity had little to no effect on the crop success (Dias 2011). A similar study was done on corn with similar results (Dias 2011). While desalinization is a step towards using the whole of your environment via the incorporation of sea water, unless the brine can be used in
alternative ways such as in agriculture through hydroponics then the risk factor undertaken with the loss of biodiversity and over salinized water sources is too great. Ancient water management system engineers would analyze the environment on a broad perspective to weigh the pros and cons of every possible outcome. The gradient of the slope in the pipelines at Petra were so carefully designed to minimize erosion and pressurization of water so that the pipeline itself and the surrounding environment would be protected. Thus, it is not enough to provide a solution if it entails harming another aspect of nature. Alternative disposal methods should be considered.

**Water Treatment**

Water recycling, or treating the waste water for re-use, is another modern method, though expensive and unpopular due to psychological aversion (Richter 2014) and the need for intensive processing.
management (Carr & Potter 2013). The treatment of the water for cleanliness is expensive in a similar context as desalinization – it requires high energy levels. In many places where wastewater reuse is implemented, the processed water is mixed in with a local waterway to diffuse the idea of aversion (Carr & Potter 2012). Figure 9 shows water routes in Jordan that are representative of waste water diffusion. There are some risks associated with wastewater reuse, mostly associated with human health and the possibility of developing pathogens. The quality of the reuse water depends on the quality of the source and its intended use. If the water is for agricultural purposes, the quality does not need to be as high as for human consumption (Carr & Potter 2013). Wastewater contains nutrients that function like a fertilizer and would thus work well for the agricultural sector (Carr & Potter 2013). In working as both a fertilizer and a hydration method for the plant, farms would be saving money.

It must also be noted that too much wastewater in the agricultural sector, especially in arid regions, can damage the soil. Cleaning product residue in the wastewater can lead to accumulations of ions such as sodium chloride and boron (Carr 2011). “The problems of solute accumulation include salinity (high salt content), sodicity (high sodium content), anion toxicity (high concentrations of chloride, carbonate or bicarbonate) or specific toxicity by minor elements (e.g. boron)” (Carr 2011). Even the good nutrients can become a problem in excess. For example, if too much nitrogen accumulates than there is less product produced by the plant (Carr 2011). If careful monitoring is in place, the farmers are able to combat this by limiting the amount of wastewater used for irrigation and introducing fertilizers that combat the deficiencies presented (Carr 2011). Likewise, water importation is yet another modern, though not new, water management technique. Many ancient systems such as the Angkor slope discussed, use gravity
as the major propellant in the movement of water. That is not the present case. In many areas water is moved uphill, proving water distribution to be extremely costly. Large transports also spread the issue of water scarcity from the initial location to the new providing location. Because most areas produce wastewater, the increased usage of waste water would eliminate the need for water importation. 65% of Jordan is connected to the sewage system, thus producing 80 million cubic meters of waste (Carr 2011). The water would enter a cycle of use, process and reuse which would aid in limiting the alarming spread of extreme water scarcity. Also, the use and reuse of wastewater would provide some time for groundwater levels to recover since the extraction of groundwater would not need to be so great.

The ramifications for wastewater usage can be dangerous if not properly monitored at the processing and distribution levels. Public engagement is a way to monitor this. Just as civilians from the Aztec empire were held responsible for the assurance of water quality in the lakes by holding one another accountable, so too can the practice be implemented here. Giving residents the proper knowledge and understanding of how the system works and what is being done allows for them to assist in the process. By the government diffusing the wastewater back into streams and rivers without keeping the public informed, the public is being risked both in health (through exposure to pathogens) and their economic prosperity if they are reliant on farming (due to potential soil damage). Incorporating the public in water monitoring not only raises awareness for the water scarcity problem but alleviates the workforce needed at the institutional level of water management. It is this level of cooperation which ensures the function of the overall water system so that it does not fall into ill-repair due to negligence, or short staffing.
Dams

Another contributor to water scarcity is dams. Though excellent providers for water storage, dams block off water flow or change its course – not only removing the water source for those downstream but disrupting the eco-system and cutting back biodiversity (Richter 2014). The lack of water reaching downstream areas lowers the opportunity for groundwater recharge in those areas, minimizing available water and leading to the abandonment of wells and other water features (Missimer et al. 2014). People who reside in these areas find themselves forced to relocate to cities or other rural areas due to lack of resources once the dams are constructed (Missimer et al. 2014). This displacement is a social factor that should be considered when attempting to implement dams as part of the water management system.

Water storage systems such as dams are now known to lose a large portion of water to evaporation, making them less effective than originally expected (Richter 2014). In most cases, dams will help recharge the groundwater system though this is not always true as seen in areas where dam construction is in conjunction with water channel systems as in Cambodia (Missimer et al. 2014). The channel and dam combination help contain and store water from flash floods. This can be detrimental to the recharge factor as sediment and other materials such as clay can wash in with the storm, settling at the floor level and blocking any potential infiltration into the aquifer (Missimer 2014). Loss can escalate up to 80% in reservoirs that have faced sediment or clay deposition for extended times (Missimer 2014). To reduce this, measures such as scraping the bottom of the reservoir during the dry season have been implemented (Missimer 2014).

