WATER STORAGE TECHNOLOGY AT TIKAL, GUATEMALA

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Dedication

This thesis is dedicated to Paula and to our cat, Pooka.
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Introduction: Maya Water Management

Purpose and Method

This thesis examines how an ancient preindustrial city managed water. It focuses on the prehistoric city's reliance on artificial water storage devices (reservoirs) and answers the question of whether or not the artificial media alone were sufficient to meet the water needs of the citizens.

The methodology used in this study includes

(1) Establishing ranges for data on rainfall, evaporation, surface seepage, reservoir capacity, rainwater-collection-area capacity, population and water consumption through the use of maps, illustrations and text,

(2) Organizing the data by classifying reservoirs in terms of the quality of the water they held and by grouping reservoir, population and water-consumption data by demographic zone,

(3) Refining the data by throwing out low or high ends of ranges, and

(4) Analyzing the data in a variety of ways in order to establish a model that could be extended to fit other preindustrial cities.

The results of the thesis confirmed that the reservoirs alone made the focus city water-sufficient, and established that ruling elite controlled a large portion of available water at the city,
giving them much influence over their constituents but not absolute power.

This thesis demonstrates that water management can be considered to be an index of centralization. Centralization may be related to water management in a variety of ways, such as by comparing the ability of reservoir capacity to meet water demands in different demographic zones, by noting the relationships between reservoir location, population density and water flow, or by demonstrating the sophistication of design that went into reservoir systems. All of these methods are demonstrated in the thesis.

Overview

All large urban centers require carefully designed and well-maintained water supplies for drinking, cooking, bathing and cleaning. This study examines how the Classic Maya urban center of Tikal provided water for these requirements. Tikal, located in the Department of El Peten in the southern Yucatan, manipulated the landscape to meet at least part of its water requirements through the collection and storage of rainwater in permanent artificial reservoirs, most of which were constructed during the Late Classic period (A.D. 550-900).¹

The Maya are renowned for their ability to manage water, which enabled them to meet the challenges of their ecological

setting. Though the southern Yucatan contains lakes and rivers, much of its surface is covered by swamps. Tikal was located near swampland away from lakes and rivers leaving it no natural source of fresh water.

The particular set of water management problems that Tikal confronted had already been faced by two other Maya centers during the Late Preclassic period (250 B.C.–A.D. 250). The types of solutions employed by Tikal were similar to the solutions used at these two centers. Cerros in northern Belize was a coastal site and is not located close to any body of fresh water. It has been shown to have had a "sophisticated water control system" consisting of canals that acted as both water transport and water storage devices. According to Scarborough, the canals were probably used for agricultural purposes, and a system of complementary reservoirs was used for potable water. Scarborough hypothesizes that the undisturbed setting for Cerros was a freshwater lagoon-estuary, which was the original source of potable water. Subsequently, the first canal was constructed and

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2Numerous Mayanists have confirmed this. An excellent discussion of the range of water systems is contained in Matheny's 1978 article.
3This study examines the Peten lake region which was located in the southern Yucatan (Tamayo and West 1964, pp. 99-101).
4Rice 1978, p. 42.
5Other centers used reservoirs. These included Uxmal in the northern Yucatan, and El Mirador and Calakmul in the Peten (Matheny 1982, p. 168).
6Scarborough 1990, personal communication.
8Ibid, pp. 725-727.
a nearby aguada\textsuperscript{10} was modified to form the initial human-made rainwater collection system.\textsuperscript{11} Although Scarborough does not explicitly state that the water system at Cerros adequately handled the residents needs, this is implied in his article.\textsuperscript{12}

Matheny documented another site with similar problems and similar solutions: Edzna, located in Campeche, Mexico.\textsuperscript{13} "By Late Preclassic times, a hydraulic system involving several canals and reservoirs had been conceived and constructed at Edzna."\textsuperscript{14} The Maya built this system starting with nothing but aguadas.\textsuperscript{15} Matheny discusses the probable use of the canals for transportation, defense and agriculture as well as drinking water.\textsuperscript{16} Matheny believes that this system collected more than enough rainwater to meet the needs of Edzna's inhabitants. He demonstrates this by comparing estimates of population and water consumption rates per capita with the total capacity of the canals.\textsuperscript{17}

Tikal is located between two large bajos,\textsuperscript{18} to the east and west.\textsuperscript{19} Curiously, it is not located near a major source of fresh

\textsuperscript{10}An aguada is a shallow pond of water lined with impermeable clay. Aguadas are usually permanent and may be human-made (Tamayo and West 1964, pp. 99-100).
\textsuperscript{11}Ibid, p. 738.
\textsuperscript{12}The canal system handled agricultural as well as other water needs. Also, no extinct fresh water sources were proposed (1983, pp. 740-741).
\textsuperscript{13}Willey 1978, p. 329.
\textsuperscript{14}Matheny 1978, p. 199.
\textsuperscript{15}Ibid, p. 198.
\textsuperscript{16}Ibid, pp. 201-206.
\textsuperscript{17}Ibid, pp. 203-204.
\textsuperscript{18}A bajo is a low-lying marshy area enclosed by higher well-drained terrain. Bajos may become periodically flooded, but may also be drained
water, although the Peten region does have lakes and rivers. The planners of Tikal seemed to be taking advantage of the defensive advantages of the relative height of the area in locating the central precinct of the community.\(^\text{20}\) In addition, natural defense was offered by the bajos,\(^\text{21}\) and reinforced by earthenwork barriers to the north and south.\(^\text{22}\) Tikal was worth defending for a number of reasons. It was an important link in an extensive trade route,\(^\text{23}\) and was probably one of four Lowland Classic Maya regional capitals.\(^\text{24}\) It is likely that Tikal had to be defended because of the frequency of territorial-military and political struggles for dynastic power between itself and the nearby rival regional capitals.\(^\text{25}\) Therefore, site location was probably determined more by military and economic advantages than availability of surface water. This was possible since the technology for artificial water storage had already been developed during Preclassic times. In other words, the Maya took advantage of the locale primarily for the defensive reasons. But, in order to

\[^{19}\text{Carr and Hazard 1961, p. 9.}\]
\[^{21}\text{Puleston (1974, p. 281) discusses the difficulty of penetrating the vegetation associated with these bajos.}\]
\[^{22}\text{Morley, Brainard and Sharer 1983, p. 275.}\]
\[^{23}\text{Tikal lies between two major river systems, one running towards the Gulf of Mexico, the other towards the Caribbean, on which canoes could have been used to transport goods (Morley, Brainard and Sharer 1983, p. 114).}\]
\[^{24}\text{Marcus 1973, pp. 913-15.}\]
do so, they had to carve out the landscape to collect rainwater. Aguadas, which occur naturally near bajos and which can be easily constructed at the edge of bajos,\textsuperscript{26} probably formed the initial rainwater collection system. The system was further enhanced by the creation of numerous small and some quite substantial clay- or plaster-lined reservoirs located on high ground above the bajos.\textsuperscript{27}

This thesis is, in part, a response to the call by investigators Scarborough and Matheny to study the water technology at Maya sites.\textsuperscript{28} With studies like theirs, the carrying capacity of the environment and the sophistication of Maya technology was evaluated. But a more narrowly defined idea can be evaluated as well, namely, that the Maya were drawn to centers like Tikal primarily because of the availability of water during the dry season. Given the scarcity of natural surface sources of potable water, Tikal was set in what was effectively a desert, even though rainfall levels were above those typical of a desert. The construction of large paved plazas to prevent the high seepage rates typical of the karst landscape found around Tikal,\textsuperscript{29} and the construction of reservoirs to capture the runoff from the plazas, resulted in the creation of an "oasis" in that "desert." Like a natural oasis, this artificial oasis may have acted as a magnet to the inhabitants of the area.

\textsuperscript{26}Siemens 1978, p. 134.
\textsuperscript{27}Carr and Hazard 1961, p. 13.
\textsuperscript{29}Siemens 1978, p. 117.
This idea hinges on the relationship between the capacity of the reservoirs and the number of inhabitants at Tikal. Though previous researchers assumed that Tikal's reservoirs were sufficient for its needs,\textsuperscript{30} no study has yet been done to verify this.\textsuperscript{31} The specific question that this study addresses then can be formulated as two competing hypotheses, H1 and H2\textsuperscript{32}:

H1 — Enough rainwater was stored in the Tikal reservoirs to support the population during the dry season. (This gives credibility to the "oasis" idea.)

H2 — The rainwater stored in the Tikal reservoirs was insufficient to meet the needs\textsuperscript{33} of the population, implying that an as-yet-undocumented natural reservoir existed to serve Tikal.\textsuperscript{34}

Since the results of this study confirm H1, it can be reasonably assumed that other sites which have no apparent nearby natural source of potable water contained artificial water storage devices. Had H2 been correct, it would have strengthened several theories regarding the former existence of a freshwater lake in either of the large bajos,\textsuperscript{35} and the bajos found near sites similar to Tikal

\textsuperscript{31}Scarborough 1990, personal communication.
\textsuperscript{32}These hypotheses were derived in consultation with Scarborough (1990).
\textsuperscript{33}Needs include preventing dehydration, preparing food and maintaining hygiene. Secondary uses, such as agriculture, will be considered but not included in the calculations.
\textsuperscript{34}Numerous investigators have postulated that the bajos may have formerly been lakes (Siemens 1978, pp. 142-143).
\textsuperscript{35}The following theories are representative: (1) The lakes were silted in due to swidden agriculture (Scarborough 1988b, p. 43). (2) The small areas mapped as bajos within the central 16 square kilometers of Tikal probably
would have been viewed as probably having once been sources of potable water, as well as agriculturally exploitable land\textsuperscript{36} and transportation routes.\textsuperscript{37}

The thesis is divided into four chapters. Chapter 1 contains information regarding the climate of the region, including monthly rainfall and evaporation estimates generated using data gathered at and near Tikal. The specifications of Tikal's reservoir system are presented in Chapters 2 and 3, including reservoir collection areas (catchments) and reservoir capacities determined from the nine University of Pennsylvania maps of Tikal.\textsuperscript{38} In Chapter 4, data presented in the previous chapters is combined with demographic and water-consumption data gathered by other investigators. The data are analyzed both by directly comparing water supply and demand and by simulating one year of water management at Tikal. This chapter's conclusion ends the thesis with a discussion of the results and implications of the analyses.

\textsuperscript{36}Scarborough (1988a, p. 43) outlines the highly controversial, but increasingly studied, subject of raised-field agriculture in chinampa-like settings within the bajos. (For a discussion of chinampas, artificially raised gardens bordered by canals, see Armillas 1971.)

\textsuperscript{37}Canals may have been built in the bajos for canoe transport (Culbert 1988, p. 95).

\textsuperscript{38}Carr and Hazard 1961.
Chapter 1: Climate, Rainfall and Evaporation

Climate

This chapter describes the climate of Tikal's setting. Though Tikal's annual rainfall yield was well above measurements for arid conditions, Tikal did have a substantial dry season. Furthermore, monthly rainfall varied significantly from year to year. (See Table 1.1.) The seasonality and unpredictability of rain put pressure on Tikal's people to devise a way to smooth out the fluctuations in available water. Artificial water storage devices would have been just what was needed.

### TABLE 1.1

Four Years of Rainfall at Tikal^{2} (mm)

<table>
<thead>
<tr>
<th>Month\Year</th>
<th>1959</th>
<th>1960</th>
<th>1961</th>
<th>1962</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>300</td>
<td>227</td>
<td>215</td>
<td>213</td>
</tr>
<tr>
<td>July</td>
<td>120</td>
<td>272</td>
<td>330</td>
<td>156</td>
</tr>
<tr>
<td>August</td>
<td>110</td>
<td>156</td>
<td>115</td>
<td>151</td>
</tr>
<tr>
<td>September</td>
<td>155</td>
<td>201</td>
<td>89</td>
<td>260</td>
</tr>
<tr>
<td>October</td>
<td>75</td>
<td>161</td>
<td>277</td>
<td>218</td>
</tr>
<tr>
<td>November</td>
<td>100</td>
<td>232</td>
<td>84</td>
<td>62</td>
</tr>
<tr>
<td>December</td>
<td>60</td>
<td>60</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>January</td>
<td>25</td>
<td>120</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>February</td>
<td>5</td>
<td>63</td>
<td>5</td>
<td>70</td>
</tr>
<tr>
<td>March</td>
<td>50</td>
<td>26</td>
<td>26</td>
<td>75</td>
</tr>
<tr>
<td>April</td>
<td>101</td>
<td>52</td>
<td>125</td>
<td>0</td>
</tr>
<tr>
<td>May</td>
<td>131</td>
<td>115</td>
<td>78</td>
<td>50</td>
</tr>
</tbody>
</table>

---

1"Although the rain is abundant in season, the onset of rain tends to be unreliable" (Haviland 1970, p. 196).
2Derived from Puleston's rainfall chart (1974, p. 246).
Rainfall

The area in which Tikal was located is characterized as tropical rainy (warm and rainy).\textsuperscript{3} Tropical rainy areas have high humidity and afternoon showers. However, during the wetter part of the year, the rain may last for several days.\textsuperscript{4} Scarborough notes that at Cerros (which is within this type of region) as much as 128 mm of rain may fall in one day,\textsuperscript{5} an amount that may exceed monthly figures. Puleston recorded daily precipitation as high as 80 mm at Tikal.\textsuperscript{6} Such inundations have ramifications for reservoir design. Carr and Hazard note in their report on Tikal that, in some cases, water was diverted around reservoirs rather than directed into reservoirs.\textsuperscript{7} This was probably done to avoid potentially destructive spillovers or actual damage to the reservoir walls from excessive water pressure.

Regional average monthly rainfall varies in a fairly regular seasonal pattern. The wetter months are September, October and November. The drier months are February and March.\textsuperscript{8} However, Puleston's four-year rainfall measurements at Tikal (Table 1.2) yielded monthly averages that indicated that the rainiest months were June and July followed by less rain in August and more rain in September and October. In November, rainfall begins to decline and the six months from December through May are the driest.

\textsuperscript{3} Vivo Escoto 1964, p. 207.
\textsuperscript{4} Ibid, p. 213.
\textsuperscript{5} Scarborough 1983, p. 739.
\textsuperscript{6} Puleston 1974, p. 244.
\textsuperscript{7} Carr and Hazard 1961, p. 14.
\textsuperscript{8} Vivo Escoto 1964, p. 213.
Ten years of precipitation data gathered at the modern city of Flores\(^9\) (Table 2) indicates that the heavy rains begin in late April or early May, and that the rainy season lasts through October.\(^{10}\) Considering both sets of data, the four months from December through March constitute the heart of the dry season. It is during these months that the reservoir capacities were stretched.

**TABLE 1.2**

Monthly Rainfall Averages at Tikal\(^{11}\) and Flores\(^{12}\) (mm)

<table>
<thead>
<tr>
<th>Month</th>
<th>Tikal</th>
<th>Flores</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>239</td>
<td>249</td>
</tr>
<tr>
<td>July</td>
<td>220</td>
<td>240</td>
</tr>
<tr>
<td>August</td>
<td>133</td>
<td>214</td>
</tr>
<tr>
<td>September</td>
<td>176</td>
<td>362</td>
</tr>
<tr>
<td>October</td>
<td>183</td>
<td>204</td>
</tr>
<tr>
<td>November</td>
<td>120</td>
<td>88</td>
</tr>
<tr>
<td>December</td>
<td>37</td>
<td>99</td>
</tr>
<tr>
<td>January</td>
<td>39</td>
<td>50</td>
</tr>
<tr>
<td>February</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>March</td>
<td>44</td>
<td>45</td>
</tr>
<tr>
<td>April</td>
<td>70</td>
<td>179</td>
</tr>
<tr>
<td>May</td>
<td>94</td>
<td>240</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1391</strong></td>
<td><strong>2006</strong></td>
</tr>
</tbody>
</table>

Together, the two columns of figures in Table 1.2 constitute a range of low-to-high estimates of rainfall at Tikal. The expected annual rainfall in a tropical rainy environment is given as 1500–

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\(^9\) Flores is located less than 50 km southwest of Tikal.

\(^{10}\) Culbert et al. 1978, p. 161.


\(^{12}\) Flores data was extracted from Culbert et al.'s precipitation table (1978, p. 161).
2000 mm. Puleston and Culbert's annual rainfalls are respectively 1391 mm and 2006 mm. Their data falls reasonably close to the expected annual range.

**Evaporation**

For every millimeter of rainwater going into an aguada or reservoir, a certain percentage will be lost due to evaporation. Temperature and humidity both affect evaporation. Generally, when the temperature is higher, the rate of evaporation becomes greater. However, if the moisture content of the air is very high (high relative humidity), then this will retard the rate of evaporation.\(^{14}\)

Precise evaporation data for Tikal is not available.\(^{15}\) In order to estimate the evaporation rate at Tikal, evaporation data already gathered by Matheny for Edzna was used.\(^{16}\) Matheny estimated that 0.6% of the water stored at Edzna was lost daily due to evapotranspiration (evaporation from soil and plants\(^{17}\)) and also due to seepage. For purposes of this study, seepage was calculated separately from evaporation. (See Appendix B for Tikal's

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\(^{13}\) Vivo Escoto 1964, p. 213.

\(^{14}\) Wind velocity also affects the evaporation rate since wind will carry away water molecules that would otherwise return to their source (Thorntwaite and Holzman 1942, pp. 6–10). However, wind velocity data is not available for Tikal. Furthermore, wind velocity is considered less consequential, given the standard vegetation and the windblind-like effect a tropical forest would have on relatively small bodies of water (Scarborough 1990, personal communication).

\(^{15}\) Evaporation rates are difficult to measure in general (Thorntwaite and Holzman 1942, p. 10).

\(^{16}\) Matheny 1978, p. 204.

\(^{17}\) Which is a way of approximating water evaporation (Puleston 1974, pp. 241–242).
seepage calculations.) In order to separate the true evaporation rate from the seepage rate, the latter was estimated in the following manner.

Edzna's canal system was built over highly permeable, naturally occurring clay basins. However, according to Matheny, some seepage occurred (perhaps due to cracks in the basins). To estimate the clay lining's seepage, the permeability factor was increased. (Even so-called impermeable substances have some positive amount of permeability.) The factor chosen was based on a moderate amount of compacting of the clay instead of a higher amount of compacting, which would normally be used for impermeable linings or surfaces. The factor chosen was .0001 ft/day, which yields an effective rate of .003048 m/day. By assuming that the canals all averaged 1.5 m in depth, the total surface area of the canals at Edzna was calculated. Then the surface area was multiplied by the permeability rate to yield a total daily water loss of 4064 m³. This is 0.2% of the total water stored at Edzna (over 2,000,000 m³). Matheny's original figure was 0.6%. Of that, 0.2% can be attributed to seepage, which leaves 0.4% daily stored water loss due to evapotranspiration (an estimate of water evaporation).

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19 Based on chart in Cedergren (1967, p. 41), using a gradient of .001 for a standard shallow sloping canal (Scarborough 1990, personal communication).
20 Matheny noted that the larger canals were 1.5 m deep (1978, p. 204).
21 12,000,000 m³/1.5 m = 1,333,333 m². Matheny calculated 2,000,000 m³ or more of available storage at Edzna (1978, p. 204).
Tikal's evaporation rate was slightly lower than Edzna's due to climatic differences between the two sites. Edzna is located in a climatic region that is characterized as *tropical wet and dry*, which has a longer and drier dry season than an area classified as tropical rainy.\(^{22}\) The two sites share the same average yearly temperature.\(^{23}\) However, for half the year, the humidity at Edzna is lower than that at Tikal.\(^{24}\) The difference in humidity at the two sites was translated into a 6.25% drop in the rate of evaporation calculated for Edzna to get a rough estimate of Tikal's rate.\(^{25}\) Applying this figure yields a daily rate of 0.375%, which can be converted into a rate of 10.7% per month.\(^{26}\)

It is possible to establish a range of evaporation rates by considering that the Maya most likely made use of certain techniques to reduce the reservoirs' evaporation rates. For instance, Matheny notes that ancient Maya probably made use of aquatic plants such as water lilies in their storage devices.\(^{27}\) Scarborough has noted that these plants occur naturally and thus could have been used in all of the reservoirs, not just the larger...

