ENVIRONMENTAL VERSUS SOCIAL PARAMETERS, LANDSCAPE, AND THE ORIGINS OF IRRIGATION IN SOUTHWEST ARABIA (YEMEN)

DISSERTATION

Presented in Partial Fulfillment of the Requirements for

the Degree Doctor of Philosophy in the Graduate

School of The Ohio State University

By

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ABSTRACT

Using the Wadi Sana watershed of Hadramawt Governate, Yemen as a case study, this dissertation examines how environmental and social factors structured the origins of irrigation in prehistoric Southwest Arabia. It applies three methods, archaeological survey, geomatics, and ethnoarchaeology set within a framework of scientific and humanistic landscape archaeology. Results of archaeological survey and radiocarbon dating confirm that irrigation originated in Southwest Arabia during the mid 6th millennium calibrated BP and identify shrūj surface runoff irrigation as one of the earliest irrigation techniques in the region.

Conflicts between explanations emphasizing environmental versus those stressing social factors have long structured investigations of prehistory and models of transitions to agriculture. To evaluate the relative, interconnected influence of environmental versus social factors this study applies: 1) geomatics to evaluate the hypothesis that locations of ancient irrigation structures in Wadi Sana are closely associated with hydrological variables reflecting close behavioral ties to environmental conditions, and 2) ethnoarchaeology to interpret sociocultural, political, and ideological parameters of ancient irrigation. A sample of 174 irrigation structures is statistically compared with satellite imagery-derived data including landform and hydrological Geographic Information System (GIS) map data layers. A cross-cultural overview of irrigation, synopses of typological and social aspects contemporary irrigation in Yemen, and a preliminary ethnoarchaeological study of water-use and irrigation in present-day Wadi Sana help illustrate how organizational/logistical challenges and perceptions of landscapes and water-rights shaped irrigation’s origins.

Collective results illustrate why a combination of processual and postprocessual perspectives including both quantitative hypothesis testing and qualitative interpretation best illustrate the relative importance of environmental and social factors. Research findings demonstrate that ancient forager-herders in Wadi Sana chose irrigation structure
locations based on intimate knowledge of low-energy monsoon runoff along rocky hillslopes, and that new understandings of landscapes as hydraulically malleable domains of anthropogenic control, exclusive rights to water, and new forms of territoriality were crucial to irrigation’s origins.
For my parents, and my brother Bill.
ACKNOWLEDGMENTS

Yemen is a tremendously fascinating country in so many ways; the greatest thanks must go to the people of Yemen and the Hadramawt who have been such wonderful, gracious hosts.

At lunch under the Khuzmum during my first fieldwork in Yemen Joy McCorriston suggested a study of water management in Wadi Sana might provide an excellent dissertation topic. At first the idea seeming daunting—how could one date any of these structures, surely they would not seriate into neat groups? But as I began to appreciate the importance of irrigation in Yemen (through the work of Abdu Ghaleb, R.B. Serjeant, Daniel Varisco and others) the idea seemed increasingly appealing. Without Dr. McCorriston, the Roots of Agriculture in Southern Arabia (RASA) Research Project, and project co-directors Eric Oches, and Abdalaziz Bin ‘Aqil this dissertation would have never made its way from lunchtime to thesis. Joy has offered incalculable assistance, pushed me along, served as a tireless advocate, counselor and has been patient enough to withstand my sometimes taxing enthusiasm, stubborn rhetoric, and when all else failed let me flounder and discover on my own. My sincere thanks to RASA for allowing integration of project findings, purchase of QuickBird imagery, the photograph in Figure 7.1, and use of published and unpublished radiocarbon dates in Table 8.1.

Members of the RASA Project team, many of whom volunteered their time and expertise, deserve many thanks. A diligent and dedicated colleague, Catherine Heyne has seen RASA through many hours of hiking cliffs and ‘ashara-meter transects. Dawn Walter, Margaret Wilson, Nisha Patel, Ghufran Ahmad, and Ramzy Ladah are due important debts of gratitude. Thanks to Franc Braemer and the Mission archéologique dans le Jawf-Hadramawt for collaborative support, particularly Rémy Crassard, Julien Espagne, and Tara Steimer-Herbert whose complementary interests have clarified a great many issues of prehistory in the region. RASA project geologists including Joshua Anderson, Stephen DeVogel, Kirk Sander, and Scott Anderson have helped build geological understanding and correct geoarchaeological speculation.
My sincere gratitude to the Republic of Yemen, General Organization of Antiquities, Museums, and Manuscripts (GOAMM) particularly Dr. Yousef Abdullah, Ahmed Shemsan, and Muhammad al-Asbahi for their support, and the privilege of working in Yemen. GOAMM representatives Abdalbaset Noman, Eda Al-Amary, Khalid BaDhofary, Abdul Karim al-Barakany, and Muhammed Sinnah have been invaluable colleagues, offering crucial assistance over many long days of fieldwork. Thanks also to Mohammed Aidrus (Project Director, Southern Governates Rural Development Project, Seiyun) for his advice and assistance and to his son Mahzen Aidrus for his time working with us in Wadi Sana.

Without the assistance of Nexen Petroleum Inc. (formerly Canadian Occidental Petroleum Inc.) who made their production facility available as a base of operations, provided fuel, food, and water RASA’s fieldcamp and fieldwork would be next to impossible. Particular thanks to Bob Simpson, Kevin Tracy, Rick Jensen, Neil Bennett, Muhammad Lardy, Jamal Karama, Ahmed al-Aghbary, Mohammed Bin Nabhan, Hakim as-Samawy, Roy Swystun, and Alan Brinkley.

The American Institute for Yemeni Studies (AIYS) deserves great appreciation for facilitating this research, particularly Resident Director Chris Edens for ironing-out innumerable logistical challenges and offering many clarifying insights about Southwest Arabian prehistory.

In addition to the indispensably crucial support of Joy McCorriston and Eric Oches, thanks also to dissertation committee members William Sumner, Mei-Po Kwan, and William Dancey for wading through drafts and straightening out ramblings of my thesis.

I am glad to acknowledge the University of Michigan, Museum of Anthropology for hosting me as a Committee on Institutional Cooperation (CIS) Traveling Scholar. Particular thanks to Joyce Marcus and Kent Flannery for offering unwavering encouragement and to Henry Wright, and Alexander Knysh for clarifying aspects of Middle Eastern archaeology and Hadrami culture respectively.

Since my first course in archaeology Dr. Catherine D’Andrea of Simon Fraser University has proved of tremendous help, cogent advice, and encouragement. Gulo Makeda Research Project co-directors Diane Lyons and Lawrence Pavlish deserve mention for tutelage and guidance.

The Ohio State University, Department of Anthropology, particularly Clark Larsen, Richard Yerkes, Bram Tucker, Jean Whipple, Anita Ridenour, and Wayne Miller have offered crucial assistance. The Ohio State University Center for Mapping for
provided remote sensing and GIS software licenses and support. Thanks to Carolyn Merry and other faculty in the Department of Civil and Environmental Engineering and Geodetic Science including Dorota Brzezinska and William Hazelton for technical assistance and loans of equipment.

A grant to Joy McCorriston from the Foundation for Exploration and Research on Cultural Origins (FERCO) and advice from Ron Blom (Jet Propulsion Laboratory, Pasadena, CA) and Juris Zarins (Southwest Missouri State University) facilitated the beginnings of my geomatics research with RASA and set the foundations for this dissertation. My sincerest gratitude to the National Aeronautics and Space Administration (NASA), particularly the Jet Propulsion Laboratory and the Earth Observing System (EOS) for providing free-of-charge access to MODIS and ASTER satellite imagery, and to Digital Globe Inc. for the opportunity to purchase QuickBird imagery. Radiocarbon assays were run by the University of Arizona Accelerator Mass Spectrometry (AMS) Laboratory. A two-year Social Sciences and Humanities Research Council of Canada (SSHRC) Doctoral Fellowship allowed time for fieldwork, analyses, and writing. This material is based in part upon work supported by the National Science Foundation Dissertation Improvement Grant # BCS-0332278. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

Finally, my heartfelt thanks to my fiancée Amy Nicodemus who has offered love, support, and astute advice on all manner of archaeological and practical details.
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Major Field: Anthropology

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TABLE OF CONTENTS

Abstract.....................................................................................................................ii
Dedication....................................................................................................................iv
Acknowledgments ........................................................................................................v
Vita...............................................................................................................................viii
List of Tables ................................................................................................................xiii
List of Figures ...............................................................................................................xv
Transliteration ............................................................................................................xvii

Chapters:

1. Introduction, Objectives, and Relevance..............................................................1

2. Analytical Framework.............................................................................................6
   2.1 Problems with Archaeology as Scientific-Materialism.................................9
   2.2 Problems with Archaeology as Humanistic-Idealism.................................11
   2.3 Toward Intermediary Perspectives...............................................................15
   2.4 Landscape Methods as Means of Integration..............................................18
      2.4.1 Landscapes and Archaeological Survey.............................................20
      2.4.2 Landscapes and Geomatics.................................................................21
      2.4.3 Landscapes and Ethnoarchaeology.......................................................24
   2.5 Summary..........................................................................................................26

3. The History of Research on Ancient Irrigation in Southwest Arabia..................27
   3.1 Investigations Before 1970..............................................................................27
   3.2 Investigations After 1970..............................................................................30
   3.3 Discussion........................................................................................................33

4. Analytical Methodology.........................................................................................35
   4.1 Archaeological Survey...................................................................................37
   4.2 Geomatics Analyses.......................................................................................39
   4.3 Ethnoarchaeology..........................................................................................44
   4.4 Summary..........................................................................................................46

5. Ethnology of Irrigation.........................................................................................51
   5.1 Foragers...........................................................................................................53
   5.2 Pastoralists.....................................................................................................55
10.4 Spatial Modeling II: Sampling and Modifiable Areal Unit Problem (MAUP) Issues ......................................................... 141
10.4.1 Sample Universe Issues ...................................................... 142
10.4.2 Data Categorization Issues ...................................................... 143
10.4.3 Site-type Issues ................................................................. 145
10.4.4 Buffering/Data Generation Issues ........................................... 146
10.5 Ethnoarchaeology ................................................................. 147
10.6 Summary .............................................................................. 151

11. Discussion: Wadi Sana and the Origins of Irrigation in Ancient Southwest Arabia ................................................................. 184
11.1 Summary .............................................................................. 190

12. Conclusions: The Relative Influence of Environmental versus Social Parameters ................................................................. 192

List of References ........................................................................ 200

Appendices:

Appendix A: Water Management Site Recording Form .............................. 265
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Types of satellite imagery used for this study</td>
<td>50</td>
</tr>
<tr>
<td>8.1</td>
<td>RASA Project radiocarbon dates for silts along middle Wadi Sana and the mouth of Wadi Shumlya</td>
<td>108</td>
</tr>
<tr>
<td>8.2</td>
<td>Radiocarbon dates for Wadi Sana irrigation structures</td>
<td>111</td>
</tr>
<tr>
<td>10.1</td>
<td>Ancient irrigation structures in the Wadi Sana watershed documented by archaeological survey</td>
<td>171</td>
</tr>
<tr>
<td>10.2</td>
<td>Landform class definitions</td>
<td>175</td>
</tr>
<tr>
<td>10.3</td>
<td>Landform classification accuracy assessment error matrix</td>
<td>176</td>
</tr>
<tr>
<td>10.4</td>
<td>Landform classification accuracy assessment statistics</td>
<td>176</td>
</tr>
<tr>
<td>10.5</td>
<td>List of GIS hydrological modeling procedures</td>
<td>177</td>
</tr>
<tr>
<td>10.6</td>
<td>Spatial modeling data code abbreviations</td>
<td>177</td>
</tr>
<tr>
<td>10.7</td>
<td>Kolmogorov-Smirnov results for Irrigation-Present vs. Irrigation-Absent Sample 1</td>
<td>178</td>
</tr>
<tr>
<td>10.8</td>
<td>Kolmogorov-Smirnov results for Irrigation-Present vs. Irrigation-Absent Sample 2</td>
<td>178</td>
</tr>
<tr>
<td>10.9</td>
<td>Logistic regression results for Irrigation-Present vs. Irrigation-Absent Sample 1</td>
<td>178</td>
</tr>
<tr>
<td>10.10</td>
<td>Logistic regression results for Irrigation-Present vs. Irrigation-Absent Sample 2</td>
<td>179</td>
</tr>
<tr>
<td>10.11</td>
<td>Kolmogorov-Smirnov results for Check Dams vs. Irrigation-Absent Sample 1</td>
<td>179</td>
</tr>
</tbody>
</table>
10.12 Logistic regression results for Check Dams versus Irrigation-Absent Sample 1
10.13 Kolmogorov-Smirnov results for Diversion Channels vs. Irrigation-Absent Sample 1
10.14 Logistic regression results for Diversion Channels vs. Irrigation-Absent Sample 1
10.15 Kolmogorov-Smirnov results for Check Dams vs. Irrigation-Absent Sample 2
10.16 Logistic regression results for Check Dams vs. Irrigation-Absent Sample 2
10.17 Kolmogorov-Smirnov results for Diversion Channels vs. Irrigation-Absent Sample 2
10.18 Logistic Regression results for Diversion Channels vs. Irrigation-Absent Sample 2
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>MODIS satellite image of Southwest Arabia</td>
<td>5</td>
</tr>
<tr>
<td>4.1</td>
<td>ASTER satellite image of the Wadi Sana watershed</td>
<td>47</td>
</tr>
<tr>
<td>4.2</td>
<td>The Wadi Sana main channel just north of Qalat Habshiya</td>
<td>48</td>
</tr>
<tr>
<td>4.3</td>
<td>The middle Wadi Sana landscape</td>
<td>48</td>
</tr>
<tr>
<td>4.4</td>
<td>Quickbird image of middle Wadi Sana</td>
<td>49</td>
</tr>
<tr>
<td>4.5</td>
<td>Two categorizations of slope for the Khuzmum area</td>
<td>50</td>
</tr>
<tr>
<td>7.1</td>
<td>House structure (037-3) near the Khuzmum excavated by the RASA Project and dated to the 7th millennium BP</td>
<td>96</td>
</tr>
<tr>
<td>10.1</td>
<td>Ancient irrigation structures along middle Wadi Sana</td>
<td>153</td>
</tr>
<tr>
<td>10.2</td>
<td>A typical <em>shrūj</em> water diversion channel (W16-1B)</td>
<td>154</td>
</tr>
<tr>
<td>10.3</td>
<td>A typical <em>shrūj</em> check dam (W6-1)</td>
<td>154</td>
</tr>
<tr>
<td>10.4</td>
<td>The Khuzmum area at the mouth of Wadi Shumlya showing 009-1 and vicinity</td>
<td>155</td>
</tr>
<tr>
<td>10.5</td>
<td>Plan map of rock-bordered canal 009-1</td>
<td>156</td>
</tr>
<tr>
<td>10.6</td>
<td>Southeast end of rock bordered canal 009-1</td>
<td>157</td>
</tr>
<tr>
<td>10.7</td>
<td>Rock-bordered canal 009-1 embedded boulders</td>
<td>157</td>
</tr>
<tr>
<td>10.8</td>
<td>Rock-bordered canal 009-1 naturally-cut section</td>
<td>158</td>
</tr>
<tr>
<td>10.9</td>
<td>Test pit 1 of rock bordered canal 009-1</td>
<td>158</td>
</tr>
<tr>
<td>10.10</td>
<td>Test pit 2 of rock bordered canal 009-1</td>
<td>159</td>
</tr>
</tbody>
</table>
10.11 Test pit 3 of rock bordered canal 009-1.........................................................159
10.12 Check dam 000-1......................................................................................160
10.13 Plan map of water diversion structure 013-1..............................................160
10.14 The vicinity of WATER 1..........................................................................161
10.15 Check dam W1-1......................................................................................161
10.16 Hearth W1-4-1 near check dam W1-1.......................................................162
10.17 The vicinity of WATER 5..........................................................................162
10.18 Check dam W5-1......................................................................................163
10.19 Check dam W5-1 section drawing...............................................................163
10.20 Check dam W19-1....................................................................................164
10.21 The vicinity of WATER 6 through 9............................................................164
10.22 WATER 7 diversion channels.....................................................................165
10.23 WATER 8 gully between bedrock slope and silts........................................165
10.24 Circular tower tomb near WATER7............................................................166
10.25 Wadi Sana Digital Elevation Model (DEM) extracted from ASTER imagery..........................167
10.26 Wadi Sana watershed landform classification.........................................168
10.27 Wadi Sana drainage network and catchments.........................................169
10.28 Flow accumulation for check dams and diversion channels vs.
    Irrigation-Absent Sample 1 locations.........................................................170
10.29 Flow accumulation for check dams and diversion channels vs.
    Irrigation-Absent Sample 2 locations.........................................................170
TRANSLITERATION

The *International Journal of Middle East Studies* transliteration system is used for this thesis. Arabic words commonly used in English (e.g., wadi) are not transliterated or italicized. Place names are transliterated without macrons and dots, and commonly used English equivalents are used instead of transliterated Arabic for names of major cities (e.g., Sana’a instead of Ṣan‘ā’; and Aden instead of ʿAdan). Although Arabic plurals are periodically mentioned, for most plurals an “s” is simply added to make them easier to recognize for those not familiar with Arabic (e.g., wadis; shaykhs).
CHAPTER 1

INTRODUCTION, OBJECTIVES, AND RELEVANCE

This dissertation examines the origins of irrigation in ancient Southwest Arabia. It concentrates on the relative, yet interrelated influence of environmental and social parameters of irrigation as they pertain to early trajectories of societies in the region. Analyses and conclusions are based on overview of regional evidence, cross-cultural consideration of irrigation, and archaeological fieldwork conducted predominately throughout the Wadi Sana watershed of Hadramawt Governate, Yemen (Figure 1.1). The relative extent to which environmental versus social factors are responsible for human behavior and choices is crucial to explanations of transitions from foraging to agriculture and the emergence of ancient states. This research comparatively evaluates: 1) the quantitative extent to which the location of mid-Holocene irrigation structures in the Wadi Sana watershed of Hadramawt Governate, Yemen are correlated with hydrological variables reflecting behavioral ties to environmental circumstances, versus 2) the extent to which irrigation was only loosely connected to environmental conditions and more primarily influenced by social issues including territoriality, water-rights, and logistical challenges of organizing irrigation. Three primary methodologies are used to evaluate these alternatives: 1) archaeological survey and test excavation to record and date irrigation structures, 2) geomatics analyses to model irrigation structure locations in terms of hydrological variables, and 3) ethnoarchaeology to examine small-scale irrigation and help determine how ancient irrigation in Wadi Sana operated. For each of these methods approaches grounded in both scientific and humanistic landscape archaeology integrate and help ameliorate divides between processual and postprocessual perspectives.
Research findings confirm that incipient forms of irrigation developed in Southwest Arabia as early as the middle 6th millennium BP\(^1\), and provide important new evidence clarifying the type and function of early systems. Results of archaeological survey and test excavation show that a type of surface runoff irrigation known locally in eastern highlands of Yemen as *shrūj* irrigation was one of the technological and socio-organizational precursors to more elaborate, large-scale systems including those that supported the rise of Yemen’s earliest states during the late 4th through 3rd millennia BP. Irrigation’s origins in Southwest Arabia are linked to evidence from the Levant, Mesopotamia, Iran, and Africa to generate an inter-regionally informed picture, and to help examine the extent to which irrigation developed locally or was the result of wide inter-regional contacts. Geographic Information Systems (GIS) spatial modeling demonstrates that early irrigators strategically selected irrigation structure locations based on detailed knowledge of hydrologic conditions, and preliminary ethnoarchaeological investigations suggest that incipient irrigation was likely organized without supra-household coordination but involved new understandings of landscapes as hydraulically malleable domains of anthropogenic control that required exclusive rights to water and new forms of territoriality. Research findings depict irrigation’s connections with a range of influencing factors, including accumulating knowledge of irrigation techniques, climate change, population pressure, culture, politics, and ideology.

This dissertation holds important relevance for understanding the role of environmental versus social factors in transitions to agriculture. Models of transitions from foraging to agriculture fundamentally grapple with what influenced prehistoric people the most—climates, environments, subsistence economics, and demographics, or social relations, ideologies, and politics. The Fertile Crescent region is well known as a crucial center of plant and animal domestication (e.g., Bar-Yosef and Belfer-Cohen 1989; Bar-Yosef and Meadow 1995; Henry 1989; McCorriston and Hole 1991), and considerable evidence now documents the spread of agriculture to Europe (e.g., Barker 1985; Dennell 1992; Price 2000). Far less is known about the origins and spread of agriculture throughout adjacent regions including Central Asia, South Asia, Africa, and Southern Arabia (see Edens and Wilkinson 1998; Harris 1996). Although such regions are often considered peripheral because their earliest farmers in many cases utilized plant and animal species first domesticated in the Fertile Crescent; ostensibly peripheral regions are nevertheless crucial for evaluating and refining general, inter-regional models

\(^1\) Dates throughout this dissertation are referred to in calibrated years Before Present (cal yr BP) based on CALIB v5.0.1 software.
of transitions to agriculture. Numerous competing general explanations of agricultural origins that emphasize factors including changing social relations (Bender 1978; Hayden 1995), demographic stress (Cohen 1977; Rosenberg 1998), human-plant coevolution (Rindos 1984), and climatic/ecological change (Richerson et al. 2001) presently coexist. Although such models incorporate a tremendous diversity of evidence from a variety of regions, one of the primary conflicts among them arises because of a wide and contentious gap between ecological, economic, and demographic factors as premised by some researchers (e.g., Cohen 1977; Piperno and Pearsall 1998; Richerson et al. 2001), versus social, cultural, political, and ideological factors as emphasized by others (e.g., Cauvin 2000; Hayden 1995; Hodder 1990). This distinction is particularly evident for Southwest Asia, where some of the best preserved and most detailed evidence is available. Some researchers stress ecological changes in the distribution of cereals and game (e.g., Henry 1989; Bar-Yosef 1996), while others emphasize social and ideological changes, as reflected in non-utilitarian artifacts and art (e.g., Cauvin 2000). This point of explanatory departure reflects debates between processual and postprocessual perspectives in archaeology that have deep roots in conflicts between scientific-materialist versus humanistic-idealistic epistemologies (Trigger 1998). Such conflicts have structured debates about agricultural origins from some of the first fieldwork-based investigations to the most recent, contemporary explanations. Just as Childe (1952) and Braidwood (1958) disagreed about the relative importance of climatic/environmental and social factors, major differences between recent models center on analogous issues (e.g., Bender 1978; Hayden 1995; Keeley 1995; Richerson et al. 2001). Although transitions from foraging to agriculture must be considered complex combinations of both sets of factors, untangling their relative importance is challenging. This dissertation provides a case study of a lesser-known region that applies a unique combination of methods to examine the interface of, and help ameliorate conflicts between, environmentally versus socially focused explanations for transitions to agriculture.