As is noted, these systems in both the past and present demonstrate equal strengths and weaknesses. Considering the present without the past is a set up for faulty measure for there is a lot to be learned by the juxtaposition of ancient and contemporary water management systems.
Research on the successes of the past and their application to regions that are currently experiencing water issues is limited. This research highlights features of ancient water management that can be combined with current water management techniques to create a more efficient system for increased water availability, distribution, and quality.
DISCUSSION

It is understood that the conditions of the past and present differ. Within the context of these 3 regions, the human relationship with the environment is currently much more intensive than in the past in that more waste is being produced per person and a larger amount of land is being cleared for domestic and commercial use. Globally, population is at an all-time high, further stressing the human impact on the environment. Global warming has raised temperatures across a myriad of modern environments. Elevated temperatures create higher evaporation rates, rising sea levels, and overall lower precipitation. The effects of global warming further complicate the issues within water management. Due to the aforementioned details, a return to previous water management systems and styles would be insufficient. While all these factors are relevant and important, the fact that there is much that can be learned from the past despite those differences is also true. Figure 10 demonstrates the intersection of ancient water management and present water management. This portion of the paper will focus on how the modern

![Figure 10 Innovative Blend of Past and Present Water Management](image-url)
technologies can be utilized with or modified by the ecological knowledge and examples provided from the past to improve conditions in Mexico City, Angkor, and Petra. The examples presented from here shall be considered a recap from those discussed earlier in the paper.

Ancient civilizations had an ecological understanding that they readily implemented in every aspect of their water management. The Nabateans managed to create a surplus of water in an arid region. They could even afford to be wasteful while still providing clean water to various parts of the empire (Ortloff 2014). The channels in Petra contained filtration holes to serve the dual purpose of transporting and purifying (Ortloff 2014). Modern civil engineers should contemplate the construction of infrastructure that serves a dual purpose such as transport and purification, as was seen in Angkor as well where the roads were also part of the water collection system. Dual infrastructure means less land usage overall. In this respect, there will be less to maintain and the emphasis can then be refocused on supply.

Ancient populations also sacrifice immediate results for long-term sustainability. The Aztecs would shut down the dams to routinely service them so that the features would last (Sosa-Rodriguez 2010). The people of modern Mexico City and Petra are already experiencing rations and limited access to water. Instead of building new infrastructure using the same methods, the focus needs to shift to fixing the old infrastructure and then using the allotted ration periods for routine maintenance and inspection to lower leakage rates. Lowering the number of leaks would limit water loss, thereby increasing the quantity of water that can be provided. The number of pipes built with metal in Jordan, later to be replaced by polythene ones is unreasonable (Darmame and Potter 2011). Common knowledge states that metal is negatively affected by water, the very object which the pipes were meant to transport in this region. Research is not
being done on the building materials to assess the durability and chemical responsiveness to water. Unfortunately, that approach leads to the urgent need for future replacement, calling for extensive monetary action. The Nabateans of Petra used ceramic for the creation of their pipelines and they remain to this day, centuries later. If the proper materials could be used upon the first construction of the water management system, there would be less of a need for continuous construction and renovation to the systems in place. The decrease in the funding needed for new projects will open resources to other industries that may also need attention such as the agricultural sector.

Another reason to study ancient populations is to analyze their adjustment to urban booms and consistent growth. Although the population sizes are drastically different from the past to the present, their coping mechanisms may still be of use. For example, the multiple levels of collection in Angkor (household, temple, and barays) is a system that could be implemented in arid regions. Rainfalls are sparse but if every person participated in a small collection at the household level, then a good portion of the water would be used rather than being lost in the asphalts of the city, evaporating back into the atmosphere. With the incorporation of the other levels there is a triple tier system working synonymously to provide water to local inhabitants. Not only does this provide additional water security but it diminishes any class distinctions that can affect access to water such as those experienced within the tandeo system in present day Mexico City. Mexico City would also benefit tremendously from a multi-effort collection system to minimize the aquifer drainage in addition to the income/water access disparity. In the future, research will have to be done on the feasibility of the suggested concepts such as dual-purpose design, and the processes involved in the decisions concerning water management within these
regions. Future research on these two matters will provide the necessary knowledge to implement the innovative blend of past and present water management.
**CONCLUSION**

Rain will pour, floods will rise, temperatures will increase, desertification will occur. Humans cannot command the environment. The reaction, however, can be controlled and this begins with a change in discourse. An archaeological perspective is uniquely suited to mediate this discourse because it views the current water crisis through assessing the vulnerabilities and strengths of past water management systems. Analyzing the dynamics of water management and approaches through time allow for better predictions on future implementations. More importantly, ancient people had a great understanding of the environment and incorporated that into their engineering design. This is something that can be borrowed in a modern age attempting to stabilize resources. Future research should focus on investigating the feasibility of an innovative design combining past and recent elements through small-scale experimentation and model building. Successful model building and small-scale experimentation could open yield support for larger scope options. Support from the political sector and the general population are necessary to construct effective water management. Although this thesis focuses on the study and incorporation of ancient water management methods to address the water crisis, in focusing on the prevalent issue of water it inadvertently works to secure the survival of the human population, ensure the continuity of biological diversity, contribute to the success of global and local economies, and facilitate an open conversation for international peace through a joint effort in water management.
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