\(^{22}\) Vivo Escoto 1964, pp. 207, 212.
\(^{23}\) Ibid, p.200, f. 6.
\(^{24}\) The average humidity during the peak of the dry season at Edzna is 70%, while it is 80% during the same period at Tikal. During Edzna's wet season, both have about 80% humidity (Vivo Escoto 1964, p. 200, f. 7, 8).
\(^{25}\) By comparing relative humidity at both sites, ratios of 70:80 and 80:80 were combined to get a ratio of 15:16 (Edzna:Tikal). This ratio can be expressed as a 6.25% difference (1/16). Tikal is 6.25% more humid and so has a 6.25% lower evaporation rate. This is obviously an approximation.
\(^{26}\) Formula: \(1-(1-x)^y\), where \(x = .00375\) and \(y = 30\).
\(^{27}\) These plants could have actually lowered a reservoir's surface water temperature by a few degrees (Matheny 1978, p. 205). This would have reduced the rate of heat transfer and thus the evaporation rate.
centralized ones.\textsuperscript{28} In addition, the reservoirs at Tikal were most likely deeper than they appear now.\textsuperscript{29} Deeper reservoirs lose less water to evaporation than shallower ones.\textsuperscript{30} From this qualitative analysis, an arbitrary figure of $1/3$ was used to indicate how much these techniques would have reduced the evaporation rate. This yielded a daily rate of 0.25\%, which translated to a monthly rate of 7.2\%. (See footnote 26; $x=0.0025$.)

To encapsulate the results of this section, the following range of evaporation rates was derived: \textbf{7.2–10.7\% of stored water/month}.  

\textsuperscript{28}Scarborough 1990, personal communication.  
\textsuperscript{30}Scarborough 1988a, p. 35.
Chapter 2: The Reservoirs

The purpose of Chapter 2 is to establish the limits of reservoir capacity found in the central 9 km² of Tikal (divided into 9 mapped 1 km² quadrangles\(^1\)). Figure 2.1 shows the layout of the quadrangles of Tikal.\(^2\) Reservoirs can be found in each of the quadrangles except Encanto. In this chapter, consideration is given to each reservoir's volume, surface area and elevation (measured from the top of a reservoir) as indicated by the nine detailed maps of Tikal.\(^3\) This is referred to as the extant version of each reservoir. In addition, the dimensions of each reservoir are re-examined given their use. The result is referred to as the projected version of each reservoir. Evidence suggests that, as a consequence of erosion and neglect since the Maya collapse (A.D. 830\(^4\)), reservoir water levels have dropped lower than when they were actually used.\(^5\) Following this logic a bit further, it is highly likely that some of the smaller reservoirs may no longer be visible. In those cases where contour lines show strong evidence of a former depression, a reservoir has been projected to have existed there. (See, for instance, reservoir 2E1A). These cases are not frequent.

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\(^1\)Each quadrangle is represented by a 1 km x 1 km map (Carr and Hazard 1961).

\(^2\)Each 1 km² quadrangle is divided into four 500 m x 500 m squares. Each of these squares is identified by the number of its row and the letter of its column on the master map of Tikal (Carr and Hazard 1961).

\(^3\)Carr and Hazard 1961.


The next chapter examines the rainwater collection areas, or catchments, for the reservoirs. Some catchments appear to be quite large when compared to the size of their corresponding reservoirs. In some cases, this along with other evidence suggested the presence of an originally larger reservoir. However, in most cases this anomaly can be explained by noting that these larger collection areas also may have had a much higher rate of seepage due to a higher average permeability in their collection area surface.\(^6\) For example, significant catchments in *epicentral* Tikal,\(^7\) though smaller, tended to have lime plaster surfaces that

---


\(^7\)Puleston defines epicentral Tikal as "the core of Tikal which has sometimes been referred to as the 'ceremonial nucleus,' though it also contains what are probably elite residences" (1974, p. 20, 22). Most of epicentral Tikal falls within the Great Plaza map with smaller portions in the quadrangles around it. Also, see Figure 2.2.
were highly impermeable, while those significant collection areas
further out, though larger, tended to have less surface area
covered by plaster.

In this chapter and the next, reservoirs are divided up by
quadrangles. If a reservoir crossed quadrangle boundaries, it was
placed in the quadrangle that contained most of that reservoir.
Those portions of a reservoir's catchment falling outside of its
quadrangle were still included as part of the same catchment.
However, some catchments were incomplete because portions of
them fell outside of the 9 km$^2$ boundary.

Although some large reservoirs were already named by Carr
and Hazard, many of the smaller ones had no names. Instead of
naming all the reservoirs (79 extant and 76 projected), a simple
identification scheme, based on a suggestion by Shook and W. Coe,
was used for identifying reservoirs. Within each map square,
each extant reservoir was given a unique number prefixed by the
map square designation (Figure 2.1). Reservoir numbers were
assigned strictly by location. Starting at the northern-most
reservoir, progressively higher numbers were assigned to
reservoirs further south. In the case of a tie, the reservoir to the
west received a lower number than the one further east. This
scheme allows one to recreate the identification of each extant
reservoir directly from the map. The same number was assigned

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81961, pp. 13, 14, 24, maps.
9More prominent projected reservoirs were given names including
"Maler," "Mendez" and "Floodgate."
10In Tikal Report No. 5 (1961, p. 6).
to a projected reservoir as its corresponding extant reservoir (regardless of whether or not the projected reservoir was thought to have had more volume than the extant one). When a projected reservoir had no corresponding extant reservoir, it was assigned the number of the closest reservoir to the north, suffixed by an "A." For those cases where a projected reservoir represented the combination of two or more extant reservoirs, its number was the combination of the numbers of the extant ones with redundancies eliminated. For example, reservoirs 2E3 and 2E4 were combined to form projected reservoir 2E34.

**Volume, Surface Area and Elevation**

Reservoirs were divided into several categories by Carr and Hazard: Deep dug or constructed, modified aguadas, natural aguadas, quarry pits, pozas and special cases.\(^{11}\)

**Deep Dug or Constructed**: These reservoirs were very large, were lined with plaster (or clay) and were located in the epicenter (Figure 2.2), which was entirely covered with plaster surfaces either on the buildings or on plazas.\(^{12}\) Reservoirs with catchments

\(^{11}\)Ibid, p. 13.

\(^{12}\)Figure 2.2 shows the area circumscribed by the epicenter boundary. For purposes of this thesis, the area circumscribed was considered to have been fully paved with a thick layer of impermeable plaster. Abundant evidence exists for this. Of the eight types of features found in the epicenter, causeway, acropolis, plaza, temple, reservoir, palace, complex and group, examples exist of plastered surfaces for each of the first five types (W. Coe, 1967, pp. 28, 72, 82; 1975, pp. 793, 798; Spier and Hall 1975, p. 802; Carr and Hazard 1961, p. 13, 14, maps; Haviland 1970, p. 190). In addition, general references to a central paved area have been made (Puleston 1974, p. 261; Carr and Hazard 1961, p. 13). Heavily travelled central areas would tend to have had compressed surfaces due to the constant pounding of human feet. So epicentral areas that may not have
in the epicenter tended to be very efficient in capturing rainwater. The Temple Reservoir (5D2) was an example of a deep dug reservoir.

**Modified Aguadas:** These reservoirs tended to be even larger than the deep dug ones (at least in their projected form). But they tended to be located away from residential sections and were all outside of the epicenter. They also had huge collection areas but less reliable runoff, with the notable exception of the Tikal Reservoir (4F4), which apparently had artificial aids to collect rainwater. (See Camp subsection.) These reservoirs had once been natural aguadas resting in a deep bed of impermeable clay near bajos, but were dug deeper and expanded using earthenwork or clay dikes.\textsuperscript{13} Some very large tanks were constructed in this manner.

**Natural Aguadas:** The unmodified aguadas were much smaller. They tended to be located in or next to bajos away from residential areas. Natural reservoirs like the Aguada Subin were assumed to have varied little over time. (The artificial reservoirs were considered to have been greatly affected by the passage of time since their initial construction produced a dynamic imbalance

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\textsuperscript{13}Puleston 1974, p. 261.
between themselves and the environment. The process of erosion and plant invasion constituted a return to the initial balanced condition.)

**Quarry Pits:** These pits apparently served the dual purpose of capturing runoff as well as providing construction material.\(^{14}\) They are often associated with structures. For example, quarry pit 3E1 is associated with structure 3E38.\(^{15}\) They are also usually more than 1 m deep. The deepest and largest example of a quarry pit which was converted into a reservoir is the Madeira Reservoir (6D5).\(^{16}\)

**Pozas:** Pozas are small depressions about 1 m deep, usually associated with residential structures. Those few pozas not

---

\(^{14}\) Carr and Hazard 1961, p. 12.
\(^{15}\) Ibid.
\(^{16}\) Ibid.
associated with residences were usually located near bajos and could have been small aguadas. Pozas outnumber all other kinds of reservoirs (for instance 52 out of 79 extant reservoirs). However, the volume of the 52 extant pozas put together was only a small fraction of the total volume of all 79 extant reservoirs. (This was also true for projected pozas.) Scarborough noted that the multiplicity of small residential reservoirs was likely due to the ease of creating them.\textsuperscript{17}

**Special Cases:** This is a category that Carr and Hazard created for the Perdido Reservoir,\textsuperscript{18} but that can be extended to include other special types of reservoirs such as possible canals and a (projected) temporary holding tank dubbed the "Floodgate."

Before beginning the discussion of the individual reservoirs, a few comments about the methodology follow. First, for the purposes of this chapter, the typology outlined above suffices. Later, in Chapter 3, a modified version of this typology is discussed. Second, all the calculations that produced the volumes and areas in Tables 2.1 through 2.8 can be found in Appendix A. Third, the dimensions of the projected reservoirs are based on the following sources of information: the maps in *Tikal Report No. 11*,\textsuperscript{19} comments by the authors of that report and comments by other researcher's familiar with Tikal.\textsuperscript{20}

\textsuperscript{17}1988b, p. 48.
\textsuperscript{18}1961, p. 13.
\textsuperscript{19}Carr and Hazard 1961. A set of these maps (Appendix C) accompanies this thesis. The maps have been modified to show projected reservoirs and their catchments.
\textsuperscript{20}Comments by Carr and Hazard (1961, pp. 13, 14) about the Perdido, Hidden, Corriental and "Mendez" reservoirs; comments by W. Coe (1967,
(It is advisable to refer to the maps in Appendix C when reading the following sections.)

Great Plaza

Squares: 4D, 4E, 5D, 5E.

Major Reservoirs: (extant) Temple (5D2), Palace (5D3), Hidden (5E2), Causeway (4D2), "Maler" (4D1).

Pozas: (extant) 4D3, 5D1, 5E1.

| TABLE 2.1 |
| Great Plaza |

Reservoir Volumes (m$^3$), Surface Areas (m$^2$) and Elevations (m)

<table>
<thead>
<tr>
<th>Extant</th>
<th>Projected</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>--------</td>
</tr>
<tr>
<td>4D1</td>
<td>2,510</td>
</tr>
<tr>
<td>4D2</td>
<td>14,270</td>
</tr>
<tr>
<td>4D3</td>
<td>24</td>
</tr>
<tr>
<td>5D1</td>
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<td>5D2</td>
<td>27,140</td>
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<td>5D3</td>
<td>38,680</td>
</tr>
<tr>
<td>5E1</td>
<td>27</td>
</tr>
<tr>
<td>5E2</td>
<td>2,620</td>
</tr>
</tbody>
</table>

The Temple Reservoir, located near Temple II and Temple III, is a deep dug reservoir (7.4 m deep in its extant version). Carr and Hazard give it a capacity of about 27,000 m$^3$. The dimensions of

pp. 71, 72) about the Palace Reservoir; comments by Puleston (1974, p. 256) about the Causeway, Tikal and Perdido reservoirs; comments by Scarborough (1990, personal communication) about the "Floodgate" Reservoir.
the projected version of this reservoir were based on the following considerations. There appears to have been a dike to the east which eroded away. The top of this dike was at least 2 m higher than the current height of the reservoir (248 m versus 246 m). An increased depth of over 1 m was assumed given the accumulation of silt in the reservoir over the 1100 years since the Classic occupation of Tikal.\textsuperscript{21} The new bottom of the reservoir was estimated at 237 m (instead of 238.6 m). The sides of this reservoir were assumed to be steeper. What appears to have been a desilting tank\textsuperscript{22} on its southern boundary was assumed not to be, so that this portion of the projected reservoir was wider and deeper than the corresponding portion of the extant version. Putting all these factors together, yielded a deeper reservoir (11 m versus 7.4 m) with a much larger capacity (roughly 71,000 m\textsuperscript{3} versus 27,000 m\textsuperscript{3}).

The Palace Reservoir, located just east of the Temple Reservoir, was also considered to have had a lower bottom\textsuperscript{23} and higher and steeper walls. Its projected height suggested by the contour lines

\textsuperscript{21}Carr and Hazard 1961, p. 13, discuss the silting in of all deep dug reservoirs. For the Temple Reservoir, they had no specific estimate of the depth of this silt though they do give a 2 m estimate for the Hidden Reservoir. I used a slightly lower estimated depth of 1.6 m for the Temple Reservoir. (See Appendix A for a complete list of reservoir depths.)

\textsuperscript{22}Scarborough and I noted the type of shape characteristic of a desilting tank for a reservoir on a map of Seibal (Willey et al. 1975). However, at Seibal, it was clear that water would have only entered the reservoir through the desilting tank. For the Temple Reservoir, there is at least one more point of entry (from the north). Thus, not all water would have passed through its desilting tank, if indeed it had one.

\textsuperscript{23}Carr and Hazard do not give an estimate of the depth of the silt in the Palace Reservoir. I used a conservative 1 m estimate.
of the eroded dike to the east was 239 m (instead of 237 m).\textsuperscript{24} The resulting capacity was almost double the original extant capacity.

The Hidden Reservoir, located to the east of the Palace Reservoir, was constructed by digging out a portion of the ravine and adding a retaining wall to the northeast (following the course of the ravine). This retaining wall was also part of the Mendez Causeway. Whether or not it worked as a dam that could periodically release water is speculative. It too was projected to have had greater depth\textsuperscript{25} and surface elevation, greatly increasing its capacity.

The three reservoirs discussed above are located in a ravine that cuts through the heart of the ceremonial district. It is interesting to note that their elevations become progressively lower as one goes west to east. (See Table 2.1, reservoirs 5D2, 5D3, 5E2.) It would have been possible (and perhaps desirable) to periodically empty each of the higher reservoirs into the adjacent lower one, and perhaps to empty the Hidden Reservoir into the Tikal Reservoir.\textsuperscript{26} (See the Camp section and Chapter 3 for further details on drainage patterns.)

\textsuperscript{24} W. Coe (1967, pp. 71-72) considers the maximum height possible to have been below Structure 5D131. This structure was discovered after the Tikal maps were published (Puleston 1974, p. 443). The location of this structure was determined from the map in Figure 3b in Tikal Report No. 13 (Puleston 1983). When I compared the two maps (Figure 3b and Great Plaza), I found it to lie just above the 239 m mark.

\textsuperscript{25} Carr and Hazard estimate the Hidden Reservoir to have been 2 m deeper than the extant version but calculate the extant version without this extra depth (1961, pp. 13, 24).

\textsuperscript{26} The catchment for the Tikal Reservoir would have included a portion of the Hidden Reservoir's spilloff if water had been allowed to pass under
Further north, lying in a triangle enclosed by the Maler, Maudslay and Tozzer Causeways, is the deep dug Causeway Reservoir. It too was estimated to have been deeper (4 m deeper) as well as higher due to a partially eroded dike found on its downhill side. The water from this reservoir may have been periodically released into the drainage heading to the huge Tikal Reservoir which lay to the east.27 (See the Camp section.) Furthermore, water flowing into the Causeway Reservoir may have been temporarily held up in a holding tank to the west called the "Floodgate" Reservoir.28 (See Chapter 3 as well as Temple IV section.)

Following the Maler Causeway north of the Causeway Reservoir up towards the North Zone leads one to a portion of the causeway where the western parapet was thickened by Late Classic Maya architects. Just to the left lies a reservoir, marked on the Great Plaza map as a shallow depression, and dubbed here the "Maler" Reservoir. Carr and Hazard do not discuss this reservoir although it is quite similar to the "Mendez" Reservoir which they do discuss. (See the Temple of the Inscriptions section). It also resembles the more clearly defined Hidden Reservoir. First, the Maler Causeway

the Mendez Causeway. The rest of the spilloff would have emptied into a bajo just south of the Causeway Reservoir.

27 Assuming a sluice existed under the Maler Causeway that could have periodically allowed water to pass through. Although the Maler Causeway does not act as the dike for the Causeway Reservoir, it does lie between it and the Tikal Reservoir.

28 I do not consider this feature (first noted by Scarborough 1988) to be a permanent reservoir, but rather some sort of holding tank that may have been used on a seasonal basis.
acts, like the Mendez Causeway does for the Hidden Reservoir, as the "Maler" Reservoir's retaining wall. Second, both reservoirs lie in large drainage ditches that empty into bajos to the east of the epicenter of Tikal. The "Maler" Reservoir was projected to have been 1 m deeper. Expanding its height to the 215 m mark necessitated truncating its northern portion. (Otherwise structure 4D5 would have been underwater.) Still, the resulting dimensions yielded a much greater capacity. (See Chapter 3 for a discussion of the drainage pattern associated with this possibly significant reservoir.)
Camp

Squares: 4F, 4G, 5F, 5G.

Major Reservoirs: (extant) Tikal (4F4).

Pozas: (extant) 4F2, 4F3, 5F1, (projected) 4F1A

Quarry Pits: (extant) 4F5.

TABLE 2.2

Camp

Reservoir Volumes (m$^3$), Surface Areas (m$^2$) and Elevations (m)

<table>
<thead>
<tr>
<th></th>
<th>Extant</th>
<th></th>
<th>Projected</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elev.</td>
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<td></td>
<td></td>
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<tr>
<td>4F1A</td>
<td>47</td>
<td>94</td>
<td>211</td>
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</tr>
<tr>
<td>4F2</td>
<td>11</td>
<td>20</td>
<td>212</td>
<td>4F2</td>
</tr>
<tr>
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</tr>
<tr>
<td>5F1</td>
<td>42</td>
<td>85</td>
<td>203</td>
<td>5F1</td>
</tr>
</tbody>
</table>

The Tikal Reservoir, located to the east of the epicenter, is a modified aguada. A nearby bajo lies to its east. Two natural drainages enter into the Tikal Reservoir from the west and southwest. The one from the west could have received water from the Causeway Reservoir, and the one from the southwest could have received water from the Hidden Reservoir. Puleston has noted the presence of a dendritic system of clay-lined drainage ditches (discovered by Bennett Bronson) which drained

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29 Found in a map prepared by Carr in 1959 of (structure) groups 4F1 and 4F2 (Haviland 1985, f. 1).
30 Quarry pit 4F1 was determined to be modern and was not included as a Classic Maya reservoir.
upland areas, including portions of the paved epicenter, into the Tikal Reservoir.\textsuperscript{31}

The Tikal Reservoir must have had a much larger capacity than Carr and Hazard calculated because it handled the runoff from two independently large drainage. (See Chapter 3 for details on the determination of the total amount of runoff, considering surface characteristics as well as the artificial drainage devices mentioned above.) Judging from four mounds that surround the reservoir and appear to be the remains of earthenwork walls around the reservoir, the reservoir must have had a higher level in the past. Though the walls are as high as the 203 m contour line in elevation (6 m above the present surface of the reservoir), judging from the Camp Quadrangle map, the inlets could only have been as high as the 200 m contour line (unless the erosion had been catastrophic). Still, this added height together with an extra meter of depth\textsuperscript{32} would have yielded a capacity over four times as great as the extant capacity. (See Table 2.2.) Carr and Hazard suggest that walls on the uphill side of a reservoir could have been used to keep water out.\textsuperscript{33} This, along with the above-mentioned, clay-lined drainage ditches, indicates the complexity of design that went into the Tikal Reservoir.

\textsuperscript{31}Puleston 1974, pp. 261, 290.
\textsuperscript{32}Following Carr and Hazard's suggestion that the reservoirs were silted in over time (1961, p. 13). I have assumed 1 m of silt, unless otherwise indicated.
\textsuperscript{33}1961, p. 13.
Temple of the Inscriptions

Squares: 6F, 6G, 7F, 7G.