In addition to its significance for understanding and modeling transitions from foraging to agriculture, this dissertation also helps clarify irrigation’s role in ancient sociopolitical relations. As agriculture became increasingly prevalent among post-Pleistocene populations, irrigation in many regions became a crucial means of increasing agricultural production with long-postulated significance for the origins of states. Although Wittfogel’s (1957) deterministic contention that irrigation was the primary factor responsible for the emergence of centralized political authority and state societies has been discredited on a variety of grounds (see Adams 1966: 66-75; Nissen 1988: 60;
Scarborough 2003: 17-19; Trigger 2003: 676), it remains difficult to ignore the prevalence of irrigation throughout regions of state formation (Mabry 2000). Wittfogel’s hydraulic hypothesis has undoubtedly served as a centralizing framework for the study of irrigation, but most now recognize that relationships between irrigation and society require substantially more sophisticated explanations (e.g., Butzer 1996; Kelly 1983; Mabry 1996b, 2000; Scarborough 2003). Although much ground still remains to be covered in understanding irrigation’s impacts on societies, and societies’ impacts on irrigation, recent investigations have focused not only on large-scale irrigation but on small-scale strategies that, as Mabry noted, are frequently “the most common and enduring systems” (1996b: 4-5). Archaeological fieldwork conducted for this dissertation documents some of the earliest irrigation in Southwest Arabia, and applies a combination of approaches that enlighten understanding of irrigation’s connections with ancient sociopolitics.
Figure 1.1: MODIS satellite image map of Southwest Arabia (white teardrop-shaped outline depicts boundary of the Wadi Sana watershed).
CHAPTER 2

ANALYTICAL FRAMEWORK

In addition to the regional goal of advancing understanding of irrigation in ancient Southwest Arabia, this dissertation applies methods that explore the divide between (and potential for complementary integration of) disparate scientific-materialist versus humanistic-idealist epistemologies in archaeology. Conflicts between processual and postprocessual approaches have reached a crescendo, where scholars interested in many of the same archaeological records are pursuing research agendas so disparate they create largely independent communities with little intermediary dialogue (see Bintliff 2000; Kristiansen 2004a, 2004b). These debates not only involve specific research findings but (more critically) the questions that can and should be addressed. Although conflicts between processual and postprocessual archaeologies are diverse, they arise to a substantial degree because of an expansive divide between conflicting ontologies and their corresponding epistemologies. While materialist ontology holds that the world is composed of empirically definable physical objects and processes, idealist ontology maintains that human worlds are constructions of perceptions and understandings (Niiniluoto 2002: 21-23; Trigger 1998: 10). This stark conceptual divide between materialism and idealism has structured archaeological theory in part because of selective borrowing from philosophy, where analogous debates have led to similarly conflicting views regarding objectivity versus subjectivity in social science research (e.g., Bunge 1998; Turner and Roth 2003). Particularly among prehistorians, research perspectives vary dramatically from those emphasizing environment, technology, and economics (e.g., Binford 1987, 2001; Dunnell 1982), to those underscoring sociocultural relations, politics, and ideology (e.g., Hodder 1986, 1990; Shanks and Hodder 1995).

The approach adopted for this dissertation centers on the contention that neither materialist-nomothetic perspectives that emphasize science and objectivity, nor idealist-
idiographic perspectives that emphasize humanism and subjectivity are mutually exclusive, that neither can nor should usurp the other, and that integration of both positions provides more accurate understandings than either in isolation. Numerous commentators have recommended integration of processual and postprocessual schools (Bintliff 2000; Knapp 1996; Kristiansen 2004a; Preucel 1991; Trigger 1989, 1998; Van Pool and Van Pool 1999), but these recommendations have been predominantly on a theoretical level and have not been met by integration of methods for particular archaeological problems. Demonstrating the contributions of both perspectives for particular archaeological topics can help moderate conflicts between increasingly divorced scholarly communities and ameliorate segregation of archaeological investigations along epistemological lines (Kristiansen 2004a; Schiffer 2000).

To help integrate processual and postprocessual perspectives, this dissertation adopts landscape as a mediating framework, and a heuristic distinction between environmental and social factors, to facilitate understanding of ancient irrigation. Archaeologists have long grappled with human societies as complex products of a multifaceted range of factors including those premised by materialists—environment, technology, and economics, versus those emphasized by idealists—culture, politics, and ideology. In their broadest and most simplistic formulation these elements can be divided into, environmental circumstances—those related to the material, economic world humans rely on to survive—and social circumstances—those related to cultural and political interactions of humans’ with each other. Although this distinction between environmental and social factors is a heuristic simplification that does not separate human affairs into rigid, mutually exclusive categories, it nevertheless provides a powerful conceptual basis for evaluating factors influencing human activities. Human life necessarily involves the influences of both environmental conditions and social circumstances, so the two are necessarily interrelated. As Trigger (1998: 31; 2003: 3-14) has argued, extreme versions of processual and postprocessual archaeologies frequently espouse either environmental or cultural determinisms, when a more appropriate balance must lie somewhere in-between. Landscape analyses have long and diverse histories in archaeology that span theoretical divides, and therefore offer a mediating framework around which these two determinisms can be examined. As explanations in archaeology have become increasingly structured by disputes between scholars advocating scientific versus humanistic approaches, landscape methods have traced a similar path. As a spatial domain where humans interact with each other and their environments, landscape also offers a particularly appropriate framework for the study of irrigation. Irrigation
structures are widely distributed across landscapes in ways connected to both hydro-
ecological conditions and sociocultural relations. While examining the totality of
environmental and social contingencies structuring human choices (even among a
particular group) would be an enormous task, choosing a specific domain of human
behavior, such as irrigation, narrows subject matter and provides a judicious starting
point for examining these critical dimensions of ancient life.

To understand why and how scientific-materialist and humanistic-idealist
perspectives might be complementary it is necessary to briefly describe and outline
problems with both. Although investigations of specific topics—such as the transitions
to agriculture—are crucial, epistemological divisions have had critical influences on the
goals and methods of contemporary archaeological research. The key arguments of
processualism and postprocessualisms’ most vigorous proponents show why strict
adherence to either scientific or interpretive methods is counterproductive. These
extremes pit hyper-materialist (e.g., Binford 1987) versus hyper-idealist (e.g., Shanks and
Tilley 1987a, 1987b) epistemologies against one another with few elaborately explored,
chronologically situated archaeological examples. Rather than attempting to avoid
theoretical disputes by uncritically adopting methods of one side or the other,
archaeologists more appropriately explore the boundaries of disparate perspectives and
evaluate ramifications for analytical outcomes in specific archaeological cases.
Archaeological problems where a range of materialist and idealist approaches have been
applied, show that movements toward the end goals of archaeology—understanding and
explaining past human life—are most readily achievable through approaches that
integrate both quantitative-scientific and qualitative-humanistic evidence. Investigations
of Levantine agricultural origins, for instance, have generated a wide range of materialist
(e.g., Bar-Yosef 1996; Byrd 1989; Henry 1989, 1995; McCorriston and Hole 1991;
Moore and Hillman 1992) and idealist (e.g., Cauvin 2000; Perrot 2001; Valla 1999)
perspectives. Neither seems on the verge of replacing the other and there is an increasing
degree of dialogue among widely divergent approaches (e.g., Kuijt 2000; Rosen 1991).
Clearly both science-centered and interpretive perspectives have played crucial roles in
archaeology. This study examines (using a study of irrigation’s origins in Southwest
Arabia) how interconnection of both avenues of investigation holds potential to produce
more holistic and accurate understandings and move archaeology beyond a divisive
subdivision between processual and postprocessualism.
2.1 Problems with Archaeology as Scientific-Materialism

The empirical, scientific nature of archaeology at first seems obvious; investigations are simply concerned with determining “the way things actually happened” and letting the “facts speak for themselves” (cf. Bryant 2000: 492). But a more critical consideration reveals that these common sense views are colloquial truisms with questionable foundations that neglect to account for the complexity of relationships in which archaeologists become embroiled.

Processualist efforts to establish scientific approaches in archaeology including hypothetico-deductive methods (e.g., Binford 1962; Clarke 1968; Watson et al. 1971) have had crucial and enduring impacts. But emphases on science were not entirely new to archaeology in the 1960’s and had a long history in archaeology dating to at least the early 1930’s (Wylie 2002: 25-41). Advocates of immutable scientific objectivity associate established scientific authority, “Newtonian mechanics, Darwinian evolutionary biology, Lyellian geology, Einsteinian physics” (Wylie 2000: 230), for instance, with perceived scientific unity (Wylie 1999, 2000). These dramatic scientific advancements have undoubtedly had revolutionary impacts, but delineating specific procedures or standards of objectivity that can unite them is challenging in the extreme (Aronld and Wilkens 2001; Aronowitz 1998; Kuhn 1996 [1970]; Wylie 1999, 2000). Unfortunately, building archaeology around an exclusively scientific paradigm has proved neither as easy in application, nor as immutable, as some contend. Efforts to develop criteria that delineate an idealized interdisciplinary model of science have been a prominent concern of philosophers for centuries (Bacon 2001 [1605]). Karl Popper (1963), for instance, is well known for his falsification criteria and Thomas Kuhn (1996 [1970]) for describing puzzle-solving periods of normal science punctuated by revolutionary paradigmatic upheavals. To date, however, there are no widely accepted, precise criteria to define science and/or scientific procedures that can be adopted and transferred wholesale to archaeology (Arnold and Wilkens 2001; Hutson 2001; Trigger 1989; Wylie 1999, 2000). Although hypothesis testing experiments are sometimes employed, scientific perspectives in archaeology are frequently more of an objectivist, rationalist mind-set than any specifically definable set of procedures (Jones 2002: 1-22).