Major Reservoirs: (extant) Inscriptions (6F4), (projected) "Mendez" (6F23).

Pozas: (extant) 6F1, 6F3, 6F5, 6F6, 7F1, 7F2, 7G1, 7G2, 7G3.

<table>
<thead>
<tr>
<th>Extant Reservoir</th>
<th>Volume (m³)</th>
<th>Surface Area (m²)</th>
<th>Elevation (m)</th>
<th>Projected Reservoir</th>
<th>Volume (m³)</th>
<th>Surface Area (m²)</th>
<th>Elevation (m)</th>
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</thead>
<tbody>
<tr>
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<td>79</td>
<td>203</td>
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<td>39</td>
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<td>57</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The Inscriptions Reservoir was a modified aguada. Compensating for erosion and silting, its projected capacity would have been double its extant capacity.

Carr and Hazard reported that a section of the Mendez Causeway may have acted as a dam to capture water naturally flowing into a low-lying area (around 205 m elevation) that was the terminus of a substantial drainage found mostly in square 6E. Taking into

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account the poza that lies quite close to the causeway (6F3), what appear to be retaining walls at the 208 and 210 m level just south of this poza plus the absence of buildings within the 210 m contour line, a very large elongated reservoir was projected. This reservoir (called the "Mendez") would have had an inlet from the southwest at its longitudinal center as well as one from the south where it may have received spilloff from the Inscriptions Reservoir which was situated slightly higher (212 m).

The Inscriptions Reservoir in conjunction with the "Mendez" Reservoir constitute a residential reservoir system with over 120,000 m³ of capacity. Unlike other similarly sized reservoirs not located in the epicenter, these reservoirs were located near densely populated areas (areas of high structure concentration).

Two of the pozas were projected to be larger than their extant versions. Extant poza 7F1 may have been originally higher. The 216 m contour surrounds 3/4 of the reservoir. The downhill side probably eroded away over time. Quarrying marks, also, suggest an originally higher surface. This poza may have actually been a quarry pit. The projected 2 m depth would have been typical for a quarry pit. Poza 7G1 was situated in a substantially larger catchment (rainwater collection area) than any of the other pozas in this quadrangle. This poza may have originally been at the 204 m contour line. Quarrying marks around this poza also indicate a possibly larger reservoir. At more than 1000 m³ of capacity, 7G1 was one of the larger residential pozas. It (and poza 7G2) could have been used by residents of Structures 7G24–7G36 and 7F25–7F28 (17 structures).
Corriental

Squares: 6D, 6E, 7D, 7E.

Major Reservoirs (extant): Corriental (7E1), Madeira (6D5), (projected) "Bajo" (7D1A).

Pozas: (extant) 6D1, 6D2, 6D3, 6D4, 6D6, 7D1, 6E1, 6E2.

<table>
<thead>
<tr>
<th>TABLE 2.4</th>
<th>Corriental</th>
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<tbody>
<tr>
<td>Reservoir Volumes (m$^3$), Surface Areas (m$^2$) and Elevations (m)</td>
<td></td>
</tr>
<tr>
<td><strong>Extant</strong></td>
<td><strong>Projected</strong></td>
</tr>
<tr>
<td>6D1</td>
<td>119</td>
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<td>21</td>
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<tr>
<td>7E1</td>
<td>17,380</td>
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</tbody>
</table>

The Corriental Reservoir was a large modified aguada with two separate inlets at different elevations. Presumably, the Maya took advantage of both inlets, closing the lower inlet when the water level had reached the 205 m mark. This feature is a good example of the sophistication of design that went into the reservoirs at Tikal, because it shows how the Maya were able to take advantage of the varying elevations at the site. Carr and

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Hazard's estimate for this reservoir's capacity (used here as the extant version) assumed that the water was at the level of the southern or lower inlet (205 m).\textsuperscript{36} The projected version of this reservoir sets the level at 208 m, which was the level of the higher or northwestern inlet.\textsuperscript{37}

The Corriental Reservoir has walls that are 3 m higher than the maximum elevation of this reservoir. They probably were used to divert some water away from entering the reservoir. This type of construction was also used at the Tikal Reservoir. (See Chapter 3 for a discussion of the purpose of this type of reservoir.) Carr and Hazard note that the walls suggest that there was more than enough water for the residents\textsuperscript{38} (otherwise it would not have been turned away). Scarborough interprets the walls differently.\textsuperscript{39} His interpretation considers the walls to be a sign that water often fell all at once making it impossible to completely utilize, leaving a deficit in the dry season. Either interpretation may be correct: while overall there was sufficient water at Tikal, some specific zones had wet-season surfeits followed by dry-season deficits. (See Chapter 4 for more details.) For purposes of this chapter, it suffices to note that water could have been turned away to prevent destructive reservoir overflow. The water that

\textsuperscript{36}Ibid, p. 24.
\textsuperscript{37}Ibid, p. 14.
\textsuperscript{38}1961, p. 14.
\textsuperscript{39}Personal communication 1990.
was diverted away from these reservoirs flowed into nearby bajos where it may have been used for agriculture.\textsuperscript{40} To the west of the Corriental lies a portion of a bajo in square 7D that Carr and Hazard believe could have contained a basin.\textsuperscript{41} Only a projected version of this reservoir was considered. A substantial amount of water could have been retained in it (over 4000 m\textsuperscript{3}). The dimensions of this reservoir were obtained by assuming it had a disk-like shape 1 m in depth and that its surface area was the area demarcated as bajo at the southeast corner of square 7D. This "Bajo" Reservoir was at a higher elevation than the Corriental Reservoir and could have emptied into it (assuming that the Corriental Reservoir had an additional western inlet). The "Bajo" Reservoir may have originally been a natural aguada that subsequently dried up.

The Madeira Reservoir, located on the southern edge of the epicenter, was a very large quarry pit that served as a water supply for a densely populated area. Carr and Hazard believe that this pit was 6 to 7 m deep at its deepest point.\textsuperscript{42} The projected version of this reservoir was estimated to have had a 6 m depth all the way across its bottom.

Finally, poza 6D6 was assumed to have been larger because it had a substantially larger catchment than the other pozas in this quadrangle, and because the 234 m contour line along with

\textsuperscript{40}Scarborough (1990, personal communication) believes that raised-field agriculture was feasible along the margins of the bajos surrounding Tikal.
\textsuperscript{41}Carr and Hazard 1961, p. 15.
\textsuperscript{42}Ibid, p. 12.
structures 6D42 and 6D49 could have formed a depression capable of retaining water.

**Perdido**

Squares: 6B, 6C, 7B, 7C.

Major Reservoirs: (extant) Perdido (6C4), Aguada Pital (7B1).

Pozas: (extant) 6C1, 6C2, 6C3, 6C5, 7B2, 7C1, 7C2, (projected) 7C1A.

Quarry Pits: (extant) 6B1.

<table>
<thead>
<tr>
<th>Table 2.5</th>
<th>Perdido</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Volumes (m³), Surface Areas (m²) and Elevations (m)</td>
<td></td>
</tr>
<tr>
<td>Extant</td>
<td>Projected</td>
</tr>
<tr>
<td></td>
<td>6B1</td>
</tr>
<tr>
<td></td>
<td>6C1</td>
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<tr>
<td></td>
<td>7B1</td>
</tr>
<tr>
<td></td>
<td>7B2</td>
</tr>
<tr>
<td></td>
<td>7C1</td>
</tr>
<tr>
<td></td>
<td>7C1A</td>
</tr>
<tr>
<td></td>
<td>7C2</td>
</tr>
</tbody>
</table>
The Perdido Reservoir is perhaps the most unusual reservoir at Tikal\textsuperscript{43} because of its above-ground construction as well as its canal-based drainage system.\textsuperscript{44} The Perdido had a spillway at its southwest end which emptied into a nearby bajo. Given its relatively small capacity (less than 5,000 m\textsuperscript{3}), this reservoir may have acted more like a valve that pushed water into the bajo when it was needed to keep planted fields moist.\textsuperscript{45}

This type of function would have been consistent with other similarly situated reservoirs such as the Tikal and Corriental. Though much larger than the Perdido\textsuperscript{46} (87,000 m\textsuperscript{3} and 58,000 m\textsuperscript{3}, respectively), these two reservoirs were, like the Perdido, situated near bajos and away from residential areas. The fact that they were not close to heavily populated areas, and therefore not readily accessible, suggests that these reservoirs were not intended to supply drinking water. (See Chapter 3 for further discussion on the purpose of this type of reservoir.) All three reservoirs were designed to capture specific amounts of water. In the case of the two larger ones, water was deliberately diverted

\textsuperscript{43}Carr and Hazard (1961, p. 13) put the Perdido Reservoir in its own special category.

\textsuperscript{44}Both Puleston (1974, p. 261), and Carr and Hazard (1961, p. 13) note an artificial drainage system associated with the Perdido. Neither, however, discuss the presence of canals in this quadrant for which there is clear evidence on the maps (Temple IV, Perdido). The Catchment section contains a complete description of the entire system.

\textsuperscript{45}Scarborough 1990, personal communication. Carr and Hazard note that the bajos were completely dry during the dry season (1961, p. 15).

\textsuperscript{46}Scarborough (1990, personal communication) notes that this difference in volume may have been linked to the differences in the amount of planted bajo margin land they serviced. The presence of larger bajos to the east where the larger Tikal and Corriental reservoirs are located strengthens this idea.
away from the reservoirs. (See Corriental and Tikal sections.) In the case of the smaller one, much effort went into ensuring that all available water was captured. Specific quantities of water would have been important to an activity, such as field agriculture, where too much water can be as damaging as too little.

Carr and Hazard estimated that the Perdido Reservoir was over 1 m deep.\textsuperscript{47} However, they measured its capacity as if it were 1 m deep. The projected version was measured as if it were 1.5 m deep.

The Aguada Pital was not modified. Its projected version was considered to be the same as its extant version. This rule of thumb was followed for the other natural aguadas (the Subin and Las Chamacas in the Temple IV and North Zone quadrangle maps, respectively).

Pozas 6C3 and 7C1A both deserve mention. Poza 6C3 was probably a quarry pit, given the quarrying marks around its edges. Its true surface level was probably 237 m (instead of 236 m). Just west of structure 7C25 at the 248 m contour line is what appears to have been a natural depression, identified here as projected poza 7C1A. (See also projected reservoir 2E1A.)

\textsuperscript{47}Carr and Hazard 1961, p. 13.
Temple IV

Squares: 4B, 4C, 5B, 5C.

Major Reservoirs: (extant) Aguada Subin (4B2), (projected) "Floodgate" (5C1A), "Canal" (5C4).

Pozas: (extant) 4B1, 4C1, 4C2, 4C3, 4C4, 5B2, 5B4, 5B5, 5B7, 5C2, 5C3, 5C5, (projected) 4C12.

Quarry Pits: (extant) 5B1, 5B3, 5B6.

<table>
<thead>
<tr>
<th>Extant Reservoir Volume (m³)</th>
<th>Surface Area (m²)</th>
<th>Elevation (m)</th>
<th>Projected Reservoir Volume (m³)</th>
<th>Surface Area (m²)</th>
<th>Elevation (m)</th>
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<tbody>
<tr>
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<td>121 253</td>
<td>4B1</td>
<td>60</td>
<td>121 253</td>
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<tr>
<td>4B2</td>
<td>400</td>
<td>424 242</td>
<td>4B2</td>
<td>400</td>
<td>424 242</td>
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<td>4C1</td>
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<td>6,361 245</td>
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<td>5C5</td>
<td>71</td>
<td>141 252</td>
<td>5C5</td>
<td>71</td>
<td>141 252</td>
</tr>
</tbody>
</table>

In square 5C, dividing the Tozzer Causeway in half, is a south-to-north section, 70 m wide, of a larger drainage that terminates
at the Causeway Reservoir. At the place where this drainage bends to the east, there is a row of three structures aligned with the northern edge of the Tozzer Causeway. This set of structures is believed to have been the remnants of a floodgate or dam.\textsuperscript{48} This dam acted in concert with the two retaining walls that formed an artificial north-to-south drainage to hold water that would otherwise have flowed past this point to the east. The 245 m contour line was considered to have been the southern boundary of this "Floodgate" holding tank. Using these boundaries yielded a capacity of nearly 20,000 m\textsuperscript{3} for this projected reservoir.

Perhaps this reservoir was used to retain water during the wetter months when the huge natural collection area for the Causeway Reservoir would have captured more than sufficient rainwater to fill it. A dam cutting off part of this drainage would have ensured that the Causeway Reservoir did not become damaged by an overabundance of water. During the dry spells, the water retained in the "Floodgate" tank could have been released into the Causeway Reservoir to maintain the latter's water level. Perhaps also, some type of filtration system was devised to capture debris that would otherwise have fouled the water in the Causeway Reservoir.\textsuperscript{49} Regardless, the Maya appear to have deliberately modified the Tozzer Causeway to accommodate natural drainage patterns. Given the large amount

\textsuperscript{48}First noted by Scarborough 1988.
\textsuperscript{49}Scarborough (1990, personal communication).
of reservoir activity at Tikal, it can be safely assumed at the very least that the purpose was water related.

Pozas 4C1 and 4C2 probably were the remnants of a larger reservoir with a capacity of over 1000 m³, which abutted the Maudslay Reservoir and served a cluster of nearby structures (4C30 through 4C39 and 4D21 through 4D26—a total of 16 structures).

Poza 5B2 is situated at the convergence of two very large drainages (one from the northeast and one from the southwest) with a combined catchment (collection area) of over 114,000 m², which is on the order of the size of the catchment for the Inscriptions Reservoir. Clearly, a much larger reservoir could have existed here. A conservative estimate puts the upper level of this reservoir at the 233 m contour line giving it dimensions of an 80 m x 32 m elliptical cone with a depth of 5 m yielding a volume of 3351 m³.

The top of poza 5B3 appears to have been eroded away. Its true top would have been 254 m. Its estimated projected capacity is 284 m³.

As was mentioned in the Perdido section, canals were found to be a part of an artificial drainage system that served the Perdido Reservoir. In the middle of square 5C, in a north-to-south direction, runs a set of elongated contour lines at the crest of a hill (over 260 m high). In the middle of this contour line is a small poza (5C4). This poza was probably all that remained of a much larger canal, part of which was used to store water. Extending down the hill towards the south in the direction of the Perdido
Reservoir are two straight parallel lines of quarry marks following the natural drainage that could have been the remnants of the lower inclined portion of this canal. The "Canal" Reservoir was estimated to have been at least 1 m deep and 10 m wide. The flat level portion of the canal was 90 m long. This yielded a conservative estimate of 900 m$^3$ of capacity. (See the Catchment section for a description of the entire canal system.)

**Bejucal**

Squares: 2B, 2C, 3B, 3C.

Major Reservoirs: (extant) Bejucal (3C4).

Pozas: (extant) 2C1, 3B1, 3B2, 3C1, 3C2, 3C3, 3C5, 3C6, 3C7,
(projected) 23C123.

**TABLE 2.7**

Bejucal

Reservoir Volumes (m$^3$), Surface Areas (m$^2$) and Elevations (m)

<table>
<thead>
<tr>
<th>Extant</th>
<th>Projected</th>
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<td>3B1</td>
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<tr>
<td>3B2</td>
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<tr>
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<tr>
<td>3C6</td>
<td>71</td>
</tr>
<tr>
<td>3C7</td>
<td>20</td>
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</tbody>
</table>

Like the Corriental, Tikal and Perdido reservoirs, the Bejucal Reservoir is located near (actually in) a bajo and away from
residences. Also, like those reservoirs, the Bejucal Reservoir appears to have been modified so as to take in a specific amount of water.\textsuperscript{50} High walls (assumed to be about 1 m in height) around the inlet (which was on the southeast side) kept some water from entering the reservoir. A surface level of 213 m and a bottom at 211 m (instead of 211.3) was assumed when measuring its projected capacity.

Pozas 2C1, 3C1, 3C2 and 3C3 may have been the remnants of a single reservoir (23C123) bordered by structures 2C27 and 2C28. This poza was estimated to have held about 1000 m\textsuperscript{3} of water, more than sufficient to supply the 16 nearby structures (2C16–2C31).

\textsuperscript{50}Carr and Hazard 1961, p. 14.
North Zone

Squares: 2D, 2E, 3D, 3E.

Major Reservoirs: (extant) Aguada Las Chamacas (2E5).

Pozas: (extant) 2D1, 2E1, 2E3, 2E4, (projected) 2E34, 2E1A.

Quarry Pits: (extant) 2E2, 3E1.

TABLE 2.8
North Zone

Reservoir Volumes (m³), Surface Areas (m²) and Elevations (m)

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<th></th>
<th>Extant</th>
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</thead>
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<tr>
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<tr>
<td>2E2</td>
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</tr>
<tr>
<td>2E3</td>
<td>15</td>
<td>31</td>
</tr>
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<td>2E4</td>
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<td>3E1</td>
<td>118</td>
<td>118</td>
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</table>

Two pozas and one quarry pit were projected to have been originally larger. Pozas 2E3 and 2E4 (associated with structure 2E32) may have been the remnants of a single reservoir with a capacity of 66 m³. To the southwest of poza 2E1 there appears to be the remnants of another poza (2E1A) with a capacity of 275 m³. Finally, quarry pit 2E2 was assumed to be larger, as indicated by a ring of quarry work around it that was 1 m higher than its extant surface.
Chapter 3: Catchments

This chapter focuses on the catchment (collection area) associated with each reservoir discussed in Chapter 2. Two key quantities were calculated for each catchment in order to subsequently determine the total volume of rainwater collected in each catchment. These key quantities were the total surface area of a catchment and the total water lost to seepage (absorption of rainwater into ground). Catchment surface areas were measured directly from the Tikal maps. Determining seepage required considerable calculation. (Seepage is expressed in the same units used for rainfall in Chapter 1—millimeters per month.) Finally, this chapter discusses natural and artificial drainage features for each quadrangle. Each of the following sections covers a quadrangle (an arrangement similar to the one in Chapter 2).

In order to determine water loss due to seepage, average seepage rates were first generated for every map square that contained one or more catchments. (See Appendix B for details.) In the figure associated with each quadrangle are darkened squares that represent map squares with catchments for reservoirs that are within a quadrangle. The seepage rates associated with each map square are also shown. Next, for each catchment, the percentage of the catchment falling within a map

---

1 Catchment boundaries were determined by examining mapped contour lines, structures and elevation marks (Carr and Hazard 1961, maps). In the cases of the Great Plaza and Temple IV quadrangles, information from text, photographs and illustrations was used (Coe 1967, pp. 40, 41, 54, 55, 80, 81; Carr and Hazard 1961, pp. 13-15).
square was determined for every map square covered by that catchment. This is represented by the distribution percentage columns in the table for each quadrangle. Finally, these percentages were used to weight the seepage rates from each map square in order to determine the average seepage rate for the catchment. This methodology tended to work well for most of the catchments. Those catchments for which this methodology would not have been accurate were handled differently. (See the comments under each table and in the text for the details of those calculations.)

For purposes of this chapter, catchment surface materials were considered to fall into three categories: plaster (highly impermeable), clay (highly impermeable) and silt-loam soil (permeable). The plaster surfaces tended to be associated with monumental architecture and household clusters. Clay surfaces tended to occur near and inside bajos. Silt-loam soil covered the rest. Underneath any of the three surfaces was a layer of generally soft limestone that was highly permeable. Since any water reaching this level was sure to be lost, the characteristics of what lay above strictly determined the amount of runoff going to the reservoirs. (See Appendix B for more details.)

Before beginning the discussion of the individual catchments, a few comments about the tables follow. First, the rows of the

---

²Puleston 1974, p.18  
⁴Ibid, p. 256.  
⁵Ibid, p. 238.
tables contain specifications for individual catchments. Instead of devising separate catchment identification, each catchment was identified by the reservoir for which it collected water. Second, catchment dimensions did not differ between extant and projected versions. This made it possible to save space by just showing information about extant reservoir catchments and catchments for projected reservoirs with no corresponding extant version. For example, the specifications for the catchment of projected reservoir 6D1 were not shown since they were the same as those for the catchment of extant reservoir 6D1, but specifications for the catchments of projected reservoirs 7D1A and 4C12 were shown since they were new data. Finally, all seepage rates were expressed as ranges. Given the lack of direct data on seepage rates at Tikal, only rough estimates could be made which were best represented as ranges.