Since the 1960’s proponents of processual archaeology have struggled to develop rigidly scientific methods that would lead to holistic explanations of long-term culture change. While these efforts developed a vast range of methods that are undoubtedly successful in great many respects, they are frequently linked to materialist ontology and have failed to demonstrate that archaeology can rely on exclusively scientific methods.
Rigidly scientific methods are undoubtedly workable where hypothesis-testing experiments are replicable (e.g., microwear analyses, studies of taphonomy), but quantitative testing is far more difficult to apply at higher levels of abstraction (cf., Hodder 1999: 21). Historic (or prehistoric) events considered in holistic entirety are inherently non-replicable (and to some extent particularistic) phenomena that require very different analytical procedures than phenomena of experimental or observational sciences that are repeatedly observable in controlled contexts (Nagel 1961). Social and ideological relations, for instance, because they are difficult to directly observe and quantify are commonly relegated to superficial, secondary consideration. Even if emic understandings are as hard to get as Harris (1979) suggests, should archaeologists ignore idiosyncratic understandings even though they are demonstrably critical to choices, action, and agency? While middle range theory in archaeology was initially espoused as a means to connect “statics” of archaeological records with “dynamics” of human behavior in a way that would purportedly lead to higher level theories about culture change (Binford 1977), middle range theory became virtually synonymous with considerations of site formation processes and continually postponed explanations (or even theories about) societal transformations (Raab and Goodyear 1984). Even if archaeologists can objectively identify specific behaviors via middle range theory, can they maintain rigid objectivity while facing choices between diverse realms of evidence, such as paleoclimate data that are readily quantified, versus ideological or religious understandings that require qualitative interpretations? Science-centered procedures emphasize quantitative evidence and therefore premise economic, materialist, ecosystemic explanations involving data that are easier to quantify (cf., Saitta 1991). It therefore becomes extremely difficult (or impossible?) to ensure that tests are objective and adequately include more transient social understandings that have clearly important influences on human choices. In ways analogous with the present, ancient human life involved both empirical and readily quantifiable economic and ecological influences in tandem with transitory human motivations, agency, and ideology (cf., Trigger 1998). Many still advocate exclusively scientific methods, including approaches under the heading of cognitive archaeology that move beyond “subsistence-settlement archaeology” to address “cosmology, religion, ideology, and iconography” (Flannery and Marcus 1996). But there remains wide disagreement about whether scientific approaches are the only appropriate way to address these and other social dimensions (e.g., Jones 2002). When it comes to choosing between what types of archaeological evidence to collect and how to examine them, archaeological topics are not devoid of observational
perspectives in any manner that can be explicitly defined. Nor, undoubtedly, can any generalized, model of science proposed thus far form the basis of analytical procedures that ensure archaeologists have objectively weighed the wide range of environmental, economic, technological and social, cultural, and political factors implicated in societal changes.

2.2 Problems with Archaeology as Humanistic-Idealism

While many have argued that archaeology cannot feasibly be modeled exclusively after experimental or observational sciences that deal with phenomena that are repeatedly observable in controlled contexts, without some degree of objective knowledge archaeology would collapse in a quagmire of interpretive hyper-relativism. Although archaeologists have questioned the existence of empirical realities (e.g., Shanks and Tilley 1987a, 1987b), the extreme “postmodernist notion that there is no truth, and that everything is a construction, is in fact the ultimate contradiction” (Knapp 1996: 138). It is utterly illogical. If the statement—there are no empirical realities—is accurate, then this statement itself must not be reliable. The statement assumes truth but contradicts itself and therefore, cannot be any more credible that the opposing position that there are empirical realities.

Postprocessual archaeology has made critical contributions by pointing out flaws in attempting to mold archaeology around an exclusively scientific framework. But acknowledging that archaeologists cannot be completely objective is often implicitly linked to hyper-idealistic ontology and conflated with the notion that archaeological subject matter is almost entirely subjective (see Trigger 1989, 1998; Watson 1990, 1991). Although the most vigorous proponents of postprocessualism claim to reject extreme relativism, arguments that leave almost no room for independence between theories and observations (e.g., Shanks and Tilley 1987a, 1987b), whether admittedly or not, advocate an extreme form of subjective idealism (see Watson 1990; 1991). Although Shanks and Hodder (1995) attempt to distance themselves from, “judgmental relativism [that] makes the…claim that all forms of knowledge are equally valid” (1995: 19), they go on to advocate a slightly less excessive form of idealism that maintains there are extremely few (if any) accurate ways to distinguish the accuracy of different interpretations. In the introduction to their edited volume on landscape, Layton and Ucko (1999) similarly remind us about lingering notions “that there is no (meaningful) world external to consciousness, or that meaning can make no reference to the world, since the meaning of words is defined only in relation to other words” (1999: 6). Again, they do not explicitly
reject this hyper-idealist assertion, but instead briefly explain its history and purported justification. Such hyper-idealist views are central to conflicts between processual and postprocessual archaeologies. Although Layton and Ucko later point out that human beliefs “must at least produce behavior that is compatible with survival” (1999: 8), such statements accord material (environmental, economic, and technological factors) an extremely limited role in which they are only capable of preventing a tiny subset of behavior but have no significant importance. Assertions that archaeology is almost entirely subjective are very similar to the notions that archaeology can be almost entirely objective—they are both untenable oversimplifications that prompt archaeologists to adopt rigidly exclusionary perspectives. There are numerous examples of how archaeology has supported discrimination, subjugation of indigenous peoples, and violently racist ideologies (see Conkey and Spector 1984; Garlake 1973; Silverberg 1968). But recognizing that scholarship occurs in a political milieu is entirely different than asserting that archaeology is merely a political/ideological tool with little or no ability to develop increasingly accurate representations of the past (cf., Shanks and Hodder 1995: 3). Proponents of hyper-relativism emphasize philosophies that advocate ‘anything goes’ styles of theoretical anarchism (e.g., Feyerabend 1975), but this is certainly not a consensus view among philosophers of social science, some of whom still recommend exclusively materialist perspectives (e.g., Bunge 1996; 1998).

Just as processualists developed a scathing critique of culture-historical perspectives in archaeology to justify a shift in the discipline (e.g., Taylor 1948), postprocessualists have relied on similarly dogmatic portrayals of science and scientific methods. Interpretative archaeologies seem to defy categorization, while scientific perspectives have been characterized as pursuing “timeless and value-free knowledge” that never changes (Shanks and Hodder 1995: 3). Shanks and Hodder (1995: 18) argue that “objectivity is not an absolute or abstract quality towards which we can strive. Objectivity is constructed”, but they go on to describe statements with objectivity as statements which are “strong” and proceed to discuss how scholars pursue statements with “strength” (Shanks and Hodder 1995: 18-19). Ultimately their arguments are self-contradictory and simply replace the abstract quality of statement “objectivity” with the abstract quality of statement “strength”, consistently clinging to the notion there are almost no reliable ways to distinguish accurate from inaccurate assertions. Hodder continues to shun “science” according to a well-worn line of critique:
Some archaeologists wish to make contributions to scientific knowledge, or they might wish to provide knowledge so that people can better understand the world around them. But in a postcolonial world, such aims of a distanced objective archaeology can easily appear narrow, self-interested and even colonial (Hodder 2001: 5).

But in a contemporary world that might be better described as wantonly neo-colonial (or culturally imperialist) rather post-colonial (see Said 1993; Sartre 2001 [1964]), who is to judge if archaeology is really less ‘narrow, self-interested, and colonial’ under an interpretive rubric than it was under a scientific one? Arguably post-modern introspection is even more obscure to those outside academia than culture history or science, but regardless, if archaeologists are as wedded to their theories as is often claimed no single theoretical school can be appointed arbitrator of this complex issue.

After more than twenty years of critiquing science postprocessualism has engendered crucial insights by emphasizing the culturally construed, theory-laden nature of archaeological research, but efforts to exclude science from theory while simultaneously emphasizing multivocality and dialogue are fundamentally contradictory and needlessly divisive. Postprocessual archaeologies have gained a considerable number of advocates (see Whitley 1998; Hodder 2001; Hodder et al. 1995; Preucel 1991; Preucel and Hodder 1996) and can no longer claim to be unrecognized in a field entirely dominated by science. While a number of new journals are largely dedicated to issues postprocessualism has raised (e.g., Archaeological Dialogues, Journal of Social Archaeology), the dialogues generated are far less inclusionary than acknowledged. Even as Hodder (2003) recommends inviting communities outside the academia to dialogue, he also recognizes, “evidence that archaeological theorists are trapped in separate non-communicating discourses” (Hodder 2001: 11). Although he advocates multivocality, discourse, and dialogue, Hodder (2003: 93-96) is apparently not concerned about the disintegration of the four-field approach to anthropology. He contends archaeology has just expanded its horizons to other disciplines, including interpretive perspectives in psychology and geography with which he feels more comfortable (Hodder 2003: 96). But postprocessualism has fostered as much fragmentation as dialogue, and has favored theoretical branches of some disciplines while disavowing relationships with any traditionally considered scientific. There is hardly a discipline with which archaeology has not had contacts throughout its history, philosophy, chemistry, physics, geology, geography, sociology, history, art history, and psychology.
(for example) have all made substantive contributions. Beyond merely fostering dialogue for its own sake, there are substantive reasons to maintain close associations with a wide range of disciplines, including those grounded in empirical science. As Hodder recognizes,

most archaeologists spend much of their time in the field worrying about radiocarbon dating, geophysical prospection surveys, DNA sampling, Munsell color charts, Harris matrices, micromorphology, phytolith analyses, and so on (Hodder 2003: 6).

But Hodder does not explicitly acknowledge any need for practitioners of interpretive archaeologies to engage scientific experts in any of these fields in dialogue, which would seem to be crucial, since science is not conducted in a vacuum devoid of interpretive liberties! Hodder’s comments regarding the status of science in archaeology are illustrative of an implicit attempt to exclude any role for science in archaeological theorizing. Although Hodder suggests that,

some parts of archaeology would be better served either by separating from anthropology or by aligning themselves to human geneticists, the natural sciences, biology, behavioral sciences, and so on (Hodder 2003: 95; my emphasis).

Hodder also contends that, “there seems to have been an unhelpful confusion between scientific archaeology and archaeological science” (Hodder 2003: 95). Although there is apparently room for interpretive methods and therefore interpretive archaeologies, in contrast, there would appear to be room for scientific methods but not scientific archaeology? Hodder appears to envision two brands of archaeology, one aligned with science and one not, but the one aligned with science does not rise to the level of scientific archaeology; it merely applies scientific techniques. Although Hodder might not mind that anthropology is fragmenting, if the dialogue he advocates is genuine it would seem to be a mistake to dissolve dialogues that have already been established, including those with anthropologists, because (quite obviously) physical anthropologists study people that actually produced archaeological records and sociocultural and linguistic anthropologists study descendent languages and cultures.