Finally, in order to illustrate the relative capacities of the major catchments, volumes of water collected were estimated for each one. Every annual and monthly accumulation of rain in this chapter used an annual rainfall of 1500 mm (an average of 125 mm/month). This figure is based on the annual rainfall range established in Chapter 1, and is a convenient, conservative estimate.

(It is advisable to refer to the quadrant maps in Appendix C when reading this chapter.)
Great Plaza

FIGURE 3.1
Great Plaza Catchment Squares
with Seepage Rates (mm/month)

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
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TABLE 3.1
Great Plaza Catchments

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<th>Distribution (%)</th>
<th>Seepage (mm/month)</th>
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</thead>
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<td>4C</td>
<td>4D</td>
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</tbody>
</table>

*The catchment lies completely within the paved portion of the map square(s).

This quadrangle's reservoir catchments capture a greater volume of rainwater than any other quadrangle's catchments. This is due to the high percentage of impermeable surface area found in this section of Tikal. Nearly all surfaces in these three map squares are paved and all are part of one catchment or
another. (See Great Plaza map in Appendix C.) This results in a highly compact but efficient water collection zone.

The major reservoirs in the Great Plaza Quadrangle, the "Maler," Causeway, Palace, Temple and Hidden reservoirs, together with the "Floodgate" Reservoir from the Temple IV Quadrangle, constitute the central-precinct⁶ system of reservoirs that served epicentral Tikal. Water collected in these reservoirs was used by the residents of the epicenter, which included the ruling elite, their families, servants, and royal guards, noblemen with their families and servants, artists, sculptors, architects, masons, plasterers, and other construction related workmen, market administrators, military personnel, and other bureaucrats with their staffs.⁷ Given the quantity of water stored here, it is likely that not all of it was used by the epicentral residents. Portions of it may have been used to supply potable water for those living away from "downtown" Tikal. Also, nonpotable water may have been sent from these reservoirs, via artificial drainages,⁸ to the Tikal Reservoir located east of the residential section of central Tikal and to fields next to bajos that also lay to the east.⁹ Within the epicentral part of Tikal about 930,000 m³ of water were collected every year. Based on maximum projections, the central-precinct reservoir capacity was about 245,000 m³.

⁶ Coined by Scarborough, central-precinct is synonymous with epicentral.
⁸ The clay-lined dendritic system of ditches discovered by Bronson is a strong piece of evidence that supports this contention.
⁹ Scarborough and Gallopin 1990.
Depending on relative water levels during the span of a year, the 930,000 m³ accumulated in epicentral Tikal had to not only enter the reservoirs, but also to exit them in some fashion. Otherwise, the central-precinct reservoirs would have flooded. A substantial amount of the water was consumed directly or lost to evaporation; however, it is likely that a substantial amount also left via spillways and sluices. (See Chapter 4 for further discussion.)

The central-precinct collection zone consists of three large drainages. The first services the northern portion of the triangle enclosed by the Maler, Tozzer and Maudslay causeways. The immediate terminus of this drainage is the Maler Causeway, which acts as a dam to the "Maler" Reservoir. This drainage has a catchment that collected about 205,000 m³ annually and a reservoir capacity of about 15,000 m³. This translates to a monthly flow of 17,000 m³ over 100% of capacity. Compared with the two drainages discussed below, this rate of turnover was high.

Two major factors come to mind. First, assuming that the Maler Causeway could have let water pass, this drainage ultimately terminates in a bajo 400 m to the northeast. Second, the "Maler" Reservoir is located in a sparsely populated section of the epicenter. It may have been that the water flowing out of this reservoir was tainted and fit only for fields. This drainage and reservoir may have been used to move human waste from

---

10 If all the reservoirs began the year empty and ended the year full then a much lower volume of 675,000 m³ would have left the reservoirs. However, this could only happen for one year because in the next year the reservoirs would begin full. For purposes of this discussion, it is easier to assume that reservoir levels tended to be pretty constant in the long run.
epicentral Tikal. A high rate of turnover would have helped to prevent disease associated with pools of standing polluted water.

The drainage just south of the "Maler" Reservoir drainage is larger. Bordered by Temple IV to the west, the crest of a hill 230 m south of the "Floodgate" Reservoir marks the uphill end of this drainage, which bends to the east and terminates at the Causeway Reservoir. Beyond this point lies the Maler Causeway, the entry to the enormous Tikal Reservoir catchment. The capacity of the Causeway Reservoir drainage is 70,000 m$^3$, and it handles an annual flow of about 415,000 m$^3$. That is over 35,000 m$^3$ monthly or about 50% of capacity. The lower turnover suggests less pollution associated with this drainage's reservoirs. Still, the rate is very high and the area of the Causeway Reservoir is sparsely settled (which is not the case for the "Floodgate" Reservoir). So, this drainage and reservoir may have been used in a manner similar to the "Maler."

The largest of the three drainages is the one that bisects the core of the monumental architecture at Tikal. This drainage begins at Temple III to the west and terminates at the Mendez Causeway which blocks the northeastern end of the Hidden Reservoir. This drainage includes the Temple and Palace Reservoirs, too. Together, these three reservoirs contain more water than the reservoirs from any other quadrant in this study. The combined capacity of 160,000 m$^3$ handles a volume of 300,000 m$^3$ of water collected from the following epicentral features: the North, South and Central acropolises; Temples I, II, III and V; the Great, West and East Plazas; the Plaza of the Seven Pyramids; Group G; and
structures 5C54, 5D105–5D107, 5D113, 5D114 and 5D44–5D46.\textsuperscript{11} Monthly, the flow was 25,000 m\textsuperscript{3}, only about 16\%. This slower turnover suggests that water was being kept around longer in these reservoirs. Thus, it was not as likely to have been contaminated. This fact plus the fact that the Temple, Palace and Hidden reservoirs were located close to concentrations of inhabitants in the acropolises suggest that most of the drinking water for epicentral Tikal was held in them.

The chart below encapsulates the aforementioned relationships among rate of water flow, proximate population density and water quality. (It is helpful for understanding similar relationships for reservoirs discussed in the following sections.)

\begin{center}
\begin{tabular}{lcc}

Water Flow & Population & Density \\
\hline
low & potable & low \\
nonpotable & high & X \\
low & potable & X \\
nonpotable & high & X \\
\end{tabular}
\end{center}

(Note that in this and the following sections, reservoir capacities were based on projected, not extant, versions of each reservoir. Also note that monthly rates are averages that do not reflect wet- and dry season fluctuations in rainfall.)

\textsuperscript{11}W. Coe 1967, p. 20, map.
FIGURE 3.2
Camp Catchment Squares
with Seepage Rates (mm/month)

<table>
<thead>
<tr>
<th>2</th>
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<th>4</th>
<th>5</th>
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<th>7</th>
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<td>B</td>
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<table>
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<tr>
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<tr>
<td>4F</td>
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<td>5E</td>
<td>9.91</td>
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<tr>
<td>5F</td>
<td>71.708</td>
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TABLE 3.2
Camp Catchments

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<th>Reservoir</th>
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<th>Distribution (%)</th>
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<tr>
<td>4F1A</td>
<td>.12</td>
<td>100</td>
<td>73-733</td>
</tr>
</tbody>
</table>

*The high end of the range was significantly reduced because the Tikal Reservoir was served by clay-lined drainage ditches ensuring that drainage from the paved epicenter plus other uphill areas reached it.

Illustration 1\(^{12}\) shows the Tikal Reservoir catchment and drainage. (See, also, the Great Plaza and Camp maps in Appendix C.) Depending on whether or not the Mendez and Maler causeways had appropriately located sluices,\(^{13}\) water from the

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\(^{12}\) Taken from Scarborough and Gallopin 1990, Fig. 3.

\(^{13}\) Puleston (1974, p. 290) indicates that the clay-lined drainage ditches discovered by Bronson were located in map square 5E. This would have placed them downhill from the Hidden Reservoir to the east of the Mendez Causeway.
southern central-precinct drainages, mentioned previously, would have emptied into the Tikal catchment past these two causeways.

As noted in Table 3.2, the Tikal Reservoir catchment's seepage rate was recalculated for the upper end of its range. This was done because of the presence of the above-mentioned clay-lined ditches draining water from the paved portions of this catchment. A simple assumption was made that all rainfall falling on paved portions reached the reservoir via the clay-lined ditches, and that the rest of the rainfall was all lost to seepage. Using an average monthly precipitation of 125 mm/month (1500 mm/year), the
percentage of rainfall lost was converted into a monthly seepage rate. This then became the new upper limit on the seepage range.

Applying the seepage rates yielded an annual range of 300,000–590,000 m$^3$ of water accumulation in the catchment or 25,000–50,000 m$^3$ per month. The Tikal Reservoir had a capacity of over 87,000 m$^3$, so the percentage of monthly turnover was 30–60%, not a low turnover rate. This reservoir, as mentioned in Chapter 2, was most likely not used for drinking water, but instead probably had an agricultural function.$^{14}$

Handling large quantities of water that were not immediately consumed required mechanisms designed to prevent tank overflow. Two methods were available: one was to release water at the downhill end of the reservoir via a spillway or sluice, the second was to intermittently prevent water from entering the reservoir.

Since water flowing through the Camp Quadrangle would have reached bajo-margin fields (250 m to the east of the Tikal Reservoir) whether or not a reservoir was present, the only time water from a reservoir would have been necessary was during long dry spells. During these times, water stored at the Tikal Reservoir could have been released into the fields. Although no direct evidence exists of a water distribution system,$^{15}$ it can be

---

$^{14}$ Although no direct evidence exists yet, a number of investigators believe that raised-field agriculture was practiced at Tikal (Scarborough 1990, personal communication; W.Coe 1975, p.795; Hammond 1988, p.162-163).

$^{15}$ Bronson (1978, p. 279) believes that the clay-lined ditches he discovered were a portion of a water distribution system. However,
inferred. Some direct evidence, however, exists to support the idea that the Maya were periodically blocking water from entering this reservoir, namely, the earthen wall built around the reservoir and the presence of two entry ways to the reservoir. This design is similar to the Corriental Reservoir design, which, as noted in Chapter 2, had a variable entry way.

Variable entry would have allowed the Maya to reduce flow into a reservoir when they felt it was necessary, thereby enhancing its capability. Not only could it have acted as an "insurance policy" against a lack of sufficient rainfall and runoff for the fields, but it could also have acted as a buffer with which field moisture levels could have been regulated. Opening an entryway would have captured part of the runoff before it could reach the fields, and closing an entryway would have allowed runoff to reach the fields.

The only threat to this system would have been an extreme amount of rainfall which would have led to uncontrollable reservoir spillover, flooding already overwatered fields. One has to assume that the Maya calculated reservoir capacities according to past experience regarding average annual rainfalls. At the other extreme, extended droughts could have also beaten this system. But such phenomena were clearly beyond the control of the Maya and are still devastating modern countries.

Puleston (1974, p. 290) believed that they represented a water collecting system only.
Temple of the Inscriptions

FIGURE 3.3
Inscriptions Catchment Squares
with Seepage Rates (mm/month)

<table>
<thead>
<tr>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>SQ SEEPAGE</th>
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<tbody>
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TABLE 3.3
Inscriptions Catchments

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<th>Distribution (%)</th>
<th>Seepage (mm/month)</th>
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<td>42.74</td>
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*6F2-"Mendez," 6F23-"Mendez" (Projected), 6F4-Inscriptions.

The number of catchment squares belonging to this quadrangle exceeds all others. Catchments here tend to be more scattered than in the last two quadrants, and seepage rates tend to be much
higher. Nevertheless, two very large reservoirs collect water in this zone.

Covering map squares 5D, 5E, 6D, 6E and 6F, and stretching from the edge of the Madeira Reservoir to the Mendez Causeway, the "Mendez" Reservoir catchment collects at least 43,000 and at most 510,000 m$^3$ of water per annum (depending on the seepage rate).\textsuperscript{16} This translates to 3,600–42,500 m$^3$ of water per month, 4–45\% of the 95,000 m$^3$ capacity of the reservoir, a very low rate of turnover. This, along with the general proximity of this reservoir to a densely populated portion of Tikal, points to its being a source of drinking water. Another piece of evidence, the reservoirs shape, supports this notion. This reservoir compares well with the Temple, Palace and Hidden reservoirs, which are side-by-side drinking water reservoirs. Together they form a slightly arced, elongated, four-sided shape of about 100 x 500 m. The "Mendez" Reservoir also had a slightly arced, four-sided shape with dimensions of 60 x 400 m. This reservoir, along with the Inscriptions and Madeira reservoirs, formed a triad of major reservoirs serving the largest concentration of nonelite residences in central Tikal and are known as the major \textit{residential}\textsuperscript{17} reservoirs.

\textsuperscript{16}The low end of this estimate uses the high end of the seepage rate for the "Mendez’s" catchment. This seepage rate exceeds the average 125 mm/month, meaning that no rainwater other than that falling directly on the reservoir would have reached the reservoir. This rule of thumb was followed consistently in this chapter.

\textsuperscript{17}Coined by Scarborough 1990. See Scarborough and Gallopipin 1990.
Like the "Mendez," the Inscriptions Reservoir catchment has a high rate of seepage. It collects between 23,000 and 85,000 m$^3$ annually or 2,000 and 7,000 m$^3$ monthly. This is about 7-23% of the Inscription Reservoir's 30,000 m$^3$ capacity, a low rate of turnover. The Inscriptions Reservoir is the "sister" reservoir of the "Mendez" Reservoir to which it was closely located (35 m northeast). The Inscriptions was uphill from the "Mendez" and may have fed it during the year.

The Maderia Reservoir sits just to the west of the western edge of the "Mendez" catchment in square 6D. It may be considered a central-precinct reservoir in that it drains the southern side of the Temple of the Seven Plazas, but it really belongs to the group of residential reservoirs because it is located outside of the epicentral boundary in a populous residential area. Unlike the other two major residential reservoirs, the Madeira had a catchment surface with a high proportion of impermeable surface. For this reason, the high-end seepage rate was adjusted to a smaller amount.$^{18}$ The estimated volume of rainfall was 24,000–29,000 m$^3$ per annum or 2,000–2,400 m$^3$ per month. This was 23-28% of capacity (8,700 m$^3$), again a low rate suggesting a source of drinking water. Unlike the Inscriptions catchment, any connection between the Madeira and "Mendez" catchments is very tentative. Although the Madeira was situated at a higher elevation than the "Mendez," there was too much distance (over 800 m) and too

---

$^{18}$This figure was calculated in the same way that the Tikal Reservoir catchment's high-end seepage rate was calculated. (High-end refers to the upper limit of an estimated range; low-end refers to the lower limit.)
much absorbent surface between them for spilloff from the Madeira to have reached the "Mendez." With no evidence of artificial drainage devices as yet uncovered, one has to conclude, for now, that the water going into the Madeira Reservoir remained there.

Before closing this section, it is important to mention that the pozas in this quadrangle were substantially larger both in capacity and quantity of flow than those in the other two quadrangles just discussed. This is consistent with the larger number of residences in this section. (See Chapter 4 for complete coverage of the relationship between extant structures and population estimates at Tikal.)
Corriental

FIGURE 3.4
Corriental Catchment Squares
with Seepage Rates (mm/month)

<table>
<thead>
<tr>
<th>B</th>
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<th>D</th>
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| TABLE 3.4 |
| Corriental Catchments |

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<th>Size(ha)</th>
<th>Distribution (%)</th>
<th>Seepage (mm/month)</th>
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*The catchment lies completely within the paved portion of the map square.
**The high end of the range was significantly reduced because catchment is mostly within a paved area and the terrain has a steep gradient.
#6D5-Madeira, 7E1-Corriental, 7D1A-"Bajo"

Other than the Madeira catchment, which was discussed in the previous section, the major catchments in this quadrangle include
the Corriental Reservoir's catchment and the "Bajo" Reservoirs catchment. A link may have existed between the two catchments.

The Corriental Reservoir appears to fall into the same category as the Tikal Reservoir, a *bajo-margin* reservoir.19 (Although in this case the nearest bajo would have been at the end of a long gulley, 400 m southeast of the reservoir.) If indeed this reservoir did not hold drinking water, then an imbalance would have existed in the distribution of residential reservoirs for the large residential area20 within map squares 5E, 5F, 5G, 6C, 6D, 6E, 6F, 6G, 7C, 7D, 7E, 7F, 7G. Not only would most of the flow and capacity have existed in the eastern portion of the area, but access to the reservoirs would have been easier for eastern residents. To minimize travel time to get potable water, one would expect another reservoir to exist on the western side of the residential area. The "Bajo" Reservoir (7D1A) may have been the extra reservoir needed to redress the imbalance.

Located less than 400 m to the west and uphill from the Corriental Reservoir, this shallow basin held over 4,600 m$^3$ of water and handled a flow of anywhere between 7,000 and 230,000 m$^3$ per annum. This translates to between 600 and 19,000 m$^3$ per month, about 13% to over 100% of capacity. This wide range points to a potential disparity between the actual size of the reservoir and the estimated size. If the reservoir was

---

20 The residential area does not include the epicenter. The Perdido Reservoir, which is within this area, is considered to have not been a source of drinking water.
significantly deeper, it may have approached the capacity of the Hidden Reservoir (13,000 m³) which had only a slightly larger surface area (5,000 m² versus 4,600 m²). Such a reservoir would have met the needs of the southwest portion of the residential area.

Spilloff from the "Bajo" Reservoir may have flowed to the Corriental Reservoir. If it did, it would have probably entered the reservoir via the southern (lower) entryway. Not counting this potential for additional flow, the Corriental catchment may have moved anywhere between 23,000 and 390,000 m³ of water into the reservoir. This is a monthly rate of 2,000 to 62,500 m³ or 3% to over 100% of the 58,000 m³ reservoir capacity. Before concluding this section, it is important to note that a large poza exists located near the Madeira Reservoir (150 m due east). This reservoir would have added another 1,300 m³ of capacity and 2,000–29,000 m³ of yearly flow, to the residential reservoirs.

(For purposes of this chapter, these wide ranges are tolerable. Later, these ranges are narrowed using a consistent technique in order to more closely approximate the amounts of water flowing through different parts of the Tikal reservoir system.)

---

21 It may have silted in.
Perdido

FIGURE 3.5
Perdido Catchment Squares
with Seepage Rates (mm/month)

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<td></td>
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<td>7C 53-527</td>
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</table>

TABLE 3.5
Perdido Catchments

<table>
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<tr>
<th>Reservoir</th>
<th>Size (ha)</th>
<th>Distribution (%)</th>
<th>Seepage (mm/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5B</td>
<td>5C</td>
<td>6B</td>
</tr>
<tr>
<td>6B1</td>
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<td></td>
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<tr>
<td>6C1</td>
<td>.87</td>
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<td>53</td>
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<td>6C2</td>
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</tr>
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<td>6C3</td>
<td>.23</td>
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<td>54</td>
</tr>
<tr>
<td>6C4-Perdido</td>
<td>21.98</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>6C5</td>
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<td></td>
</tr>
<tr>
<td>7B1-A. Pital</td>
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<td></td>
<td></td>
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<td>7B2</td>
<td>.14</td>
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<td>.08</td>
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</tr>
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</tr>
<tr>
<td>7C1A</td>
<td>.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The catchment lies completely within the paved portion of the map square.
**The high end of the range was significantly reduced because the Perdido Reservoir is fed by canals which drain paved areas.

Illustration 222 shows the Perdido Reservoir catchment and drainage. (See also the Temple IV and Perdido maps in

222Taken from Scarborough and Gallopin 1990, Fig. 2.
Appendix C. The drainage into the Perdido Reservoir included two big canals and three smaller ones. Two hundred meters to

ILLUSTRATION 2
Perdido Reservoir Drainage

the northeast of the entrance to the reservoir is the convergence point of a drainage from the north and one from the east.

The drainage from the east consisted of a big canal23 that ran due west for over 250 m and took runoff from the western

23Consisting mostly of a gully that runs between structures 6C30 and 6C31. This canal has a gradient of .08 which is fairly steep. A gradient of .001 is more typical of the canals found at other sites (Scarborough, 1990, personal communication).
portion of a courtyard just southwest of the Plaza of the Seven Temples (west of structures 5D2 through 5D7). About 80 m west from the above courtyard is the terminus of a smaller, 75 m long, feeder canal\textsuperscript{24} that drained the courtyard of structure 5C54.\textsuperscript{25} Unlike the rest of the canal, which is merely suggested by the contour lines, this feeder canal is clearly demarcated by above-ground construction (structures 6C28 and 6C29). Just to the north of the entrance to this canal is a gap demarcated by structures 6C23 and 24, which would have guided water directly into it.

Starting immediately north of the convergence point of the two drainages was the wider and less well-defined northern drainage's southern portion running for about 200 m. Above this (in the Temple IV Quadrangle) was a long 240 m canal clearly indicated by the contour lines and associated quarry markings. Poza 5C4 is all that remains of that portion of this canal that was used to retain water (the "Canal" Reservoir).

Two other minor canals belong to this canal system, one starting just west of structure 5C51 and traveling southwest to, and beyond extant poza 5C5, the other starting at the 250 m contour line south of structure 6C32 and travelling east. Both are about 80 m long. These little canals plus the big canals were considered to have been paved with impermeable materials.

All together, this system drained at least 9.46 ha of paved surface (42% of 22.95 ha, the Perdido and "Canal" reservoir

\textsuperscript{24}With a gradient of .08. 
\textsuperscript{25}The Lost World Pyramid.
catchments), accumulating between 147,000 and 275,000 m$^3$ of water per annum. This would have produced an extremely high rate of turnover, which is better measured in number of days between total water replacement$^{26}$ rather than percent of capacity. Given its projected capacity of 4,600 m$^3$ this would have come to 6–11 days. This can be compared to the Tikal Reservoir's turnover. After assuming that the central-precinct drainages entered the Tikal Reservoir catchment, a combined flow of 1,015,000–1,305,000 m$^3$ was calculated. Using the projected capacity of 87,000 m$^3$, the days between complete water change would have been 24–30.$^{27}$ Such a high rate of turnover in the case of the Perdido system may simply have to do with changes in technology. Faced with the choice between constructing a larger reservoir capable of delivering greater quantities of water at less frequent intervals or a smaller reservoirs that could deliver smaller quantities more frequently, the Maya architects opted for the latter design to save on construction labor costs.$^{28}$

Before leaving this section, a note about the smaller reservoirs: The "Canal" Reservoir was located near residences and probably held potable water. Other significant smaller reservoirs included quarry pit 6B1 and the Aguada Pital, both of which served the structures associated with the Morley Causeway.

---

$^{26}$The entire amount of water in the tank is displaced.

$^{27}$It is interesting to note that if one compares the turnover rates between the extant versions of the two reservoirs then the difference all but disappears: 4–8 days for the Perdido and 6–8 days for the Tikal.

$^{28}$Also, the kinds of crops associated with the Perdido system may have required more frequent watering.
Temple IV

FIGURE 3.6
Temple IV Catchment Squares
with Seepage Rates (mm/month)

<table>
<thead>
<tr>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>SQ SEEPAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4B 55-555</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4C 18-177</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5B 32-320</td>
</tr>
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<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5C 14-135</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

TABLE 3.6
Temple IV Catchments

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Size (ha)</th>
<th>Distribution (%)</th>
<th>Seepage (mm/month)</th>
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</thead>
<tbody>
<tr>
<td>4B1</td>
<td>.31</td>
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<td>4B2-A. Subin</td>
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<td>4C1</td>
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<td>4C2</td>
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<td>0-0*</td>
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<td>4C3</td>
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<td>55-555</td>
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<td>4C4</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>0-0*</td>
</tr>
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<td>100</td>
<td>32-320</td>
</tr>
<tr>
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<td>24</td>
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<td>5B4</td>
<td>.18</td>
<td>100</td>
<td>32-320</td>
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<td>5B5</td>
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</tr>
<tr>
<td>5B7</td>
<td>.01</td>
<td>100</td>
<td>32-320</td>
</tr>
<tr>
<td>5C2</td>
<td>.28</td>
<td>100</td>
<td>14-42**</td>
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<tr>
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<td>0-0*</td>
</tr>
<tr>
<td>5C4-&quot;Canal&quot;</td>
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<td>100</td>
<td>0-0*</td>
</tr>
<tr>
<td>5C5</td>
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<td>100</td>
<td>14-62**</td>
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<td>4C12</td>
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<tr>
<td>5C1A-&quot;Floodgate&quot;</td>
<td>7.97</td>
<td>100</td>
<td>0-0*</td>
</tr>
</tbody>
</table>

*The catchment lies completely within the paved portion of the map square (map squares in the case of 4C4).
**The high end of the range was significantly reduced because the catchment is partly within the paved portion of the map square.
This quadrangle contains the greatest number of catchments at Tikal, but most are small. Of the major catchments, two have already been discussed, the ones associated with the “Canal” and “Floodgate” reservoirs. The Aguada Subin is not very interesting. It is located in a very sparsely settled locale\textsuperscript{29} and probably served only residences outside of the nine square boundary.\textsuperscript{30} Because of this, the Aguada Subin is not considered to not have been a source of potable water. (See Chapter 4 for a complete list of sources of potable water.)

One isolated poza was rather interesting. Poza 5B2’s extant capacity was a mere 33 m\textsuperscript{3}, yet it had a catchment of 11.45 ha. Its projected capacity somewhat redressed this imbalance. Poza 5B2 lies at the convergence of two large drainages, one from the west and one from the north. The spilloff from this reservoir heads to the southwest to a bajo about 240 m away (one of the bajos associated with the Morley Causeway complex). Poza 5B2 had a capacity of 3,400 m\textsuperscript{3}, and handled anywhere between 3,000 and 120,000 m\textsuperscript{3} of yearly flow. It had two inlets and one outlet like the Tikal Reservoir, its locale was sparsely populated, and it had a high turnover rate. This poza resembles a bajo-margin reservoir and is not considered to have been a source of potable water.

\textsuperscript{29}At the western edge of map square 4B.
\textsuperscript{30}As seen from the master map (Carr and Hazard 1961).
Bejucal

FIGURE 3.7
Bejucal Catchment Squares
with Seepage Rates (mm/month)

<table>
<thead>
<tr>
<th></th>
<th>2C</th>
<th>3B</th>
<th>3C</th>
<th>3D</th>
<th>4C</th>
<th>4D</th>
<th>SQ SEEPAGE</th>
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<td></td>
<td></td>
<td>38-383</td>
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<td>5</td>
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<td>18-177</td>
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TABLE 3.7
Bejucal Catchments

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Size (ha)</th>
<th>Distribution (%)</th>
<th>Seepage (mm/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2C1</td>
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<td>3B1</td>
<td>.11</td>
<td>100</td>
<td>38-383</td>
</tr>
<tr>
<td>3B2</td>
<td>.05</td>
<td>100</td>
<td>38-383</td>
</tr>
<tr>
<td>3C1</td>
<td>.02</td>
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<td>28-284</td>
</tr>
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<td>75</td>
<td>42-421</td>
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<td>100</td>
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<td>8.85</td>
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<td>28-284</td>
</tr>
<tr>
<td>3C7</td>
<td>.04</td>
<td>100</td>
<td>28-284</td>
</tr>
<tr>
<td>23C123</td>
<td>.58</td>
<td>85</td>
<td>44-439</td>
</tr>
</tbody>
</table>

*The high end of the range was significantly reduced because a significant portion of the catchment fell within paved areas or areas with steep gradients.

Like the Camp Quadrangle, this quadrangle is dominated by a single bajo-margin reservoir, the Bejucal. This reservoir drains a densely settled area flanking the Maudsley Causeway, as well as the causeway itself. It is the only major northern reservoir. Unlike the Tikal and Corriental reservoirs, this major reservoir
appears to have only one entryway. Like the other major bajo-
margin reservoirs, its catchment may have been supplemented by
spilloff from a smaller reservoir, in this case, projected poza 4C12,
which had a capacity of over 1,000 m$^3$ and an annual flow of
6,000 m$^3$. The Bejucal Reservoir itself had a capacity of nearly
23,000 m$^3$ and a flow of 111,000–117,000 m$^3$.

The only significant poza in this section is 23C123, which
drained structures 2C17 through 2C27 and structure 3C1. It is the
largest single source of potable water in this quadrangle
(assuming that the Bejucal tank did not hold potable water).
Whether or not the inhabitants of this zone were self-sufficient in
terms of water is difficult to determine. (See the following
chapter.)
North Zone

FIGURE 3.8
North Zone Catchment Squares
with Seepage Rates (mm/month)

```
B C D E F G
2 2C 47-466
3 2D 40-402
4 2E 43-424
5 3D 16-165
6 3E 22-218
7
```

TABLE 3.8
North Zone Catchments

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Size (ha)</th>
<th>Distribution (%)</th>
<th>Seepage (mm/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D1</td>
<td>.08</td>
<td>50 50</td>
<td>44-434</td>
</tr>
<tr>
<td>2E1</td>
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<td>.03</td>
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<td>43-424</td>
</tr>
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<td>100</td>
<td>43-424</td>
</tr>
<tr>
<td>2E4</td>
<td>.02</td>
<td>100</td>
<td>43-424</td>
</tr>
<tr>
<td>2E5-A. L. Chamacas</td>
<td>.94</td>
<td>2 72 24 2</td>
<td>36-98*</td>
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<tr>
<td>3E1</td>
<td>.21</td>
<td>100</td>
<td>22-218</td>
</tr>
<tr>
<td>2E1A</td>
<td>.59</td>
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</tr>
<tr>
<td>2E34</td>
<td>.07</td>
<td>100</td>
<td>43-424</td>
</tr>
</tbody>
</table>

*The high end of the range was significantly reduced because significant portions of the catchment were on impermeable clay bottomed bajos or steep gradients.

The southern portion of this quadrangle is dominated by the northern end of Tikal's epicenter. Central-precinct residents received most of their drinking water from large centralized reservoirs (Temple, Perdido, Hidden, "Floodgate"). Small reservoirs, located at the edge of the epicenter, such as quarry pit
3E1, were probably also used by nearby residents who wished to avoid a longer trip to one of the larger sources of drinking water.

The remaining portion of this quadrangle is sparsely settled. Only one major reservoir serves this section, and it is not very large. The Aguada Las Chamacas may have been one of the original sources of potable water for Tikal. It remained unmodified, yet its natural location proved to be valuable. It was nestled between two ridges that it drained, a small one to the north and a larger one to the south. The one to the south was the north end of the epicenter. A number of residential structures are located next to the aguada. Some of them are on the northern and southern slopes nearby. Its small volume (350 m$^3$) handles a substantial volume of yearly rain accumulation (between 4,000 and 10,000 m$^3$) yielding a rapid rate of reservoir replenishment (one complete 350 m$^3$ replacement every 13 to 32 days).

Although it had a rapid turnover rate like a bajo-margin reservoir, the Aguada Las Chamacas really has to be considered as having been a residential reservoir containing drinking water. Its proximity to residences, plus the fact that it is the only potential source of drinking water in this quadrangle, strongly suggest this.
Chapter 4: Water Supply and Demand

Chapter 4 contains two major parts. The first part (consisting of two sections) summarizes how the data compiled in the first three chapters was used to determine the size of the potable water supply available to the residents of Tikal, a necessary preliminary step for the test of the two competing hypotheses discussed in the Introduction.¹ This part also presents estimates of water consumption and population size as calculated from the evidence gleaning from Tikal and the Maya and from the cultural uses to which water is put; these estimates represent data that also are necessary to test the hypotheses. The second part of Chapter 4 (consisting of three sections) presents the test itself and the implications of its results.

The results of the test showed that more than enough potable water was collected in the reservoirs to meet the needs of the residents, confirming H1 and rejecting H2.² There was even a surplus of water.³ However, this does not mean that all residents had equal access to water or consumed it at the same rate.

¹For convenience the hypotheses are repeated below:
H1: Enough rainwater was stored in the Tikal reservoirs to support the population during the dry season.
H2: The rainwater stored in the Tikal reservoirs was insufficient to meet the needs of the population. Consequently, an as-yet-undocumented natural reservoir existed to serve Tikal.

²Although H2 cannot entirely be ruled out, it is highly unlikely that Tikal built an elaborate water system that provided more than enough water for itself right next to a natural source of fresh surface water.

³This result takes into account the fact that some water, such as that flowing into the aforementioned bajo-margin reservoirs, may have been earmarked for agricultural use only. The amount of water going to these reservoirs as well as the capacity of the reservoirs themselves were both excluded from all calculations of the potable water supply.
In the previous chapters, ranges were established for rainfall, evaporation, reservoir capacity and seepage. All analyses in this chapter used combinations of the high and low ends of these ranges. When comparing total consumption with total supply, even the worst-case combination yielded enough water to meet the needs of the residents in the central 9 km² of Tikal. However, some combinations worked better than others. Also, in some sections of the central 9 km² of Tikal, the demand for water exceeded the supply.

Treating the central 9 km² of Tikal as a single unit would not have been sufficient to accurately estimate population, water consumption and water distribution. For instance, the characteristics of the epicentral zone with its elite residents would certainly have differed from areas outside of it. With this in mind, the central 9 km² of Tikal was divided into seven demographic zones as shown in Figure 4.1. The boundaries of the zones are based on Puleston's demographic analysis of Tikal.

The first of the five sections contained in this chapter (Population and the Demographics of Water Supply) discusses the demographics of the central 9 km² of Tikal, including population

---

4 In the case of monthly rainfall, an intermediate value, 125 mm, is sometimes substituted for the low end of the range, 116–167 mm. (The range is based on monthly averages derived from Table 1.2).
5 The worst-case scenario is the combination of the low end of the rainfall range (least possible accumulation of rainfall), the high end of the evaporation rate (greatest possible loss of water from reservoirs), the low end of the reservoir-capacity range (least amount of reserve for dry season), and the high end of the seepage range (greatest amount of loss of runoff from catchments).
6 Puleston divides Tikal into an epicenter, a central zone and a periphery (1974, pp. 20-24, f. 2). The detailed maps cover all of these zones. However, only the epicenter is completely shown by the maps.
estimates for that whole area and for each zone within that area. This section also shows how the reservoirs were distributed among the zones. The second section (Water Consumption) discusses water consumption rates based on class distinctions between residents of different zones. In the third section (Water Supply Versus Demand), the organization of the water supply and its overall relationship to demand is presented. In the fourth section (Simulation of One Year of Water Management at Tikal), a simulation of the interaction between water supply and demand is presented. The fifth section (Conclusion) contains a review of the process and concluding remarks.

FIGURE 4.1
Demographic Zones

KEY:
EC-Epicenter
NWC-Northwest Center
SEC-South & East Center
WP-West Periphery
EP-East Periphery
NWP-NW Periphery
SEP-SE Periphery
Population and the Demographics of Water Supply

The central 9 km² of Tikal is estimated to have held 9,782 people. Table 4.1 shows the distribution of this population by demographic zone. This estimate is based mostly on Haviland's study of Tikal's population, and partly on Puleston's own study of that site. Haviland's technique for estimating population is summarized below:

1) Count the number of structures. This can be done directly from the nine detailed Tikal maps.
2) Multiply (1) by the percent of visible structures believed to be occupied during the Late Classic (99%).
3) Multiply (2) by the percent of structures believed to be living quarters (83.5%).
4) Multiply (3) by the estimated number of inhabitants per structure (5.6).

Haviland applied his formula to all areas of Tikal except the epicenter. The following technique, based partly on research done by Harrison on functions of the structures in the Central

---

81974.
9Puleston's 1974 estimate (pp. 196, 205) was used instead of Haviland's 1965 estimate (p. 19) because it was based on more recent evidence. Puleston's estimate used ceramic evidence independent of the structure-based evidence used by Haviland.
10Haviland's 1965 estimate. This has not changed.
11This figure was determined from ethnographic surveys (Haviland 1965, p. 19; 1969, p. 429).
13Hammond (1988, pp. 186-197, 241-245) discusses how public architecture may be distinguished from private architecture in the center of Maya cities and provides some details of Harrison's research. His ideas underpin the population estimating technique I developed specifically for this study.
Acropolis, and partly on Puleston's idea that floor space and population are related, was developed to estimate the population in the epicenter.

1) Eliminate all obviously non-residential structures, such as temples and ballcourts.

2) Identify all palaces and their associated structures.

3) Estimate the number of inhabitants in a selected palace. Structure 5D165 (Maler's Palace) was estimated to have 15 occupants.

4) Using this palace as a benchmark, calculate the number of occupants in the remaining palaces by comparing their characteristics to the benchmark.

5) Apply Haviland's formula to those structures identified within the epicenter as normal-sized residences. This includes structures within palace compounds. Some palace-compound structures are as large as a palace. Directly estimate the number of occupants in these.

6) Add all estimates together.

A rule-of-thumb figure of 2% is sometimes used to calculate the number of elite living in a nonindustrial city, once its total

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14As reported by Hammond (1988, pp. 189, 243). Harrison estimated the Central Acropolis to have 200 residents. The technique employed here independently estimated a total of 216 residents.
151974, pp. 179-185. Puleston's idea was used, not his data.
16The best sources for information on this were Carr and Hazard's report (1961, pp. 17-20) and W. Coe's handbook (1967).
18The estimate is based on the amount of floor space in the palace and Harrison's functional description of it (Hammond 1988, p. 189, f. 6.7; Carr and Hazard 1961, maps).
<table>
<thead>
<tr>
<th>Zone</th>
<th>Population (For 9 km² = 9782)</th>
<th>Reservoirs (potable water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epicentral</td>
<td>Total population. 1861</td>
<td>Temple, Palace, Hidden, &quot;Floodgate&quot;, 3E1, 4C12, 4C4, 4D3, 6D1, 6D2, 6D3.</td>
</tr>
<tr>
<td></td>
<td>Number of residential strs. 185</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Residential population. 861</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of palaces and associated strs. 133</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Palace population. 1000</td>
<td></td>
</tr>
<tr>
<td>Northwest Central</td>
<td>Total population. 1721</td>
<td>Las Chamacas, 23C123, 2D1, 2E1, 2E1A, 2E2, 3B1, 3B2, 3C5, 3C6, 3C7.</td>
</tr>
<tr>
<td></td>
<td>Number of residential strs. 372</td>
<td></td>
</tr>
<tr>
<td>South and East Central</td>
<td>Total population. 4279</td>
<td>Madeira, Inscriptions, &quot;Bajo&quot;, &quot;Mendez&quot;, 4F1A, 4F2, 5F1, 6C5, 6D4, 6D6, 6E1, 6E2, 6F1, 6F5, 6F6, 7C1, 7C1A, 7C2, 7D1, 7F1, 7F2, 7G1, 7G2, 7G3.</td>
</tr>
<tr>
<td></td>
<td>Number of residential strs. 925</td>
<td></td>
</tr>
<tr>
<td>West Peripheral</td>
<td>Total population. 719</td>
<td>&quot;Canal&quot;, Pital, 4B1, 4C3, 5B3, 5B4, 5B5, 5B6, 5B7, 5C2, 5C3, 6B1, 6C1, 6C3, 7B2.</td>
</tr>
<tr>
<td></td>
<td>Number of residential strs. 128</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Residential population. 592</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of palaces and associated strs. 23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Palace population. 127</td>
<td></td>
</tr>
<tr>
<td>East Peripheral</td>
<td>Total population. 1059</td>
<td>4F3, 4F5.</td>
</tr>
<tr>
<td></td>
<td>Number of residential strs. 229</td>
<td></td>
</tr>
<tr>
<td>Northwest Peripheral</td>
<td>Total population. 74</td>
<td>No Reservoirs.</td>
</tr>
<tr>
<td></td>
<td>Number of residential strs. 16</td>
<td></td>
</tr>
<tr>
<td>Southeast Peripheral</td>
<td>Total population. 69</td>
<td>No Reservoirs.</td>
</tr>
<tr>
<td></td>
<td>Number of residential strs. 15</td>
<td></td>
</tr>
</tbody>
</table>
population has been estimated. A total of 1861 inhabitants are estimated to reside in the epicenter. Puleston states that up to 80,000 people may have lived at Tikal. The estimate for the epicenter is 2.3% of Puleston's maximum figure, which is fairly close to the rule-of-thumb percentage.