In his recent book, Archaeology Theory and Scientific Practice, Jones (2002) similarly draws a distinction between “scientific archaeology” and “theoretical archaeology”, ultimately suggesting that science can be useful as “materials science” but
falls short of adequately addressing social dimensions of human pasts. But reducing scientifically oriented archaeology to laboratory analyses of artifacts ignores the breath of science-oriented processual archaeology that continues to pursue explanations of social and cultural dimensions of variability and change (see Carnerio 1995). While Jones critiques science for claiming a privileged ability to address nature, the reciprocal critique applies to postmodernism for claiming a privileged ability to address culture. In contrast with the dichotomy Jones constructs, social and cultural factors are not the exclusive domain of interpretive archaeologies (see Schiffer 2000).

Postprocessual perspectives have engendered critically important commentaries about science and objectivity in archaeology, but interpretative archaeologies must inevitably take place in tandem with scientific perspectives because they do not completely refute and replace them. Although Shanks and Hodder (1995: 21) would have us ponder questions like, “Was the Bronze Age hut circle not there before being excavated?” such questions delve in metaphysical issues that posit an extreme form of subjective idealism. Although they are the concern of philosophers, they have little productive role in archaeology other than as thinly veiled attempts to exclude scientific perspectives (Watson 1990; 1991).

2.3 Toward Intermediary Perspectives

Since the rise of the controversy, numerous scholars have explored potential for complementary integration of processual and postprocessual perspectives (Bintliff 2000; Knapp 1996; Kristiansen 2004a; Preucel 1991; Trigger 1998; Van Pool and Van Pool 1999; Wylie 1993). Although intermediary perspectives have taken critical first steps toward mitigating theory conflicts, they have not been met by corresponding integration of methods. Indeed, the gap between processualists and postprocessualists has hardly seemed to narrow. Researchers on either side often exclude a priori evidence couched in theoretical perspectives with which they do not agree, a procedure Schiffer (2000: 2-5) refers to as “redlining”. Van Pool and Van Pools’ (1999) contention that postprocessualism is scientific illustrates the often blurry line defining science, but it is unlikely proponents of interpretive archaeologies that have relied on critiques of science would now agree to be encompassed under a wider scientific umbrella (Arnold and Wilkins 2001). Kristiansen’s (2004a) comparison of two recent books, one on evolution and one on agency in archaeology, aimed to mediate between highly divergent perspectives. But Kristiansen’s arguments prompted relatively little dialogue between scholars he critiqued; rather than exploring ways their positions might be compatible,
scholars on both sides simply defended their arguments (Robb 2004; Shennan 2004). As Kristiansen concluded, more balanced perspectives that draw on the strengths of both processual and postprocessual perspectives need to be developed via investigations of specific archaeological topics, and require a far more historical orientation than is often acknowledged (Kristiansen 2004b). Indeed, historical ecology is one of the only sub-fields that has explicitly aimed to integrate seemingly conflicting scientific and humanistic perspectives (Crumley 1994; Kirch 1994). Recognizing the importance of historical and cultural contingencies in tandem with environmental constraints, proponents of historical ecology have aimed to meld, for instance, ecological perspectives with dialectics (Balée 1998: 13). Although historical ecology leaves epistemological differences between “positivist science and relativist humanism” unresolved (Whitehead 1998: 38), this need not prohibit scholars from acknowledging that both have a role to play as opposing but complementary positions.

Critical realist philosophies offer useful means to avoid divisive materialist-positivist and idealist-relativism extremes that underlie conflicts between processual and postprocessualist archaeologies. Although Watson (1991: 279-281) argued in the early 1990’s that archaeologists did not need to concern themselves with ontology, that fact that idealist positions he critiqued (see Watson 1990) have now had major influences in archaeology makes philosophy difficult to avoid (see Holtorf and Karlsson 2000; Wylie 2002). Frequently associated with Roy Bhaskar (e.g., 1975, 1998 [1979]), critical realism maintains that empirical realities exist but are intertwined in variable, topic-dependent ways with observations, interpretations, and perspectives. A critical realist stance acknowledges that some aspects of the world are accessible with more objectivity than others and provides an intermediary stance that can mediate between positivist/empiricist contributions of science and the interpretivist/relativist stance of postmodernism in ways particularly useful to social sciences (Archer et al. 1998; Danermark et al. 2002). Bryant describes the utility of critical realism in mitigating conflicts between positivist and postmodernist perspectives in history:

Realist epistemologies are united in the postulate that what historians strive to represent in their narratives is not the reconstruction of ‘a dead world in its completeness’…but rather a concourse of the key events and institutional developments that imparted directionality and order to some selected domain of the past (Bryant 2000: 516).
His use of the term “directionality” does not imply any teleological process but instead some understandable meaningfulness that structured change in particular historical contexts. Megill (1994: 1-20) similarly describes four ‘senses’ of objectivity, including dialectical objectivity in which knowledge is constructed (or construed) at the interface of observations, and observers’ interpretations, realizations, and explanations of objects (cf., Ruby 1996). Although advocates of science claim that postmodernism undermines researchers’ ability to comparatively evaluate claims, proponents of interpretative analyses do have ways of evaluating the relative merits of competing accounts. As with science they are complex and challenging to rigidly define, but most centrally include considerations of ‘arbitrariness’—the extent to which independent evidentiary materials are consistent with interpretative contentions—that are most readily established with reference to specific cases, disciplinary procedures, and standards of argumentation (Bhaskar and Lawson 1998; Segal 1999). Although some will invariably claim that, “the evidentiary materials utilized by historians are subject to such catalytic reconstitution in the course of narrative emplotment as to render rival accounts empirically incommensurable” (Bryant 2000: 494), limited acknowledgement of postmodernisms’ contributions does not require an anarchistic free-for-all of interpretative liberty. Claims regarding topics such as ideology, intentionality, and motivations are more difficult to substantiate or refute, but they are indeed subject to critique, evaluation, and comparisons with evidence. One can identify innumerable published examples of faulty scientific and interpretive analyses, but these do not prove that the underpinnings of either are fatally flawed or that approaches aiming to draw a balance between materialism-idealism, objectivity-subjectivity, or nomothetic-idiographic perspectives are ill-advised.

Although familiarity with philosophical positions on epistemology and ontology is important, philosophers engaged in long-standing debates about subjectivity versus objectivity in the social sciences (e.g., Bunge 1998; Turner and Roth 2003) cannot conclusively resolve similar problems in archaeology for us. For example, Trigger (1989: 790) and Shanks and Hodder (1995: 19) reference Bhaskar but arrive at very different interpretations of what his writings mean for archaeology. Degrees of objectivity and subjectivity are (to a substantial degree) problem specific. As Hodder noted,

In my view it is not possible to resolve the identity of, and tensions between, object and subject except in practice. What matters is whether we can develop archaeological techniques...which are adequately integrative (Hodder 1999:24).
But it is the extent of interpretive liberties and the nature of potential integration that are the primary essence of dispute. Critical realist positions—that recognize empirical realities that are in some instances acquiescent to social construction—are superficially similar to concepts of “guarded objectivity” and “reflexivity” Hodder advocates (1991, 1999). But Hodder (1999, 2003), and Jones (2002) still aim to eliminate scientific perspectives from archaeological theory when neither limited objectivity nor reflexivity must necessarily exclude hypothesis-testing or materialist reasoning, which to many still provide highly informative means of archaeological inquiry.

2.4 Landscape Methods as a Means of Integration

Landscape approaches have long and diverse histories in archaeology that reflect theory trends and have been suggested as an avenue for bridging gaps between processual and postprocessual archaeologies (Anschuetz et al. 2001: 159; Fisher and Thurston 1999; Wilkinson 2003: 4-7; 2004: 334-336). According to contemporary theory trends, the question—what is landscape archaeology—is likely to illicit a variety of dramatically different answers. One type of response would connect landscape perspectives with cultural ecology, quantitative geography, regional and settlement pattern analyses, and geoarchaeology (e.g., Clarke 1977; Haggett 1966; Johnson 1977; Steward 1955a; Trigger 1968). Another would emphasize connections with interpretive geography and history (including Annales history), phenomenology, hermeneutics, and abstract concepts including agency, symbolism, ritual, and ethnicity (e.g., Bourdieu 1977; Braudel 1972 [1949]; Cosgrove 1984; Daniels and Cosgrove 1988; Heidegger 1996 [1927]). Both traditions apply a diverse range of landscape oriented methods from interpreting “dwelling” (Ingold 1993: 152) or “being-in-the-world” of ancient landscapes (Tilley 1994: 12), to quantifying associations between landscape conditions and human behavior (e.g., Rossignol and Wandsnider 1992). There remains, however, a distinct lack of dialogue between these two, and disagreements about whether or not traditionally materialist views of landscape need to be reoriented or replaced (e.g., Bender 1999a vs. Feinmann 1999).

Landscape perspectives have played a crucial roles in archaeological survey (e.g., Wilkinson 2003), geomatics (e.g., Gillings et al. 2000), and ethnoarchaeology (e.g., David and Kramer 2001). After a brief historical overview of different landscape approaches, discussions of these three methods will help illustrate how they can respectively drawn on the strengths of both processual and postprocessual archaeologies.
During the 1950’s and 1960’s a number of influential works, including Gordon Willey’s (1953) *Prehistoric Settlement Patterns in the Viru Valley, Peru* and Robert Adam’s *Land Behind Baghdad* (1965) began to illustrate the importance of investigating not only ancient settlements themselves but the wider distribution of sites and human activities across landscapes. Drawing on the concepts and developments in geography including the Central Place Theorem (Chistaller 1933) and locational analysis (Haggett 1966), archaeologists during the 1970’s adapted a wide range of methods for archaeological spatial analyses. Early methods included consideration of settlement pattern determinants (Trigger 1968), site catchments (Vita Finza and Higgs 1970), monument landscapes (Renfrew 1973), and a variety of spatial-statistical techniques (e.g., Hodder and Orton 1976). Through the late 1970’s and 80’s, archaeological survey and regional analysis became hallmarks of research frameworks with geographically broad objectives (Ammerman 1981; Johnson 1977). Settlement pattern studies included analyses of site hierarchies using rank-size analysis and Thiessen polygons (e.g., Johnson 1980; Renfrew 1973). Issues of survey coverage and problems encountered in categorizing areas as ‘sites’ contributed in the 1980’s and 90’s to arguments for site-less survey, Full Coverage Survey (FCS), and distributional archaeology (Dunnell 1992; Dunnell and Dancey 1983; Ebert 1992; Fish and Kowalewski 1990). More recent methods have continued to draw on point pattern and spatial analysis techniques in geography with archaeologists applying increasingly sophisticated techniques (e.g., Savage 1997; Voorrips and O’Shea 1987). Since the 1980’s, GIS as become a primary analytical tool that has led to more efficient applications of preexisting settlement pattern analysis methods (including Thiessen polygons and nearest neighbor statistics) as well as introducing new quantitative techniques, including terrain and Boolean map calculation analyses (see Kvamme 1989, 1999; Wheatley and Gillings 2002).

By the late 1980’s postprocessual critiques of scientific-materialist perspectives had begun to influence landscape oriented research. While North American researchers (particularly in cultural resource management) had become focused on economic-ecological dimensions of the human past (as evident in predictive modeling, see Judge and Sebastian 1988), many in Europe pursued interpretive approaches focused on cognitive and perceptual aspects of archaeological landscapes (e.g., Wagstaff 1987). Braudel’s (1949) seminal approach that subdivided the Mediterranean historical landscape according to events at different temporal scales (événements, conjunctures, and longue durée) sparking *Annales* history, had important role in instigating multi-temporal and multi-scalar methods that border processual/postprocessual viewpoints (Barker 1991,
Interpretive geographers who examined how ideologies are connected with ways people view and represent landscapes (e.g., Cosgrove 1984), stimulated analogous interests in ideological archaeological landscapes (e.g., Tilley 1994). Early studies considered monuments, mortuary practices and use of space (e.g., Barrett 1988; Thomas 1991), urban layout and cosmology (e.g., Ashmore 1989) and use of built-spaces as representations of social relationships (e.g., Leone 1984). Particularly since the mid 1990’s, interpretative archaeologies have generated an explosion of landscape research, resulting in a great number of edited volumes (e.g., Ashmore and Knapp 1999; Bowden 1999; Chadwick 2004; Hirch and O’Hanlon 1995; Ucko and Layton 1999) and innumerable journal publications (see Anschuetz et al. 2001). While GIS methods have retained significant popularity among proponents of postprocessualism, struggles to reconcile interpretive theory with the largely quantitative, science-oriented background of GIS have led some to argue that GIS is inherently predisposed to environmental determinism (e.g., Gaffney and van Leusen 1995; Wheatley 1993; see below).

2.4.1 Landscapes and Archaeology Survey: Since the 1950’s and 60’s landscape perspectives and archaeological survey have together developed as the result of movements away from individual sites as analytical foci. Although landscape has served as a framework for constructing narratives that pursue chronological/historical rather than explicitly processual or postprocessual methods (e.g., Banning 1996; Barker 1995, 2000; Cherry 1991; Crumley and Marquardt 1987; Wilkinson 2003), there remains a wide distinction among scientific versus interpretive approaches to landscapes and survey.

Although issues of landscape and archaeological survey span a tremendous range of topics, some of the most pronounced distinctions between processual and postprocessual methods involve conflicting views about sampling. Processual conceptions of landscapes implicitly rely on the view that for any region/time period there is an archaeological landscape waiting to be retrieved and reconstructed, while interpretive methods depend on the contention that there can be many equally appropriate, archaeologist-specific encounters with landscapes. Indeed, these views are reflected in disparate survey methods. Faced with limited time and resources, surveyors are often faced with challenging choices between systematic versus judgmental, opportunistic sampling. While advocates of scientific methods have sought increasing sophisticated sampling methods appropriate for quantitative analyses (see Banning 2002; Collins 2003; Orton 2000; Stafford 1995), interpretive studies have deliberately
eschewed systematical sampling (e.g., Tilley 1994). Unless archaeologists are beholden to rigidly materialist or idealist views of landscapes both have something significant to contribute. Non-systematic or non-random samples are inappropriate for many types of statistical analyses, but for some this is not an analytical goal. Rigid adherence to systematic sampling can result in substantial amounts of time spent in areas lacking evidence relevant to issues particularly surveys seek to address. Although judgmental or opportunistic sampling provides non-replicable information based on idiosyncratic decision making; opportunistic vehicle survey, asking local residents, or relying on past experiences are not necessarily inappropriate depending on the purpose for which they are employed. The most powerful approaches utilize a combination of both systematic and opportunistic survey so they can both generate data appropriate for quantitative analyses, and take advantage of archaeologists’ and locals’ idiosyncratic knowledge of areas where certain types of remains are likely to be found.

2.4.2 Landscapes and Geomatics: A field of study concerned with collection, management, and analysis of spatial information, geomatics offers a variety of informative means for investigating archaeological landscapes. Geomatics encompasses a range of closely-related data generating and analytical tools including satellite remote sensing, Global Positioning System (GPS), and Geographic Information System (GIS) technologies (Kavanagh 2003). Applications of each of these technologies (often independently) have recently become common in archaeology (e.g., Barratt et al. 2000; Ebert 1984; Kvamme 1999); together they offer an even more valuable research triad. Satellite remote sensing provides a variety of means for visualizing and classifying landscapes, GPS provides means for mapping archaeological remains, and GIS provides a framework within which remote sensing and GPS data can be manipulated and analyzed.

Processual and postprocessual landscape approaches apply many of the same geomatics tools and information sources, but in substantially different ways. Air photographs were used for archaeology as early as the late 1800’s (Ebert 1984; Stein 1919), but since then have become far more than just pictures from above. Although aerial and satellite imagery were initially pursued as a means of identifying undiscovered

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2The term geomatics is used here to describe a range of geospatial mapping technologies related to Geographic Information Systems, other terms including Geographic Information Science (GIScience) similarly describe the study and use of technologies for acquisition, management, and analysis of spatial data (see Longley et al. 2001: 21-23).
archaeological sites they have more recently become an important means of characterizing environments and visualizing landscapes. Air photos and satellite imagery have proved particularly useful in Southwest Asia where generally little cloud-cover provides unobstructed views of physical landscapes (Kouchoukos 2001). Since the 1980’s advances in computer software for handling imagery have dramatically increased capabilities for air photograph and satellite imagery manipulation (see Ebert 1984; Lillesand and Kiefer 1993; Sanchez and Canton 1999). New types of multispectral satellite imagery such as LANDSAT (Allan and Richards 1983; Custer et al. 1986; Clark et al. 1998), RADAR imagery (R.E. Adams 1981; Dabbagh 1998; McCauley 1986, McCauley et al. 1982; Wendorf 1987), and recently declassified satellite photographs such as CORONA (Ur 2003) have remained important tools of landscape methods. Although some have argued that “western” maps provide inherently ethnocentric views of landscapes (Bender 1999b), and satellite imagery has even been criticized adopting “god-trick” perspectives that provide culturally condescending omnipotent views from above (e.g., Zubrow 2003: 173), it is possible to acknowledge contrasting perspectives without abandoning remote sensing methods. Applications of satellite remote sensing in geography, for instance, have pursued ways of comparing imagery-derived with indigenous views of landscapes (Jiang 2003; Robbins 2001, 2003), and such methods offer a promising future avenue for ethnoarchaeological investigations, such as those briefly introduced in Chapter 10.

Geographic Information Systems (GIS) are one of the primary methodological arenas where explicit conflicts between processual and postprocessual conceptions of archaeological landscapes have centered (e.g., Gillings and Goodrick 1996; Kvanme 1997; Maschner 1996; Stoddart 1997; van Hove and Rajala 2004; Wansleeban and Verhart 1997; Wheatley 1998). GIS was traditionally lauded as a tool that could allow social scientists more objective, quantitative, scientific means for spatial analyses (e.g., Openshaw 1991). However, GIS is inherently pre-disposed to inclusion of data that are more readily available, and more easily represented as maps. For archaeology, these data are often environmental (e.g., soil cover, elevation, aspect, and slope) and GIS is therefore (to some degree) bias toward materialist analyses that consider associations between environmental conditions and ancient human behavior (e.g., Gaffney and van Leusen 1995; Wheatley 1993, 1998).

A traditionally common application of GIS in archaeology, archaeological predictive modeling makes extensive (sometimes indiscriminate) use of pre-existing environmental data sets (see Ebert 2000: 132; Maschner 1996: 303) and has been subject
to criticisms for emphasizing environmental in lieu of sociocultural factors (e.g., Gaffney et al. 1995; Wansleeban and Verhart 1997; Wheatly 1998). In a recent textbook on GIS in archaeology, Wheatley and Gillings dedicate an entire chapter to predictive modeling but conclude that, “unresolved methodological issues [and] theoretical concerns” (2002: 181) plague predictive modeling. Although admitting that they are active critics of predictive modeling (and therefore are not impartial) they surprisingly refer readers to recent literature in order to “formulate an opinion as to whether Predictive Modeling has a future in archaeology” (Wheatley and Gillings 2002: 181).

Dismissive appraisals of predictive modeling, and corresponding vigorous retorts derive from unresolved theory conflicts between materialist and idealist positions. Since postprocessualisms inception its proponents have constructed their arguments around critiques of processualism for overemphasizing the importance of ecological and economic factors. But in contradiction with such assertions, archaeological predictive modeling results demonstrate that environmental variables (such as slope and distance to water) are demonstrably associated with, and play important roles in shaping site location choices (e.g., Kvamme 1985; 1992). Such findings have prompted vigorous reactions from scholars wedded to contentions that physical environments are of limited significance, who thus accuse predictive modeling of reiterating “an environmentally or functionally determinist analytical viewpoint of a type which has largely been rejected by the archaeological community” (Gaffney et al. 1995: 211). Practitioners of predictive modeling have offered correspondingly vigorous rebuttals, emphasizing that rigid environmental determinism is a dogmatic, long-outdated standpoint that only serves as a misguided rhetorical caricature of predictive modeling (e.g., Kvamme 1997). Since spatial modeling techniques based on predictive modeling comprise a significant component of the following study, these issues reappear and will be more extensively discussed in Chapters 4, 10, 11, and 12. Even though predictive modeling does encounter problems in more readily incorporating environmental data, these problems do not necessarily render predictive modeling methods outdated or theoretically ill-informed. The most critical deficiencies lie not necessarily in predictive modeling methods themselves, but most primarily in how predictive modeling results that are bias toward environmental data have been presented as comprehensive explanations of site distributions (see Church et al. 2000; Ebert 2000).

Given criticism that GIS analyses premise materialist explanations, archaeologists on both sides of processual/postprocessual debates have sought means of better incorporating social evidence (see Church et al. 2000; Kvamme 1999; Llobera 1996,
2000, 2001; Stancic and Kvamme 1999; Wise 2000). Viewshed, visualization, and virtual reality analyses have offered insightfully new, idealist-oriented representations of landscapes (e.g., Forte and Williams 2003; Gillings and Goodrick 1996; Llobera 2001). However, these more qualitative methods are subject to many of the same information source and data manipulation challenges as predictive modeling or any other GIS method. Viewsheds, for instance, utilize elevation data (most commonly digitized from topographic maps) that requires processing and manipulation steps that can dramatically influence representational outcomes (Hageman and Bennett 2000; Lock 2000b). As first defined in geography, The Modifiable Areal Unit Problem (MAUP; see Openshaw 1983; Openshaw and Taylor 1979) describes scale and data categorization pitfalls with profound (yet seldom addressed) importance for understanding GIS results (McCorriston and Harrower 2005). MAUP and related data processing issues form a significant component of geomatics methodologies outlined in Chapter 4 and results described in Chapter 10.

Global Positioning System (GPS) mapping is now a common means of recording landscape distributed archaeological remains, but is rarely dealt with in publication (for exceptions see Barratt et al. 2000; Branting 2002; Harrower et al. 2002). How GPS recording techniques influence conceptualizations of space has been subject to surprisingly little consideration. Initially GPS receivers used in archaeology offered only the ability to record points, exasperating pointillism (the tendency to reference spatially-distributed entities as isolated points, see Gillings and Goodrick 1996). Many GPS receivers now provide the ability to record spatial data as points, lines, and polygons (vectors). These methods take continuous archaeological landscapes and make them discrete in ways that have important ramifications for recording spatially distributed evidence; more detailed considerations of their impacts are undoubtedly overdue.