As discussed in the previous chapter, the reservoirs at Tikal can be separated into two groups, those that contained potable water and those that held water fit only for agriculture. Each potable water reservoir was linked with groups of structures on the basis of proximity. Reservoirs were assigned to separate zones based on these associations. (See Chapter 3 for a discussion of those reservoirs containing nonpotable water.)

Table 4.1 shows how the reservoirs are distributed among demographic zones. It can be seen that some zones contain many reservoirs while others contain few to none. Specifically, only one of the four peripheral zones contained enough reservoirs to store substantial quantities of water for the residents of that zone. The central zones and the epicenter had the bulk of reservoir storage. This imbalance suggests that centralized control of water resources existed at Tikal during the Late Classic period.

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19Scarborough 1990, personal communication.
20This would have included those residents of the epicenter closely associated with the elite, which are listed in Chapter 3 (Great Plaza section). Add to this list astronomers, butchers, weavers, curers, brewers, embalmers, tailors and other specialists who would not have left much for the archaeological record (Haviland 1970, p. 194).
211974, p. 207. His estimate was of the entire site of Tikal.
22Haviland also suggests this in his 1970 article on Tikal (p. 196).
In her demographic study\textsuperscript{23} of Terminal Classic\textsuperscript{24} Sayil,\textsuperscript{25} McAnany notes that \textit{chultuns},\textsuperscript{26} which supplied a critical source of potable water for the inhabitants in an area of \textit{no} surface water, could only be built in those parts of Sayil where the geomorphic conditions were suitable for their construction. She believes that a strong relationship existed between the location of residences and the location of chultuns.

Individual chultuns at Sayil provided water for groups no larger than 30.\textsuperscript{27} As will become clear in the next section, the larger reservoirs at Tikal could have each supported many times this amount. Clearly, the major reservoirs at Tikal were designed for public access while those at Sayil were for immediate kin. Unlike at Sayil where there is a spacial link between plaza groups and chultuns, at Tikal there is no clear spacial link between the smaller pozas (rough equivalents to chultuns in size) and residential structures. For example, the western periphery contains many reservoirs, but less overall residential structures than the eastern periphery. Inhabitants of both zones probably relied on the larger centralized public-access reservoirs. However, having pozas and quarry pits nearby still represented a distinct

\textsuperscript{23}McAnany, in press.
\textsuperscript{24}Circa A.D. 800.
\textsuperscript{25}Sayil is located in the Puuc region of the northern Yucatan, which is noted for its complete lack of surface water.
\textsuperscript{26}\textit{Chultuns} are underground storage chambers. Chultuns occurred at Tikal, too, but were fundamentally different from those at Sayil. The chultuns at Sayil were plaster-lined and were located to capture runoff from paved areas, thus being suitable as underground reservoirs. The chultuns at Tikal were neither plaster-lined nor located to capture runoff. They were not suitable as reservoirs. (McAnany, in press; Puleston 1965.)
\textsuperscript{27}McAnany, in press.
advantage for the residents of the western periphery. Unlike the 
eastern periphery in which all structures are normal-sized, the 
west contained a palace group (structures 6B18-6B40). This 
suggests that wealthier citizens lived in this part of Tikal.

It is likely that the terrain placed restrictions on the location of 
all type of reservoirs at Tikal. For instance, major reservoirs 
tended to be constructed in strategic parts of natural drainages. 
The Tikal, Corriental and projected reservoir 5B4 were all placed 
so as to receive the runoff from more than one drainage. The 
constructors of other major reservoirs took advantage of bajos 
(Bejucal, "Bajo"). Some took advantage of monumental 
architecture, which itself was constrained by the terrain. For 
example, the Hidden, "Mendez" and "Maler" reservoirs each abut 
causeways that are all situated on ridges. The locations for quarry 
pits were also not chosen by chance. Most evidence of quarry 
work is found on the sides of hills and ridges. Occasionally, a level 
piece of land contained enough good construction limestone to 
justify its extraction and the consequent creation of a pit.28 
Although less is known about the pozas, there is some evidence 
suggesting that they too were not arbitrarily placed. The scarcity 
of pozas in the eastern periphery versus the abundance of them in 
the western periphery may indicate that they were easier to 
create in the latter zone.

At Sayil, a very dependent relationship existed between 
chultuns and habitations. At Tikal, a much looser relationship

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existed between small pozas and households. Sayil lacked the large public-access reservoirs found at Tikal, so its residents had nothing to fall back on in time of need; they relied solely on the chultuns.29 Since the residents at Tikal could fall back on public-access reservoirs (at least theoretically), pozas became more of a commodity than a necessity, reflecting the wealth of those inhabitants who had one nearby. Research into the sociology of water indicates that strong links exist among wealth, access to, and consumption of water. For instance, White et al.30 studied such relationships in several different community types in East Africa and discovered that people living closer to sources of water tended to use more than those living further away.31 They also discovered that, in urban settings with medium-to-low population density, a strong correlation existed between per capita consumption of water and wealth.32 Tikal is roughly comparable to a small, low-density modern city, so it is possible that it had the same demographic characteristics of one.

Water Consumption

The foregoing discussion implies that different classes of people existed at Tikal. In terms of access to water, the residents of Tikal can be classified into three types: those who had direct access to water and controlled it (such as the epicenter-based elite and

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29 Natural underground sources of water called cenotes were available, but many were located deep in caves which made them difficult to access (McAnany, in press).
30 1972.
31 1972, pp. 128-130.
associated bureaucrats who administered the city-state and controlled the central-precinct reservoirs); those who had direct access to water but did not control it (such as the specialists who worked at the epicenter and lived nearby in the reservoir-rich central zones surrounding the epicenter); and those who depended on others for access to water at least during the dry season and perhaps year-round (such as the laborers and peasant farmers living in the peripheries with or without access to small, unreliable pozas). 33

Since White et al. have linked water consumption with wealth, and other researchers have linked its control with power, 34 it is likely that water consumption at Tikal was not the same for all classes. With this in mind, a three-tier, water-consumption rate scale was established to correspond with the three types of demographic zones discussed above. To make calculation easier, all the residents of a particular zone were considered to be of the same class. 35 A simple 2:1 ratio was used to numerically link the rate differences between zones. Thus, the elite class was likely to have consumed water at a rate four times faster than those at the bottom. Such a difference in the rates of consumption between

33 Shallow pozas tend to dry up quickly in the dry season (Scarborough and Gallopin 1990).
34 Scarborough (in press) discusses a range of possible relationships between political economy and control of water in pre-industrial societies, including Tikal. He sees water as being a potentially scarce, controllable resource capable of yielding power to those who control it.
35 There is one exception to this: the western periphery, which combined the lowest class with the highest. (See the Simulation section for details.)
urban dwellers and country folk is not exaggerated; ratios can be even higher.\textsuperscript{36}

The simple assumption that the present-day Maya peasant families most closely resemble those that lived at the peripheral zones at Tikal was used to establish a baseline rate of water consumption for the three-tier system. Matheny estimated that a typical extended Maya family of 12 used 200 liters (or 16.6 liters/person) during the dry season at Edzna, and that they used only half of that amount during the wet season. His estimate, however, did not include water for clothes washing, which is one of the nonagricultural water needs (hygiene) included in the criteria for evaluating H1 and H2. To compensate for this, his dry-season rate was turned into an average daily rate taking into account both wet and dry seasons. The new wet- and dry-season daily rates would have been 11.1 liters/person and 22.2 liters/person, respectively. Applying this to the three-tier system results in the following set of daily rates (in liters/person):

\begin{center}
\begin{tabular}{lccc}
  & wet & avg. & dry \\
Epicenter : & 11.1 & 16.6 & 22.2 \\
Center : & 22.2 & 33.2 & 44.4 \\
Periphery : & 44.4 & 66.4 & 88.8 \\
\end{tabular}
\end{center}

\textsuperscript{36}White et al. 1972, pp. 118, 119. The biggest ratios are between dwellings where water was piped in and those where it was not. The Maya elite at Tikal did not have this kind of technical advantage over the commoners, but they did have another kind of advantage over them—access to labor, which they could have used to constantly draw water from the central-precinct tanks.
Water Supply Versus Demand

As McAnany notes in her study of Sayil, water supply is determined both by amount of storage space in the storage media and by the amount of rainwater flowing into them. Table 4.2,\textsuperscript{37} reflects this notion by comparing both reservoir capacity and catchment flow with water consumption. In this way, each zone can be evaluated for its ability to meet droughts, as well as its capacity to refill reservoirs after droughts, while still supplying the daily needs of its inhabitants.

Taking the central 9 km\textsuperscript{2} of Tikal as a whole, the extant tanks would have been large enough to provide emergency drought water for the 9800 residents for about 6 months (assuming zero rainfall and a 10.7\% rate of water loss due to evaporation, the high-end percentage\textsuperscript{38} derived in Chapter 1). The projected tanks would have been large enough to provide emergency water for about 12 months. Since the original reservoirs certainly deteriorated over time, the extant versions of these reservoirs' capacities would not be an accurate representation of their original capacity.\textsuperscript{39} Furthermore, the extant-version reservoirs would not provide much insurance for the dry season in a region

\textsuperscript{37}The rainfall rate used for this table was derived from 1500 mm/year and is considered to be a reasonable low-end estimate for the southern Yucatan (see Chapter 1). A rate of 2000 mm/year, a reasonable high-end estimate for the region yielded rainfall accumulation values too high for the capacity of the roomier projected-version reservoirs. So it was abandoned.

\textsuperscript{38}Since evaporation rate is inversely related to rainfall (see Chapter 1), using a low-end rainfall rate (125 mm/month or 1500 mm/year is slightly above the low-end 1390 mm/year given in Table 1.2) warranted using a high-end evaporation rate.

\textsuperscript{39}The extant values served as rock bottom estimates and benchmarks by which to judge the projected dimensions of the reservoirs.
TABLE 4.2
Consumption Versus Reservoir Capacity and Catchment Flow

<table>
<thead>
<tr>
<th>Zone</th>
<th>Potable Water Used per Month (m³)</th>
<th>Combined Capacity (m³) extant projected</th>
<th>SUPPLY^40 Monthly Accumulation (based on 125 mm rainfall) (m³)</th>
<th>projected low</th>
<th>projected high</th>
<th>low seepage</th>
<th>high seepage</th>
<th>low seepage</th>
<th>high seepage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epicentral</td>
<td>3,707</td>
<td>69,072 181,588</td>
<td>26,923 27,127 36,867 37,071</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northwest Central</td>
<td>1,714</td>
<td>810 1,704</td>
<td>466 1,679 560 2,315</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S &amp; E Central</td>
<td>4,262</td>
<td>44,036 142,827</td>
<td>*9,691 *32,105 *14,880 *41,157</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Peripheral #516</td>
<td>1,337</td>
<td>2,493</td>
<td>1,079 3,600 1,104 3,605</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Peripheral</td>
<td>106</td>
<td>106</td>
<td>*49 *270 *49 *270</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northwest Peripheral</td>
<td>37</td>
<td>0 0</td>
<td>0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southeast Peripheral</td>
<td>34</td>
<td>0 0</td>
<td>0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>10,797</td>
<td>115,361 328,718</td>
<td>38,208 64,781 53,460 84,418</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*These values were derived by taking the calculated ranges and narrowing them in order to improve their reliability.\(^{41}\)

Derived by using the avg. epicenter rate for the 127 palace group residents, and the avg. periphery rate for the remaining 529 residents.

\(^{40}\)The ranges established in Chapters 2 and 3 were used along with the organization of potable water reservoirs shown on Table 4.1 to come up with the supply-side values for this table. Columns are based on the high and low ends of the ranges.

\(^{41}\)A rule-of-thumb ratio of 5:1 (high:low) was used as the cutoff point above which a range-narrowing technique was used to increase the low-end and decrease the high-end of any range. The result produced new values that were proportionally correct and fell within the original range. The following formula was used to derive the new values:

\[
x_2 = e^{\left(\left(\ln x_1 + \ln y_1 \right)/2\right) + \ln x_1}/2 \quad y_2 = e^{\left(\left(\ln x_1 + \ln y_1 \right)/2\right) + \ln y_1}/2
\]

\(x_1 = \) original low end of range; \(x_2 = \) new low end of range.

\(y_1 = \) original high end of range; \(y_2 = \) new high end of range.
where a *normal* dry year could bring as little as 195 mm of rain over a six-month stretch.\textsuperscript{42} For these reasons, the columns in Table 4.2 for the projected-version reservoirs will be used for the following analyses.

Of the seven zones, two had no reservoirs at all. Another two (Northwest Central and East Peripheral) had so little tank capacity that they must have been useless in the dry season. This leaves the Epicentral, South and East Central, and West Peripheral zones as the only ones with any dry-season reserve at all. Of these three, only the first two had substantial periods of reserve.\textsuperscript{43} The Western Peripheral Zone residents probably had a difficult time making it through the dry season without having to get some water from the central-precinct reservoirs.

At the end of the dry season, reservoirs have reached their lowest levels for the year or else are empty. Another measure of a zone was the ability of its reservoirs to quickly refill. In three of the five zones with reservoirs, there was sufficient rainwater flowing into reservoirs to meet resident needs and to refill the reservoirs at rates from less than one month to over one year. Of the other two, the East Peripheral Zone did not have sufficient

\textsuperscript{42}Matheny (1978, pp. 204-206) derived 6 months of reserve for Edzna, too. But his consumption rate was based on a population figure way above what is accepted as reasonable at that site, thus indirectly implying that the tanks there held enough reserve to last much longer for a more reasonably estimated population. Using his rate for water lost to evaporation and seepage alone, the reservoir would have emptied (< 5\%) in about 16 months. Adding a small consumption rate would have brought this figure closer to 12 months, which is what was estimated for the projected reservoirs at Tikal.

\textsuperscript{43}The Epicentral had a 16-17 month reserve, the South and East Central had a 13-14 month reserve, and the Western Peripheral had a 3-4 month reserve.
flow into the reservoirs to meet resident needs. Its residents had a year-round dependence on the central-precinct or residential reservoirs. The Northwest zone was marginal. Its high-end estimated inflow was sufficient to meet its needs, but its low-end estimated inflow was not.

Simulation of One Year of Water Management at Tikal

The only way to thoroughly understand the water system at Tikal would be to see it in action. Short of this, some of the dimensions of the system can be modeled to create a moving picture of it. In order to properly model this simulation, two preliminary steps had to be taken. First, a suitable set of values had to be provided for rainfall, evaporation, reservoir capacity and catchment size, population estimates and water consumption rates. Second, the relationship between people and reservoirs had to be clarified. The details of these steps have already been discussed in this and previous chapters. The following discussion ties up loose ends remaining from them, before proceeding to the simulation itself.

In the previous section, four sets of possible values based on the high and low ends of ranges calculated for reservoir capacity and catchment size represented water supply for the zones at Tikal. During the analysis in that section, two of the sets of values were rejected. Both of the two remaining sets were for projected reservoirs. One was based on low seepage rates and the other on high seepage rates.
The simulation is based on the set of data derived from high seepage rates. Choosing the data set based on the low-end seepage rates would imply that the residential tanks filled up almost as quickly as the central-precinct tanks. Unlike the central-precinct tanks, the residential tanks do not appear to have had a built in way of releasing water\textsuperscript{44} and could not have handled as rapid an inflow as the central-precinct tanks without overflowing. Choosing the data based on the low-end seepage rates would also imply that the non-paved surfaces were \textit{moderately} porous. This is inconsistent with documented accounts of the hydrology of the area (discussed in the Introduction) which indicate that non-paved surfaces, consisting mostly of loam-sand soil over karst were \textit{very} porous. Thus, the set of data based on high seepage rates (and on projected reservoirs) is more suitable for the simulation.

For purposes of this simulation, it is assumed that whatever rainfall the Maya collected in portable ceramic containers independent of the reservoirs did not have a major impact on the amounts of water being drawn from the reservoirs.\textsuperscript{45} As noted above, some zones lacked sufficient reservoir capacity to supply

\textsuperscript{44}The Inscriptions reservoir may have released water into the terminus of all residential reservoirs, the "Mendez." But unlike its central-precinct counterparts, if the "Mendez" had released water under its associated causeway, that water would have meandered through residential areas before reaching a bajo, because of the much lower gradient of its drainage. Also, no evidence of artificial drainage devices have been found downhill from the "Mendez," as was the case with the central-precinct reservoirs. Finally, the Madeira tank would have had no place for its drainage to go at all, since it is located in the middle of a dense residential area. See Chapters 2 and 3.

\textsuperscript{45}It is possible that the portion of water collected in this manner was significant. But there is no clear way of estimating it.
their residents. If the residents could not rely on portable ceramic containers alone to collect rainwater, and they lacked local reservoirs, then they must have been making trips to the closest available reservoirs. With this in mind, the zones are linked in the following way based on proximity and relative supply:

NW Peripheral ——> NW Central ——> Epicentral

Southeast Peripheral ————> S & E Central
+ East Peripheral

West Peripheral

Each of the relationships sketched above corresponds to one of the following tables. Table 4.3 represents the top relationship, where the water drawers of the Northwest Peripheral Zone depended on reservoirs in the Northwest Central Zone year-round, and the water drawers of the Northwest Central Zone (including the water drawers from the periphery) depended on the Epicentral (central-precinct) reservoirs during the dry season. Table 4.4 represents the second relationship, where the water drawers of the Southeast Peripheral Zone depended on reservoirs in the South & East Central Zone year-round, and the most of the water drawers of the East Peripheral Zone depended on reservoirs in the South & East Central Zone year-round, also. Table 4.5 represents the West Peripheral Zone, which did have problems meeting its demand during the dry season but may have, with judicious water management, remained water independent.
The simulation for each zone begins halfway through the rainy season and assumes that all tanks begin half-full. All water consumption rates were based on the dry and wet season rates shown in the Water Consumption section of this chapter. Dry season rates are applied to the six months with the lowest rainfall, December through May. Wet-season rates are used for the remaining months. (See the following tables.) The monthly rainfall rates used are derived from the first column of Table 2.1 (Puleston's data). \(^{46}\) Finally, all units in the following tables, besides rainfall, consumption rates and population, are cubic meters.

\(^{46}\)The rates are segmented into five sets. Each set has been formed by substituting the average of its elements for the elements themselves. This step clarified seasonal patterns and facilitated simulation calculations.
<table>
<thead>
<tr>
<th>Month</th>
<th>Rainfall (mm)</th>
<th>Cons. Rate (liters)</th>
<th>Water in Res. at Beg. of Month</th>
<th>Cons. Plus Evap.</th>
<th>Flow Into Month</th>
<th>Net at End of Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept</td>
<td>180</td>
<td>44.4</td>
<td>90,794</td>
<td>12,194</td>
<td>53,086</td>
<td>131,686</td>
</tr>
<tr>
<td>Oct</td>
<td>180</td>
<td>44.4</td>
<td>131,686</td>
<td>16,569</td>
<td>53,086</td>
<td>168,203</td>
</tr>
<tr>
<td>Nov</td>
<td>125</td>
<td>44.4</td>
<td>168,203</td>
<td>20,477</td>
<td>36,865</td>
<td>*181,588</td>
</tr>
<tr>
<td>Dec</td>
<td>40</td>
<td>88.8</td>
<td>181,588 #3656</td>
<td>29,170</td>
<td>11,797</td>
<td>164,215</td>
</tr>
<tr>
<td>Jan</td>
<td>40</td>
<td>88.8</td>
<td>164,215 #3656</td>
<td>27,311</td>
<td>11,797</td>
<td>148,701</td>
</tr>
<tr>
<td>Feb</td>
<td>40</td>
<td>88.8</td>
<td>148,701 #3656</td>
<td>25,651</td>
<td>11,797</td>
<td>134,847</td>
</tr>
<tr>
<td>Mar</td>
<td>40</td>
<td>88.8</td>
<td>134,847 #3656</td>
<td>24,168</td>
<td>11,797</td>
<td>122,476</td>
</tr>
<tr>
<td>Apr</td>
<td>80</td>
<td>88.8</td>
<td>122,476 #3656</td>
<td>22,845</td>
<td>23,594</td>
<td>123,225</td>
</tr>
<tr>
<td>May</td>
<td>80</td>
<td>88.8</td>
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<td>125,090</td>
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<tr>
<td>June</td>
<td>230</td>
<td>44.4</td>
<td>125,090 1861</td>
<td>15,863</td>
<td>67,855</td>
<td>177,082</td>
</tr>
<tr>
<td>July</td>
<td>230</td>
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<td>177,082 1861</td>
<td>21,427</td>
<td>67,855</td>
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</tr>
<tr>
<td>Aug</td>
<td>125</td>
<td>44.4</td>
<td>181,588 1861</td>
<td>21,909</td>
<td>36,865</td>
<td>*181,588</td>
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</table>

### Northwest Central & Northwest Peripheral

<table>
<thead>
<tr>
<th>Month</th>
<th>Cons. Rate (liters)</th>
<th>Water in Res. at Beg. of Month</th>
<th>Cons. Plus Evap.</th>
<th>Flow Into Month</th>
<th>Net at End of Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept</td>
<td>180</td>
<td>22.2</td>
<td>852 1795</td>
<td>1287</td>
<td>1168</td>
</tr>
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<td>22.2</td>
<td>733 1795</td>
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<td>1168</td>
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<tr>
<td>Nov</td>
<td>125</td>
<td>22.2</td>
<td>627 1795</td>
<td>1263</td>
<td>559</td>
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<tr>
<td>Dec</td>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>Jan</td>
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<td>106 #0</td>
<td>11</td>
<td>106</td>
</tr>
<tr>
<td>Feb</td>
<td>40</td>
<td>44.4</td>
<td>201 #0</td>
<td>22</td>
<td>106</td>
</tr>
<tr>
<td>Mar</td>
<td>40</td>
<td>44.4</td>
<td>285 #0</td>
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</tr>
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<td>361 #0</td>
<td>39</td>
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<td>1261</td>
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<td>125</td>
<td>22.2</td>
<td>1069 1795</td>
<td>1310</td>
<td>559</td>
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</table>

#At the end of November, reservoir levels fell below 25% of capacity in the NW Central Zone. All residents began to draw water from epicenter, inflating its consumption rate from December through May, when reservoirs in NW Central refilled sufficiently (over 25%) to allow water drawing from them again. By June, the NW Central reservoirs were handling the total NW Central and NW Peripheral demand.