2.4.3 Landscapes and Ethnoarchaeology: Most broadly defined as “ethnography for archaeology” (David and Kramer 2001: 11), ethnoarchaeology provides a variety of informative means to enhance understanding of archaeological landscapes. Although not specifically referred to as ethnoarchaeology, using evidence of contemporary populations to understand ancient societies has an extremely long history that predates anthropology (see Hodder 1982: 31-33). Although late 19th - early 20th century methods (e.g., Morgan 1964 [1877]) were rejected for positing an ethnocentric, teleological, unilinear sequence through which human societies supposedly progressed (see Yoffee 1993); use of ethnography for archaeology has been widely prevalent, including among some of the
most vocal advocates of both processual and postprocessual archaeologies (Binford 1978; Hodder 1982). A variety of ethnoarchaeology-type methods; including action archaeology that aimed to document the material culture of living groups (e.g., Kleindienst and Watson 1956); and living archaeology that concentrates on material residues as representative of behavior (e.g., Gould 1980), are now commonly subsumed under the title ethnoarchaeology (David and Kramer 2001: 6-7).

As practitioners of ethnoarchaeology have long recognized, archaeology involves investigations of residual material remains (rather than direct observations of human behavior), so archaeologists face profound challenges in interpreting what material records do and do not reveal about ancient peoples (see David and Kramer 2001; Kramer 1979; Yellen 1977). The use and abuse of analogies has been a subject of much discussion (e.g., Aschner 1961; Binford 1985; Gould 1985; Gould and Watson 1982; Wylie 1982, 2002). Particular attention must be paid to both source (ethnographic) and subject (archaeological) side contexts since both can be prone to misinterpretation (Stahl 1993). Binford (1968; 1985), emphasizes hypothesis testing as a means of evaluating (or alternative to) analogies, and in recent monograph that examines ethnographic hunter-gatherers as “Frames of Reference” he avoids the term analogy (Binford 2001). But the hypothesis testing procedures Binford (2001) applies (like analogies) depend on interpretations of data (including interpretations of graphs) that are similarly disputable (Shott 2002). As Wylie (1982) emphasized, “An Analogy by Any Other Name is Just as Analogical”, and as David and Kramer (2001: 1-2) similarly maintain, archaeological interpretations are invariably founded on analogies drawn from archaeologists’ own and others’ cultures.

While studies of irrigation rarely utilize the term ‘ethnoarchaeology’, a wide array of ethnographic studies of irrigation, including some specifically directed toward archaeology (e.g., Kirkby 1973; Lees 1973), have addressed social aspects of irrigation (see Chapter 5). Since irrigation systems are widely distributed across landscapes, irrigation and landscape form a uniquely complementary, yet surprisingly rare thematic combination. As advocates of interpretive approaches have emphasized, landscapes are constructed not only in terms of environment, economy, and technology, but are construed according to sociopolitical and ideological understandings (Layton and Ucko 1999). Particularly since social relations (including socio-logistics of irrigation) are not directly observable archaeologically, ethnographically irrigated landscapes are of considerable utility in considering ancient ones.

25
2.5 Summary

In conjunction with the regional goal of examining irrigation’s origins in Southwest Arabia, this study explores the divide between (and potential for complementary integration of) processual and postprocessual perspectives. Archaeology has recently become increasingly divided by conflicts that reflect opposing scientific-materialist and humanistic-idealist epistemologies. While materialism and idealism are often viewed as fundamentally incompatible, intermediary positions that acknowledge empirically knowable realities in combination with the often theory-construed nature of observations provide opportunities to draw on the strengths of both scientific and interpretive archaeologies. This study utilizes a critical realist, landscape-oriented analytical framework and applies a combination of archaeological survey, geomatics, and ethnoarchaeological methods to examine how environmental and social factors shaped the origins of irrigation in ancient Southwest Arabia.
CHAPTER 3

THE HISTORY OF RESEARCH ON ANCIENT IRRIGATION IN SOUTHWEST ARABIA

While archaeological survey, geomatics, and ethnoarchaeology set within context of contemporary theory trends provide informative means of investigating the origins of irrigation in Southwest Arabia, these methods require considering what has previously been learned about irrigation in the region. Irrigation has long remained a point of scholarly interest in ancient Southwest Arabia. A considerable number of Italian, French, German, American, and Arab researchers have made tremendous strides toward understanding ancient systems particularly those of ancient state capitals. This chapter focuses on describing the history of research on ancient irrigation to convey a sense of how research has progressed, and to identify gaps in present knowledge that require continued investigation. Although a descriptive typology of Southwest Arabia irrigation systems is reserved for Chapter 6, and chronological discussion of Southwest Arabian prehistory is presented in Chapter 7, this chapter also provides some basic information on operation of irrigation. A subdivision is drawn between investigations before and after 1970. This date marks the official establishment of the Yemen Arab Republic (YAR) in the north and the People’s Democratic Republic of Yemen (PDRY) in the south and a general shift toward a greater diversity of large international archaeological projects, which include a considerable number of researchers that continue to work in the region today.

3.1 Investigations Before 1970

The 10th century geographer and historian al-Hamdani was one of the earliest scholars to provide first hand reports of irrigation works in Yemen. In the 8th book of his treatise al-Iklil, al-Hamdani describes castles and other monuments of Southern Arabia
and briefly mentions a number of large dams (Faris 1938: 34-35, 67-69). Although Yemen subsequently sparked the interest of European explorers from the 13th through 18th centuries (see de Maigret 2002: 23-91; Schippmann 2001: 23-30) it was not until the latter half of the 19th century that more published information on irrigation started to become available. In 1843 Joseph Arnaud arrived in Sana’a, visited Ma’rib and Sirwah, and made a sketch plan of ancient Ma’rib’s now famous dam (Arnaud 1874). During explorations in Yemen from 1882 to 1894 geographer Edward Glaser (1913) also visited the dam at Ma’rib and surveyed its prominent northern and southern sluices supplementing Arnaud’s description.

Although most early scholars were primarily interested in inscriptions, the 1930’s marked a period of expanding research concerns including wider archaeological exploration, excavation, and some additional information on irrigation. In 1936 Philby (1939) visited the Hadramawt where he made a map of the ancient temple complex ruins and described irrigation works of Shabwa, capital of the ancient Hadrami state. Following Freya Stark’s travels in the Hadramawt during 1935 (Stark 2001 [1936]), she returned with two companions, Gertrude Caton-Thompson and Elinor Gardner (Stark 2002 [1940]). During the winter of 1937-38 their team’s work near the town of Hureidha included excavations of the temple of the Moon God, Šīn and other nearby Iron Age tombs (Caton-Thompson 1944). In addition to excavations, Caton-Thompson and Gardner (who were trained as a prehistorian and geologist respectively) conducted innovative surveys that today would best be described as landscape geoarchaeology. They examined aeolian/alluvial silt sections, mapped an area of canals and field systems covering approximately 7 square kilometers, and traced the primary canal feeding that area for 16 kilometers (Caton-Thompson and Gardner 1939). Since their investigations were conducted prior to radiocarbon dating they could assign only approximate ages, but the pioneering geoarchaeological mode of observations they applied would later prove central to investigations of irrigation (cf. Bowen 1958; Brunner 1997a, 1997b). A number of other contributions were made during the 1930’s, including al-‘Azm’s description of irrigation at Ma’rib (see Ghaleb 1990: 68-69), and Hamilton’s (1942) brief excavations at Shabwa during the winter of 1938. During explorations in 1947, Egyptian archaeologist Ahmed Fakhry further described irrigation works near Ma’rib and Sirwah (Fakhry 1951).

Some of the most significant early advancements in the archaeology of Southwest Arabia came during the early 1950’s with the American Foundation for the Study of Man (AFSM) expedition led by Wendell Phillips (1950-1952). The AFSM team included a
number of scholars who made particularly important contributions to understanding ancient Southwest Arabia including F.P. Albright, Albert Jamme, Richard Bowen, and Gus van Beek. The team conducted excavations at Timna’ and Hajar Bin Humayd in Wadi Beihan, and of the temple of ‘Awwam at Ma’rib (Phillips 1955). They made substantive advances in deciphering inscriptions, establishing basic chronologies and artifact typologies for ancient kingdoms of Qatabān and Saba that were crucial in helping build understanding of ancient history in the region (Bowen and Albright 1958; van Beek 1952, 1969). Using air photos as a guide, Bowen (1958) surveyed ancient irrigation works along Wadi Beihan generating detailed descriptions and maps of large-scale floodwater irrigation including canals, sluices, and field systems. Although he focused on a 1200-meter long section, Bowen described systems of primary canals (up to 40 meters wide) that stretched for more than 30 kilometers. These primary canals were punctuated by periodic stone sluices that led through secondary and tertiary channels to earthen banked fields. Bowen coined the term ‘rectangular erosion’ to describe patterns of fields that along with canals and carefully masoned sluice gates were constructed as a planned, centrally coordinated system. He concluded that substantial-scale irrigation in Wadi Beihan probably developed in the eleventh or twelfth century BC, and initial systems were probably not earlier than the 2nd millennium BC (Bowen 1958: 87). Although the date of irrigation’s origins in Southwest Arabia would later be pushed back further, Bowen’s observations were ground-breaking for the time and he recognized potential links with early irrigation in the Levant/Mesopotamia that have received relatively little subsequent attention. Following fieldwork in Yemen, AFSM research in Dhofar, Oman in 1952-1953 made similarly important contributions to understanding large Iron Age settlements in a region that remains sparsely documented (Albright 1982).

A wealth of important work followed in south Yemen during the 1960’s, which until 1967 was loosely controlled by the British as the West and East Aden Protectorates. At the behest of the British Colonial Office, G. Lankester Harding (1964) conducted archaeological reconnaissance throughout portions of both protectorates in 1959 and 1960. Harding mentions remains of ancient irrigation in Wadi Jirdan (p. 33), Wadi Daw’an (pp. 27-28), and Wadi Idm (pp. 41-42) involving remnants of canals, sluices, and banked field systems preserved predominantly where stone constructions capped and prevented erosion of sediments around them. Curiously, as Ghaleb (1990: 87) noted, Harding (1964: 15) suggests a “gap in occupation…from the Neolithic period (about 5,000 B.C.) to the fifth century B.C.” for the Eastern Protectorate illustrating the extremely vague nature of information about regional chronologies available at the time.
Van Beek, Cole, and Jammes’ (1963) survey in Wadi Hadramawt during 1963 also reported on irrigation works of Hadrami landscapes, including large remnant canals in Wadi Daw‘an. Beginning as early as 1948, R.B. Serjeant (well known for work on a variety of cultural topics, see Serjeant 1995) made tremendous strides toward documenting and understanding technical and social logistics of irrigation (Serjeant 1974, 1983, 1988), and his work still provides some of the most detailed English language descriptions of Hadrami irrigation available (e.g., Serjeant 1964). Director of Antiquities in Aden during the late 1950’s and 60’s, Brian Doe also conducted important early research, later compiled in two books on South Arabian archaeology (Doe 1971; 1983).