*At end of November the central-precinct reservoirs were overflowing and the NW Central reservoirs were below 25%. At the end of April, the NW Central reservoirs refilled to over 25% capacity. In July and August, the central-precinct reservoirs were continuously sending spilloff to the Tikal Reservoir.
TABLE 4.4
South & East Central and Southeast Peripheral Water Management

<table>
<thead>
<tr>
<th>Month</th>
<th>Monthly Rainfall (mm)</th>
<th>Daily Cons. Rate (liters)</th>
<th>Water in Res. at Beg. of Month</th>
<th>Cons. Pop.</th>
<th>Flow into End of Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept</td>
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<td>71,419 #5379</td>
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<td>23,184</td>
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<tr>
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<td>12,503</td>
<td>23,184</td>
</tr>
<tr>
<td>Nov</td>
<td>125</td>
<td>22.2</td>
<td>94,055 5379</td>
<td>13,646</td>
<td>14,724</td>
</tr>
<tr>
<td>Dec</td>
<td>40</td>
<td>44.4</td>
<td>95,133 5379</td>
<td>17,344</td>
<td>3,775</td>
</tr>
<tr>
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<td>40</td>
<td>44.4</td>
<td>81,564 5379</td>
<td>15,893</td>
<td>3,775</td>
</tr>
<tr>
<td>Feb</td>
<td>40</td>
<td>44.4</td>
<td>69,446 5379</td>
<td>14,596</td>
<td>3,775</td>
</tr>
<tr>
<td>Mar</td>
<td>40</td>
<td>44.4</td>
<td>58,625 5379</td>
<td>13,441</td>
<td>3,775</td>
</tr>
<tr>
<td>Apr</td>
<td>80</td>
<td>44.4</td>
<td>48,959 #5407</td>
<td>12,444</td>
<td>8,929</td>
</tr>
<tr>
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<td>8,929</td>
</tr>
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<td>29,628</td>
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<tr>
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<td>22.2</td>
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<td>12,467</td>
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</table>

East Peripheral

<table>
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<tr>
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<th>Rainfall (mm)</th>
<th>Daily Cons. Rate (liters)</th>
<th>Water in Res. at Beg. of Month</th>
<th>Cons. Pop.</th>
<th>Flow into End of Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept</td>
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<td>11.1</td>
<td>52 #28</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>Oct</td>
<td>180</td>
<td>11.1</td>
<td>68 28</td>
<td>17</td>
<td>31</td>
</tr>
<tr>
<td>Nov</td>
<td>125</td>
<td>11.1</td>
<td>82 28</td>
<td>18</td>
<td>21</td>
</tr>
<tr>
<td>Dec</td>
<td>40</td>
<td>22.2</td>
<td>85 28</td>
<td>7</td>
<td>64</td>
</tr>
<tr>
<td>Jan</td>
<td>40</td>
<td>22.2</td>
<td>64 28</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Feb</td>
<td>40</td>
<td>22.2</td>
<td>46 28</td>
<td>7</td>
<td>29</td>
</tr>
<tr>
<td>Mar</td>
<td>40</td>
<td>22.2</td>
<td>29 28</td>
<td>7</td>
<td>*14</td>
</tr>
<tr>
<td>Apr</td>
<td>80</td>
<td>22.2</td>
<td>14 #0</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>May</td>
<td>80</td>
<td>22.2</td>
<td>27 #0</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>June</td>
<td>230</td>
<td>11.1</td>
<td>38 28</td>
<td>13</td>
<td>39</td>
</tr>
<tr>
<td>July</td>
<td>230</td>
<td>11.1</td>
<td>64 28</td>
<td>16</td>
<td>39</td>
</tr>
<tr>
<td>Aug</td>
<td>125</td>
<td>11.1</td>
<td>87 28</td>
<td>19</td>
<td>21</td>
</tr>
</tbody>
</table>

*From the East Peripheral Zone, 1031 inhabitants drew water from the (S & E Central) residential reservoirs year-round. During April and May, the remaining 28 inhabitants in the East Peripheral Zone drew water from the residential reservoirs.
*At the end of March, the East Peripheral reservoirs fell below 25% of capacity. By the end of May they had refilled to over 25% of capacity. Meanwhile, at the end of May, the residential reservoirs were at their lowest point, 30% of capacity.
TABLE 4.5
West Peripheral Water Management

<table>
<thead>
<tr>
<th>Month</th>
<th>Monthly Rainfall (mm)</th>
<th>Daily Cons. Rate (liters)</th>
<th>Water in Res. at Beg. of Month</th>
<th>Cons. Pop.</th>
<th>Evap.</th>
<th>Flow Into</th>
<th>Net at End of Month</th>
</tr>
</thead>
<tbody>
<tr>
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<td><strong>17.0</strong></td>
<td>1,247</td>
<td>719</td>
<td>500</td>
<td>1,695</td>
<td>2,442</td>
</tr>
<tr>
<td>Oct</td>
<td>180</td>
<td>17.0</td>
<td>2,442</td>
<td>719</td>
<td>628</td>
<td>1,695</td>
<td>*2,493</td>
</tr>
<tr>
<td>Nov</td>
<td>125</td>
<td>17.0</td>
<td>2,493</td>
<td>719</td>
<td>633</td>
<td>1,106</td>
<td>*2,493</td>
</tr>
<tr>
<td>Dec</td>
<td>40</td>
<td>34.0</td>
<td>2,493</td>
<td>719</td>
<td>1,000</td>
<td>282</td>
<td>1,775</td>
</tr>
<tr>
<td>Jan</td>
<td>40</td>
<td>34.0</td>
<td>1,775</td>
<td>719</td>
<td>923</td>
<td>282</td>
<td>1,134</td>
</tr>
<tr>
<td>Feb</td>
<td>40</td>
<td>34.0</td>
<td>1,134</td>
<td>719</td>
<td>855</td>
<td>282</td>
<td>*561</td>
</tr>
<tr>
<td>Mar</td>
<td>40</td>
<td><strong>88.8</strong></td>
<td>561</td>
<td>#127</td>
<td>398</td>
<td>282</td>
<td>445</td>
</tr>
<tr>
<td>Apr</td>
<td>80</td>
<td><strong>88.8</strong></td>
<td>445</td>
<td>#127</td>
<td>386</td>
<td>939</td>
<td>*998</td>
</tr>
<tr>
<td>May</td>
<td>80</td>
<td>34.0</td>
<td>998</td>
<td>719</td>
<td>840</td>
<td>939</td>
<td>1,097</td>
</tr>
<tr>
<td>June</td>
<td>230</td>
<td>17.0</td>
<td>1,097</td>
<td>719</td>
<td>849</td>
<td>2,262</td>
<td>*2,493</td>
</tr>
<tr>
<td>July</td>
<td>230</td>
<td>17.0</td>
<td>2,493</td>
<td>719</td>
<td>1,000</td>
<td>2,262</td>
<td>*2,493</td>
</tr>
<tr>
<td>Aug</td>
<td>125</td>
<td>17.0</td>
<td>2,493</td>
<td>719</td>
<td>1,000</td>
<td>1,106</td>
<td>*2,493</td>
</tr>
</tbody>
</table>

**During all the months of the year except March and April, the water consumption rate was based on 592 commoners consuming at peripheral levels and 127 palace elite consuming at epicenter levels. Since all of the residents remaining in March and April lived in the palace group, average water consumption rates went up to epicenter levels. #592 commoners had to rely on other sources for water during March and April. The tanks fell below 25% capacity at the end of February and were back over 25% at the end of April. The tanks overflowed in June, July, August, (September), October and November, creating a potential surplus.**
A quick scan of the tables shows that the water management system that was strained the least was the epicentral system, suggesting that the elite were in a position to distribute even more water if it became necessary or desirable. One way to measure this strain was to observe how close the reservoir capacity came to falling below acceptable levels. A benchmark figure of 25% of capacity is used as the minimum acceptable reservoir level. Below this level, water was considered to be unfit to drink,\textsuperscript{47} and many of the smaller reservoirs would have already dried up. At this point, alternative sources would have been used until the reservoirs filled up to levels above 25% of capacity. The total reservoir capacity in the Epicentral system (containing the central-precinct reservoirs) was always over 65% full, while the South & East Central system (containing the residential reservoirs) was dangerously close to the 25% minimum.

The West Peripheral levels fell under the minimum, suggesting that, although in terms of gross quantities they seemed to have enough water to be independent, the dynamics of fluctuating supply and demand left them short of water. They simply did not have large enough tanks to take advantage of what could have been a surplus situation. But they may have had hidden resources. Besides the obvious possibility that they may have had more reservoir capacity than was calculated for this model, it is

\textsuperscript{47}Although an exact level is not given, White et al. do note that partially dried-up water sources present greater health risks than full ones (1972, pp. 177-187).
possible that the Maya living here used other means of storage or that they traded their surplus of water to others who needed it, building up credit to later buy back water when it was needed. The fact that they did have a potential surplus put them in a better position than those in marginal areas with no surplus.

Conclusion

While the specific purpose of this thesis is to answer the simple question about the sufficiency of an artificially created water supply in a Pre-Columbian Maya city, the overall purpose is to illuminate the structure and dynamics of water management at such a place. The portion of Tikal discussed in this study is only a fraction of the size of the total site. But if the structure and dynamics has been modelled correctly for this portion, then the rest of the site simply becomes additional information to plug into the model, because this portion contains the entire range of settlement patterns found at Tikal. Furthermore, if Tikal has been correctly modelled here, then other Maya cities with similar ecological and political situations also become additional information for the water management model, perhaps fine tuning the model but not altering it in any significant way. This study has potentially created a model that can retrodict the nature of water supply and demand for an entire class of Maya cities.

To briefly review the process followed in this thesis, first, the ecological and political setting of Tikal was sketched. Tikal had a political need for a water supply independent of natural sources. It was located in an area where, with no modification of the
environment, only small settlements clustered around small natural water sources could be supported. However, with some modification of the natural environment, it was possible to take advantage of yearly rainfall capable of supporting cities with core concentrations of over 1000/km².48

Second, the details of the system used to take advantage of the rainfall was examined in detail. The Maya used technology developed at other sites to create a number of large reservoirs capable of collecting rainfall sufficient for their needs. Other smaller reservoirs were also noted on maps of Tikal. Some of the reservoirs were located in settings that suggested that they were used for agricultural purposes. Some of the reservoirs were associated with remnants of artificial drainage systems that showed that the Maya had become sophisticated water managers.

Previous research into population at Tikal was used to estimate population in the central 9 km², and to divide Tikal into zones differentiated by population concentration and class of resident. Investigations by other scientists into water consumption, insights into the link between settlement patterns and reservoir location, and evidence of a class system at Tikal were all used to derive a stratified scale of water consumption rates.

At Tikal, an elite existed who were capable of controlling the collection and distribution of rainwater in the large tanks. However, their control was not absolute because smaller localized

48 9782 people/9 km². Overall densities at Tikal are lower, and the lowland Classic Maya region is not noted for the kinds of nucleation that were present at Pre-Columbian cities in highland Mexico.
tanks were capable of providing the nearest inhabitants with water for a portion of the year. In some cases, these noncentralized groups appeared to be capable of existing independently of a ruling elite at Tikal; in effect, thumbling their noses at them and being able to say that they could not be controlled through the manipulation of water supplies. However, when a simple simulation is conducted with the compiled data, it becomes evident that this seemingly independent group would have had trouble staying completely independent of the elite, who controlled large central-precinct tanks already supporting most of the population of central Tikal. Even so, having a contentious group so close to the heart of Tikal indicates that the leaders' power was far from absolute.

This model of a partly dependent population is consistent with other findings at Tikal that point to a loosely centralized pan-Maya political system in which politically powerful groups and economically powerful groups competed and cooperated with each other in an attempt to control a populace who were not as docile as they might have wished. Even with the roughness of the estimates used in this model, when put into practice the model "worked"; it did not spiral out of control or completely collapse. One of the byproducts of this thesis is that the data collected on the reservoirs can become the foundation of a more elaborate data base that would include other Maya sites as well as further information on Tikal. If this data base were computerized, then many more simulations could be run of the type presented here.
Bibliography


Appendix A: The Derivation of Reservoir Capacities

The purpose of this appendix was to provide interested readers a way of checking my calculations. The appendix contains the sources for and detailed calculations of the volumes and surface areas for the extant and projected reservoirs listed in Chapter 2. Estimated depths of reservoirs have been included as well. The data is arranged in tabular form.

Most of the reservoir capacity data was generated in one of three ways:

1) Some extant reservoir estimates were taken directly from *Tikal Report No. 11.*\(^1\) Examples of this include extant reservoirs 3C4 and 2E5.

2) The projected deeper artificial reservoirs were measured by taking the surface area of each of its projected interior contours\(^2\) and multiplying each of them by 1 meter (creating in effect a stack of 1 meter layers). Examples of this include projected reservoirs 3C4 and 4F4.

3) Most of the smaller and shallower reservoirs (both extant and projected) were estimated by taking the formula for an elliptical cone, \(H(1/3)\pi(A/2)(B/2)\), where \(H\) is the height and \(A\) and \(B\) are the length and width of the ellipse, respectively, and modifying it to accommodate the fact that the basins tended to be more

---

\(^1\) Carr and Hazard 1961, p. 24.

\(^2\) Projected contours are derived from the Tikal maps (Carr and Hazard 1961). The contour lines showing depressions on the maps were used as a starting point to which other considerations were added, such as architecture and evidence of erosion.
spherical in shape. The derived formula, \( H^{(1/2)}\pi(A/2)(B/2) \), was used for most of the smaller reservoirs. However, some of the quarry pits were measured by using the original formula for a cone, because they tended to be more conical than other small reservoirs.

Irregular surface areas were measured directly from the maps using a planimeter. Regular elliptical areas were measured by using the formula \( \pi(A/2)(B/2) \). See Chapter 2 for a discussion about the derivation of projected reservoir depths.

Occasionally there was an unusually shaped reservoir (like 6D5). Unusual cases are commented on in the following table.

(Projected reservoirs are designated by following the reservoir identification number with "(p).")

---

\(^3\)The formula for a hemisphere is \( H^{(2/3)}\pi(A/2)(B/2) \), where \( A=B \). The derived formula used a constant \((1/2)\), which was halfway between the constants \((1/3)\) and \((2/3)\) of the formulas for a cone and a hemisphere, respectively.
<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Volume (m$^3$)</th>
<th>Surface Area (m$^2$)</th>
<th>Depth (m)</th>
</tr>
</thead>
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<td>$\pi \times (5/2) \times (5/2)$</td>
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</tr>
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<td>$\pi \times (6/2) \times (6/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>2C1</td>
<td>$1 \times (1/2) \times \pi \times (5/2) \times (5/2)$</td>
<td>$\pi \times (5/2) \times (5/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>3C1</td>
<td>$1 \times (1/2) \times \pi \times (6/2) \times (6/2)$</td>
<td>$\pi \times (6/2) \times (6/2)$</td>
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</tr>
<tr>
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<td>$\pi \times (26/2) \times (16/2)$</td>
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</tr>
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</tr>
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<td>$\pi \times (15/2) \times (12/2)$</td>
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</tr>
<tr>
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<td>$\pi \times (7/2) \times (7/2)$</td>
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</tr>
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<td>same as 3B1</td>
<td>same</td>
</tr>
<tr>
<td>3B2(p)</td>
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<td>same as 3B2</td>
<td>same</td>
</tr>
<tr>
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<td>1 × (planimeter of estimated contour at 213 m)</td>
<td>planimeter of estimated contour at 213 m</td>
<td>1.0</td>
</tr>
<tr>
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<td>(213 m) 15,584</td>
<td>planimeter at 213 m</td>
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</tr>
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<tr>
<td>2D1</td>
<td>$1 \times (1/2) \times \pi \times (12/2) \times (10/2)$</td>
<td>$\pi \times (12/2) \times (10/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>2E1</td>
<td>$1 \times (1/2) \times \pi \times (12/2) \times (9/2)$</td>
<td>$\pi \times (12/2) \times (9/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>2E2</td>
<td>$1 \times (1/2) \times \pi \times (5/2) \times (5/2)$</td>
<td>$\pi \times (5/2) \times (5/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>2E3</td>
<td>$1 \times (1/2) \times \pi \times (10/2) \times (4/2)$</td>
<td>$\pi \times (10/2) \times (4/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>2E4</td>
<td>$1 \times (1/2) \times \pi \times (8/2) \times (5/2)$</td>
<td>$\pi \times (8/2) \times (5/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>2E5</td>
<td>Carr &amp; Hazard, p. 24</td>
<td>planimeter at intermittent reservoir line (209 m)</td>
<td>1.0</td>
</tr>
<tr>
<td>Reservoir</td>
<td>Volume (m$^3$)</td>
<td>Surface Area (m$^2$)</td>
<td>Depth (m)</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------</td>
<td>----------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>3E1</td>
<td>$(2 \times (1/2) \times \pi \times (20/2) \times (15/2)) \times (1/2)^*$</td>
<td>$(\pi \times (20/2) \times (15/2)) \times (1/2)$</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>*This register is shaped as a semi-ellipse so the full ellipse is calculated and cut in half</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2D1(p)</td>
<td>same as 2D1</td>
<td>same as 2D1</td>
<td>same</td>
</tr>
<tr>
<td>2E1(p)</td>
<td>same as 2E1</td>
<td>same as 2E1</td>
<td>same</td>
</tr>
<tr>
<td>2E1A(p)</td>
<td>$1 \times (1/2) \times \pi \times (48/2) \times (4/2)$</td>
<td>$\pi \times (48/2) \times (4/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>2E2(p)</td>
<td>$2 \times (1/2) \times \pi \times (10/2) \times (4/2)$</td>
<td>$\pi \times (10/2) \times (4/2)$</td>
<td>2.0</td>
</tr>
<tr>
<td>2E34(p)</td>
<td>$1 \times \pi \times (12/2) \times (7/2)^*$</td>
<td>$\pi \times (12/2) \times (7/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>*shaped like a 1 m deep cylinder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2E5(p)</td>
<td>same as 2E5</td>
<td>same as 2E5</td>
<td>same</td>
</tr>
<tr>
<td>3E1(p)</td>
<td>same as 3E1</td>
<td>same as 3E1</td>
<td>same</td>
</tr>
<tr>
<td>4F1</td>
<td>(modern quarry; not included as ancient reservoir)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4F2</td>
<td>$1 \times (1/2) \times \pi \times (5/2) \times (5/2)$</td>
<td>$\pi \times (5/2) \times (5/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>4F3</td>
<td>$1 \times (1/2) \times \pi \times (10/2) \times (5/2)$</td>
<td>$\pi \times (10/2) \times (5/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>4F4</td>
<td>Carr &amp; Hazard, p. 24</td>
<td>planimeter at 197 m contour</td>
<td>3.0</td>
</tr>
<tr>
<td>4F5</td>
<td>$2 \times (1/2) \times \pi \times (15/2) \times (11/2)$</td>
<td>$\pi \times (15/2) \times (11/2)$</td>
<td>2.0</td>
</tr>
<tr>
<td>5F1</td>
<td>$1 \times (1/2) \times \pi \times (12/2) \times (9/2)$</td>
<td>$\pi \times (12/2) \times (9/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>4F1A(p)</td>
<td>$1 \times (1/2) \times \pi \times (10/2) \times (12/2)$</td>
<td>$\pi \times (10/2) \times (12/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>4F2(p)</td>
<td>same as 4F2</td>
<td>same as 4F2</td>
<td>same</td>
</tr>
<tr>
<td>4F3(p)</td>
<td>same as 4F3</td>
<td>same as 4F3</td>
<td>same</td>
</tr>
<tr>
<td>4F4(p)</td>
<td>(200 m) 17,675 + (199 m) 16,610 + (198 m) 15,701 + (197 m) 12,948 + (196 m) 12,208 + (195 m) 11,900</td>
<td>planimeter at estimated 200 m contour line</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>(contours are estimated)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4F5(p)</td>
<td>same as 4F5</td>
<td>same as 4F5</td>
<td>same</td>
</tr>
<tr>
<td>5F1(p)</td>
<td>same as 5F1</td>
<td>same as 5F1</td>
<td>same</td>
</tr>
<tr>
<td>6F1</td>
<td>$1 \times (1/2) \times \pi \times (10/2) \times (10/2)$</td>
<td>$\pi \times (10/2) \times (10/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>Reservoir</td>
<td>Volume (m^3)</td>
<td>Surface Area (m^2)</td>
<td>Depth (m)</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>--------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>6F2</td>
<td>(207 m) 12,213 + (206 m) 4,426 + (205 m) 4,011</td>
<td>planimeter at 207 m</td>
<td>3.0</td>
</tr>
<tr>
<td>6F3</td>
<td>1 \times (1/2) \times \pi \times (41/2) \times (21/2)</td>
<td>\pi \times (41/2) \times (21/2)</td>
<td>1.0</td>
</tr>
<tr>
<td>6F4</td>
<td>Carr &amp; Hazard, p. 24</td>
<td>planimeter at 211 m</td>
<td>2.6</td>
</tr>
<tr>
<td>6F5</td>
<td>1 \times (1/2) \times \pi \times (22/2) \times (20/2)</td>
<td>\pi \times (22/2) \times (20/2)</td>
<td>1.0</td>
</tr>
<tr>
<td>6F6</td>
<td>1 \times (1/2) \times \pi \times (22/2) \times (18/2)</td>
<td>\pi \times (22/2) \times (18/2)</td>
<td>1.0</td>
</tr>
<tr>
<td>7F1</td>
<td>.7 \times (1/2) \times \pi \times (30/2) \times (15/2)</td>
<td>\pi \times (30/2) \times (15/2)</td>
<td>0.7</td>
</tr>
<tr>
<td>7F2</td>
<td>1 \times (1/2) \times \pi \times (16/2) \times (15/2)</td>
<td>\pi \times (16/2) \times (15/2)</td>
<td>1.0</td>
</tr>
<tr>
<td>7G1</td>
<td>.7 \times (1/2) \times \pi \times (30/2) \times (15/2)</td>
<td>\pi \times (30/2) \times (15/2)</td>
<td>0.7</td>
</tr>
<tr>
<td>7G2</td>
<td>1 \times (1/2) \times \pi \times (10/2) \times (10/2)</td>
<td>\pi \times (10/2) \times (10/2)</td>
<td>1.0</td>
</tr>
<tr>
<td>7G3</td>
<td>1 \times (1/2) \times \pi \times (12/2) \times (6/2)</td>
<td>\pi \times (12/2) \times (6/2)</td>
<td>1.0</td>
</tr>
<tr>
<td>6F1(p)</td>
<td>same as 6F1</td>
<td>same as 6F1</td>
<td>same</td>
</tr>
<tr>
<td>6F23(p)</td>
<td>(210 m) 28,838 + (209 m) 22,891 + (208 m) 17,732 + (207 m) 14,841 + (206 m) 6,542 + (205 m) 4,011</td>
<td>planimeter at estimated 210 m contour line</td>
<td>6.0</td>
</tr>
<tr>
<td>6F4(p)</td>
<td>1 \times (planimeter at estimated 212 m contour) + Carr &amp; Hazard, p. 24</td>
<td>planimeter of estimated 212 m contour</td>
<td>3.6</td>
</tr>
<tr>
<td>6F5(p)</td>
<td>same as 6F5</td>
<td>same as 6F5</td>
<td>same</td>
</tr>
<tr>
<td>6F6(p)</td>
<td>same as 6F6</td>
<td>same as 6F6</td>
<td>same</td>
</tr>
<tr>
<td>7F1(p)</td>
<td>1.7 \times (1/2) \times \pi \times (40/2) \times (20/2)</td>
<td>\pi \times (40/2) \times (20/2)</td>
<td>1.7</td>
</tr>
<tr>
<td>7F2(p)</td>
<td>same as 7F2</td>
<td>same as 7F2</td>
<td>same</td>
</tr>
<tr>
<td>7G1(p)</td>
<td>1.7 \times (1/2) \times \pi \times (52/2) \times (30/2)</td>
<td>\pi \times (52/2) \times (30/2)</td>
<td>1.7</td>
</tr>
<tr>
<td>7G2(p)</td>
<td>same as 7G2</td>
<td>same as 7G2</td>
<td>same</td>
</tr>
<tr>
<td>7G3(p)</td>
<td>same as 7G3</td>
<td>same as 7G3</td>
<td>same</td>
</tr>
<tr>
<td>6D1</td>
<td>1 \times (1/2) \times \pi \times (30/2) \times (10/2)</td>
<td>\pi \times (30/2) \times (10/2)</td>
<td>1.0</td>
</tr>
<tr>
<td>6D2</td>
<td>1 \times (1/2) \times \pi \times (5/2) \times (5/2)</td>
<td>\pi \times (5/2) \times (5/2)</td>
<td>1.0</td>
</tr>
<tr>
<td>Reservoir</td>
<td>Volume ( (m^3) )</td>
<td>Surface Area ( (m^2) )</td>
<td>Depth ( (m) )</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------------</td>
<td>---------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>6D3</td>
<td>( 1 \times (1/2) \times \pi \times (5/2) \times (5/2) )</td>
<td>( \pi \times (5/2) \times (5/2) )</td>
<td>1.0</td>
</tr>
<tr>
<td>6D4</td>
<td>( 1 \times (1/2) \times \pi \times (12/2) \times (5/2) )</td>
<td>( \pi \times (12/2) \times (5/2) )</td>
<td>1.0</td>
</tr>
<tr>
<td>6D5</td>
<td>Carr &amp; Hazard, p. 24</td>
<td>planimeter at 248 m contour line</td>
<td>4.2</td>
</tr>
<tr>
<td>6D6</td>
<td>( 1 \times (1/2) \times \pi \times (18/2) \times (10/2) )</td>
<td>( \pi \times (18/2) \times (10/2) )</td>
<td>1.0</td>
</tr>
<tr>
<td>6E1</td>
<td>( 1 \times (1/2) \times \pi \times (10/2) \times (5/2) )</td>
<td>( \pi \times (10/2) \times (5/2) )</td>
<td>1.0</td>
</tr>
<tr>
<td>6E2</td>
<td>( 1 \times (1/2) \times \pi \times (10/2) \times (7/2) )</td>
<td>( \pi \times (10/2) \times (7/2) )</td>
<td>1.0</td>
</tr>
<tr>
<td>7D1</td>
<td>( 1 \times (1/2) \times \pi \times (11/2) \times (5/2) )</td>
<td>( \pi \times (11/2) \times (5/2) )</td>
<td>1.0</td>
</tr>
<tr>
<td>7E1</td>
<td>Carr &amp; Hazard, p. 24</td>
<td>planimeter at intermittent reservoir line (204 m)</td>
<td>1.1</td>
</tr>
<tr>
<td>6D1(p)</td>
<td>same as 6D1</td>
<td>same as 6D1</td>
<td>same</td>
</tr>
<tr>
<td>6D2(p)</td>
<td>same as 6D2</td>
<td>same as 6D2</td>
<td>same</td>
</tr>
<tr>
<td>6D3(p)</td>
<td>same as 6D3</td>
<td>same as 6D3</td>
<td>same</td>
</tr>
<tr>
<td>6D4(p)</td>
<td>same as 6D4</td>
<td>same as 6D4</td>
<td>same</td>
</tr>
<tr>
<td>6D5(p)</td>
<td>rhombus surface top ( 40 \times 55 )</td>
<td>rhombus surface ( 40 \times 55 )</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>rhombus surface bottom ( 30 \times 40 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>trapezoid cross section</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>height = 6 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6D6(p)</td>
<td>( 1 \times ) (planimeter at estimated 234 m contour) + 6D6</td>
<td>planimeter at estimated 234 m contour</td>
<td>2.0</td>
</tr>
<tr>
<td>6E1(p)</td>
<td>same as 6E1</td>
<td>same as 6E1</td>
<td>same</td>
</tr>
<tr>
<td>6E2(p)</td>
<td>same as 6E2</td>
<td>same as 6E2</td>
<td>same</td>
</tr>
<tr>
<td>7D1(p)</td>
<td>same as 7D1</td>
<td>same as 7D1</td>
<td>same</td>
</tr>
<tr>
<td>7D1A(p)</td>
<td>( 1 \times ) (planimeter at line circumscribing bajo in 7D)</td>
<td>planimeter at line circumscribing bajo in 7D</td>
<td>1.0</td>
</tr>
<tr>
<td>7E1(p)</td>
<td>( (208 \text{ m}) 15,145 + (207 \text{ m}) 13,416 + (206 \text{ m}) 11,618 + (205 \text{ m}) 10,775 + (204 \text{ m}) 7,469 + 1 \times (203 \text{ m}) 1,130 )</td>
<td>planimeter at estimated 208 m contour</td>
<td>5.1</td>
</tr>
<tr>
<td>Reservoir</td>
<td>Volume (m$^3$)</td>
<td>Surface Area (m$^2$)</td>
<td>Depth (m)</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
<td>----------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>6B1</td>
<td>$2 \times \frac{1}{3} \pi \times (32/2) \times (10/2)$ + $1 \times \frac{1}{2} \pi \times (20/2) \times (10/2)$</td>
<td>$\pi \times (32/2) \times (10/2)$ + $\pi \times (20/2) \times (10/2)$</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>reservoir split into 2 ellipses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6C1</td>
<td>$1 \times \frac{1}{2} \pi \times (30/2) \times (10/2)$</td>
<td>$\pi \times (30/2) \times (10/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>6C2</td>
<td>$1 \times \frac{1}{2} \pi \times (10/2) \times (10/2)$</td>
<td>$\pi \times (10/2) \times (10/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>6C3</td>
<td>$1 \times \frac{1}{2} \pi \times (10/2) \times (7/2)$</td>
<td>$\pi \times (10/2) \times (7/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>6C4</td>
<td>Carr &amp; Hazard, p. 24</td>
<td>planimeter at line deliniating retaining wall</td>
<td>1.0</td>
</tr>
<tr>
<td>6C5</td>
<td>$1 \times \frac{1}{2} \pi \times (28/2) \times (25/2)$</td>
<td>$\pi \times (28/2) \times (25/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>7B1</td>
<td>Carr &amp; Hazard, p. 24</td>
<td>planimeter at intermittent reservoir line (225 m)</td>
<td>1.1</td>
</tr>
<tr>
<td>7B2</td>
<td>$1 \times \frac{1}{2} \pi \times (11/2) \times (10/2)$</td>
<td>$\pi \times (11/2) \times (10/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>7C1</td>
<td>$1 \times \frac{1}{2} \pi \times (23/2) \times (12/2)$ + $1 \times \frac{1}{2} \pi \times (17/2) \times (5/2)$</td>
<td>$\pi \times (23/2) \times (12/2)$ + $\pi \times (17/2) \times (5/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>7C2</td>
<td>$1 \times \frac{1}{2} \pi \times (10/2) \times (6/2)$</td>
<td>$\pi \times (10/2) \times (6/2)$</td>
<td>0.1</td>
</tr>
<tr>
<td>6B1(p)</td>
<td>same as 6B1</td>
<td>same as 6B1</td>
<td>same</td>
</tr>
<tr>
<td>6C1(p)</td>
<td>same as 6C1</td>
<td>same as 6C1</td>
<td>same</td>
</tr>
<tr>
<td>6C2(p)</td>
<td>same as 6C2</td>
<td>same as 6C2</td>
<td>same</td>
</tr>
<tr>
<td>6C3(p)</td>
<td>$1 \times \frac{1}{2} \pi \times (17/2) \times (10/2) + 6C3$</td>
<td>$\pi \times (17/2) \times (10/2)$</td>
<td>2.0</td>
</tr>
<tr>
<td>6C4(p)</td>
<td>same as 6C4 with depth increased to 1.5 m</td>
<td>same as 6C4</td>
<td>1.5</td>
</tr>
<tr>
<td>6C5(p)</td>
<td>same as 6C5</td>
<td>same as 6C5</td>
<td>same</td>
</tr>
<tr>
<td>7B1(p)</td>
<td>same as 7B1</td>
<td>same as 7B1</td>
<td>same</td>
</tr>
<tr>
<td>7B2(p)</td>
<td>same as 7B2</td>
<td>same as 7B2</td>
<td>same</td>
</tr>
<tr>
<td>7C1(p)</td>
<td>same as 7C1</td>
<td>same as 7C1</td>
<td>same</td>
</tr>
<tr>
<td>7C1A(p)</td>
<td>$1 \times \frac{1}{2} \pi \times (25/2) \times (18/2)$</td>
<td>$\pi \times (25/2) \times (18/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>7C2(p)</td>
<td>same as 7C2</td>
<td>same as 7C2</td>
<td>same</td>
</tr>
<tr>
<td>4B1</td>
<td>$1 \times \frac{1}{2} \pi \times (14/2) \times (11/2)$</td>
<td>$\pi \times (14/2) \times (11/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>4B2</td>
<td>Carr &amp; Hazard, p. 24</td>
<td>planimeter (242 m)</td>
<td>1.0</td>
</tr>
<tr>
<td>4C1</td>
<td>$1 \times \frac{1}{2} \pi \times (45/2) \times (12/2)$</td>
<td>$\pi \times (45/2) \times (12/2)$</td>
<td>1.0</td>
</tr>
<tr>
<td>Reservoir</td>
<td>Volume (m$^3$)</td>
<td>Surface Area (m$^2$)</td>
<td>Depth (m)</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
<td>----------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>4C2</td>
<td>$1 \times (1/2) \times \pi \times (18/2) \times (15/2)$</td>
<td>$\pi \times (18/2) \times (15/2)$</td>
<td>1.0</td>
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<td>same as 5D1</td>
<td>same as 5D1</td>
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<tr>
<td>Reservoir</td>
<td>Volume (m³)</td>
<td>Surface Area (m²)</td>
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<td>planimeter at 227 m</td>
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Appendix B: Calculating Seepage Rates

This appendix contains the details of how the seepage rates were generated for map squares shown in the figures for each quadrangle in Chapter 3. The calculations presented here were based on the assumption that nonperishable architecture, paved areas, reservoirs and bajos all contained 100% impermeable surfaces.

The two tables in the appendix are based on those map squares that contained reservoirs. The first table presents the first part of the calculations, which involved determining what percent of each map square was covered by impermeable surfaces. Each column represents the percent of a square covered by surfaces considered to be nonporous. The first column represents that portion of the map square which fell within the epicenter.\(^1\) Figure 2.2 in Chapter 2 shows epicentral Tikal. The map upon which the figure is based\(^2\) was used as a guide to determine how much of a map square fell inside the epicenter. The second column represents that portion covered by bajos.\(^3\) Bajos are shown on the maps of Tikal.\(^4\) They were outlined and a planimeter was used to measure the total percentage of a map square covered by them. Column

---

\(^1\) Epicentral Tikal is considered to have been fully paved and heavily trafficked. The constant pounding of human feet would have kept the surface hard and compact. See Chapter 2, footnote 19, for a detailed discussion of documented evidence for the virtually complete covering of the epicenter with impermeable plaster.


\(^3\) Bajos rested on top of thick impermeable clay beds (Puleston 1974, pp. 258, 261).

\(^4\) Carr and Hazard 1961.
three contains the percentage of map squares covered by major 
architectural features with plaster surfaces. Such features include 
causeways and major reservoirs. A planimeter was used to 
measure them as well. The fourth column contains the percentage 
of a map square covered by residential structures.\textsuperscript{5} Structures 
were assumed to each have an average of 100 m\textsuperscript{2} of floor area. 
The number of structures\textsuperscript{6} inside a map square, but not within 
portions of the map square containing the epicenter, bajos or 
major features (paved portions already accounted for in the first 
three columns), were counted. This number was multiplied by 
100 to obtain total square feet of coverage. This number was then 
turned into a percentage.\textsuperscript{7}

The second table contains intermediate data used to calculate 
the seepage rates shown in the last column. Once the 
impermeable portions of map squares were calculated, the 
remaining portion (shown in column three of the second table) 
was considered to be where runoff was lost due to seepage. Once 
raw permeability was calculated for the porous portion of the 
square, it was multiplied by the percentage of porous surface in 
the map square to get a net seepage rate for the whole square.

Calculating raw permeability consisted of gleaning an average 
coefficient of permeability for all permeable areas of Tikal, 
calculating gradients for each map square, and then dividing the

\textsuperscript{5} They were situated on well-drained basal platforms (Hammond 1988, p. 166).
\textsuperscript{6} Estimation based on Puleston (1974, pp. 184-85).
\textsuperscript{7} All percentages were derived from 100xA/250,000; A = area in square meters.
coefficient of permeability by the square's gradient to get a seepage rate (raw permeability) for each square. The gradient was estimated by subtracting the highest elevation in a map square by the lowest, and dividing the result by the length of a maps square (500 m). The coefficient of seepage was derived from a table in Cedergren which gave a range of coefficients for different soil types. Soil at Tikal was a mixture of gravel, loam, clay, sand and silt. This kind of soil had a coefficient ranging from 2.59–25.92 mm/month.

---

8 According to Darcy's formula (Cedergren 1967, p. 27), seepage rates are inversely related to gradient and directly related to coefficients of permeability. The gradient measures the steepness of the surface over which water is flowing; the higher the gradient, the greater the steepness. The coefficient of permeability measures the absorbency of the surface. Water flowing over a relatively flat surface will have more time to be absorbed than water flowing over a steep surface. So the highest seepage rates will be generated by relatively flat, absorbent surfaces, while the lowest seepage rates will be generated by relatively steep, nonabsorbent surfaces.

9 Elevations were indicated by contour lines on the Tikal maps.

10 Cedergren classified mixtures of sand, silt and clay into a category with permeability of .000001 mm/s to .00001 mm/s. Multiplying this by (3600 s/hr)x(24 hr/day)x(30 days/month) yielded 2.592-25.92 mm/month.

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<th>Epicenter (%)</th>
<th>Bajo (%)</th>
<th>Features (%)</th>
<th>Structures (%)</th>
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*Based on seepage rate of 2.592–25.92 mm/month.
Appendix C: Modified Maps of Tikal

The attached set of eight maps are based on Carr and Hazard's detailed maps of Tikal (1961).

Catchment areas, projected reservoirs and canals were outlined directly over the original maps. Catchments and reservoirs were labelled using the identification scheme discussed in Chapters 2 and 3, with the following modification:

Reservoirs were prefixed with an "R."
Catchments were prefixed with a "C."