3.2 Investigations After 1970

The 1970’s onward witnessed a significant expansion of archaeological research in Southwest Arabia including a comparative wealth of new information on irrigation. Beginning in 1975, a French team directed by Jacqueline Pirenne and Jean-François Breton explored the ancient Hadrami capital of Shabwa. Research in the area later culminated in a detailed reconstruction of ancient irrigation systems (Gentelle 1991). Since 1978, studies conducted under the auspices of the German Institute including investigations around Ma’rib and in Wadi Marhah (kingdom of ‘Awsan) also substantially contributed to understanding irrigation (e.g., Brunner 1997a, 1997b, 2000; Brunner and Haefner 1986; Hehmeyer 1989; Hehmeyer and Schmidt 1991; Schmidt 1988; Vogt 2004). In particular, German studies that estimated rates of accumulation on, and radiocarbon dated, irrigation-deposited sediments (e.g., Brunner 1983, 1997a, 1997b) have helped establish the time frame of floodwater irrigation’s development (see Chapter 7).

The 1980’s saw a considerable number of new and important projects in both the former YAR and PDRY. Italian research in Khawlan and al-Hada (southeast of Sana’a) focused on periods preceding Iron Age kingdoms, including excavations of Neolithic and Bronze Age settlements that provided crucial new evidence of domestic habitations (de Maigret 1985, 1986, 1990, 2002; Fedele 1988, 1990). Geomorphological studies conducted by Bruno Marcolongo and Alberto Palmieri in the Wadi Danah watershed (the drainage feeds the dam at Ma’rib) recognized both the significance of tectonic activity in altering drainage patterns, and the utility of paleostratigraphy (including dating of paleosols) in documenting less-arid conditions during the early Holocene (Marcolongo and Palmieri 1990). Their studies also assisted in observations about dams in the area (such as those in Wadi Qawaqah) better illustrating the breadth of irrigation in an area.
that would become the hinterlands of the Sabaean state (de Maigret 1985: 348).

The American Foundation for the Study of Man (AFSM) expedition was reconstituted for investigations in Wadi al-Jubah from 1982 to 1987 (Blakely et al. 1984; Glanzman and Ghaleb 1987; Toplyn 1984). The AFSM team applied considerable energies toward reconstructing paleoenvironments (Overstreet et al. 1988; Grolier et al. 1996) and one of the team’s members, Maurice Grolier, published an informative study using LANDSAT images to examine YAR hydrology (Grolier et al. 1984). A member of the AFSM team, Abdu Ghaleb, completed a crucially important dissertation on irrigation agriculture in ancient Radman and Wadi al-Jubah that used dated excavations of associated residential occupations to place the beginnings of irrigation during the late 6th millennium BP (Ghaleb 1990).

In 1983, the Joint Soviet-Yemeni Archaeological and Ethnographic Mission began work in the PDRY. The project (continued after 1989 as the Russian Mission) conducted a wealth of new research on the Paleolithic through Islamic periods (Amirkhanov 1994, 1996, 1997; Sedov 1995b, 1996a, 1996b; Souvorov and Rodionov 1999). The Soviet-Yemeni team conducted numerous important excavations that established ceramic typologies and documented irrigation at Raybun in Wadi Daw’an, and the Hadramawt generally (Rodionov 1994; Sedov 1995a, 2000). In addition to the large flashflood water systems that supported Raybun and Hureidha, as Sedov (1996a: 275) describes, analogous smaller systems also supported settlements nearby in Wadi Al-‘Ayn.

French-led surveys of the Jawf-Hadramawt and Ramlat as-Sab’atayn also began in 1983 (Inizan et al. 1997; Inizan and Ortlieb 1987). As well as discovering many early sites along the margins of ancient lakebeds, their findings better-described the ecology and chronology of paleolacustrine environments (Lezine et al. 1998). Based in part on interpretation of satellite imagery, their research also led to the crucially important observation that the Jawf-Hadramawt formed a single large drainage system that spanned the Ramlat as-Sab’atayn Desert during the early Holocene (Cleuziou et al. 1992).

Throughout the 1990’s a number of projects began work in a diversity of regions. French investigations in Shabwa Governate along Wadi Beihan and near Nisab (ongoing since the early 90’s, Breton 2000) have included work on irrigation in Wadi Beihan, Wadi Dura (Breton and Roux 2002; Coque-Delhuille and Gentelle 1997; Gentelle and Coque-Delhuille 1998; Marcolongo and Bonacossi 1997), and Wadi Surban (Breton 2000; Darles 2000). Although these studies have contributed information on both large and small-scale systems, like all studies of irrigation they have grappled with complex
dating challenges. Use of optically stimulated luminescence (OSL) dating techniques applied by this team hold great promise for assisting with the challenges of reconstructing chronologies (Balescu et al. 1998).

Starting in 1994, a team formerly coordinated from the University of Chicago, Oriental Institute has worked in the Dhamar region south of Sana’a. Although the project has conducted wide ranging surveys and excavations (Edens 1999; Edens et al. 2000; Wilkinson 1997, 1998a; Wilkinson and Edens 1999; Wilkinson et al. 1997, 2001) it has also specifically concentrated on the archaeology of terrace agriculture (Wilkinson 1999). Like those investigated by de Maigret and colleagues, Bronze Age settlements in Dhamar were likely supported by terrace agriculture and hillslope runoff systems similar to those still used in Yemen’s western highlands of today (cf. Eger 1987). Wilkinson and colleagues discovered a valley floor terrace wall and recovered a date for it that calibrates to 5,716 yrs BP, making it the oldest directly dated agricultural installation in Southwest Arabia. Fragmentarily preserved stone alignments on hillslopes below the fortified settlement of Hammat al-Qa suggest that hillslope agriculture at the site involved water diversion.

Since preliminary reconnaissance in 1996, the Roots of Agriculture in Southern Arabia (RASA) Research Project has conducted 4 field-seasons of survey and small-scale excavation concentrated on two tributaries of Wadi Hadramawt, Wadi Sana and Wadi Idm (McCorriston 2000; McCorriston et al. 2002). Evidence of irrigation first retrieved by RASA in 1998 (McCorriston and Oches 2001) forms the starting point for this study (see Chapter 4).

A long history of archaeological, geological, and epigraphic investigations has yielded information crucial to understanding technical and operational aspects of ancient large-scale Southwest Arabian irrigation. Although I will return to chronological issues in Chapter 7, a brief description of irrigation works of Sabaean kingdom, now by far the most intensively investigated of South Arabian systems (e.g., Brunner 2000; Brunner & Haefner 1986; Clark 1976; Dayton 1979; Francaviglia 2000; Hehmeyer 1989; Hehmeyer and Schmidt 1991; Schmidt 1988), exemplifies some of what is known about irrigation among ancient states in the region. Terrace agriculture and hillslope runoff irrigation began in Yemen’s western highlands during the 6th millennium BP (Ghaleb 1990; Wilkinson 1999). Over succeeding millennia early techniques culminated in vast flash-floodwater (sayl) systems along the margins of Ramlat as-Sab’atayn Desert. The dam at

\[34,970 \pm 80 \text{^14C yrs BP, Wilkinson 1999: 185, Wilkinson and Edens 1999:3}\]
Ma’rib (one of the largest irrigation structures of the ancient world) reached its apogee during the first few centuries AD (Francaviglia 2000) and its final form during the 5th or 6th century AD (Vogt 2004). The dam spanned an approximately 680-meter gap between bedrock outcrops, was at least 16 meters high, and diverted water (via two massive stone sluices at its northern and southern extremities) into an extensive system of canals that established a vast oasis in a naturally barren land (Brunner and Haefner 1986). Fields around Ma’rib exhibit patterns of rectangular erosion showing that canals irrigated (though not simultaneously) as much as 9600 hectares (Brunner 2000; Brunner and Haefner 1986). These patterns, the enormous scale of constructions, and associated inscriptions (Brunner and Haefner 1986; Clark 1976) show that irrigation at Ma’rib was coordinated by state authorities. Although research and debates continue about Ma’rib’s famous systems (Francaviglia 2002), as described in The Holy Quran, the dam collapsed for a final time during the last decades of the 6th century AD (Vogt 2004).

3.3. Discussion

Research on ancient irrigation in Southwest Arabia has focused predominantly on state-level systems and their predecessors in locales surrounding state capitals. But advanced state-level irrigation did not appear spontaneously and must have been preceded by increasingly refined techniques from which farmers accumulated knowledge of water flow patterns and developed labor-mobilizing means to control them. If large-scale irrigation in Yemen was indeed inspired by systems in distant regions as Bowen (1958) long-ago postulated, perennial flow irrigation techniques from Mesopotamia, for instance, would have needed to be adapted to Yemen’s unique environmental and social circumstances (Harrower in press). Although some can be speculated (based on ethnographic irrigation practices) about the types of irrigation that likely preceded large state-level systems, very few ancient small-scale irrigation structures have been directly dated. A basic outline of Holocene environmental change leading up to state systems can now be delineated (see Chapter 8), but far less is known about the social contexts within which irrigation developed. Many projects are still ongoing. Collaborative Russian-German work along the coast near Aden is generating new data on Bronze Age irrigation (Vogt et al. 2002). Recent work on subterranean infiltration galleries (Lightfoot 2000a, 2000b), including those of Ghayl ba Wasir (Hehmeyer et al. 2002) complements studies of aflaj irrigation in Oman (e.g., Costa 1983; J.C. Wilkinson 1977, 1983a). Hehmeyer’s (1995) work on medieval water control along the Tihama coast similarly provides insights for understanding floodwater capture techniques. Although studies of Southwest
Arabian irrigation offer a wide range of crucially informative evidence, research has potential to benefit most substantially from considerations of archaeological and anthropological findings about irrigation in other regions of the world (e.g., Mabry 1996a, 2000; Scarborough 2003). Wittfogel’s hydraulic hypothesis is long outdated, but a tremendous wealth of literature spawned by evaluations of it, and other studies of irrigation, bear important insights for helping understand ancient Southwest Arabian strategies and their social contexts (see Chapter 5). Reciprocally, sufficient information is now becoming available to trace more comprehensively the long-term chronology of irrigation in Southwest Arabia and contribute to larger cross-cultural debates about irrigation’s diverse influences on the trajectories of ancient societies.
CHAPTER 4

ANALYTICAL METHODOLOGY

In Southwest Arabia where water availability was (and is) of particularly critical importance for agriculture, the origins and early development of irrigation offer a wealth of opportunities to examine how this critical aspect of life structured trajectories of societies in the region. What factors were most crucial in shaping the development of ancient irrigation? In arid Southwest Arabia one might expect that prehistoric agriculture was structured by opportunities to harness scarce water resources, and therefore, that irrigation strategies would be closely connected with hydrological variables, including climate, topography, potential flow accumulation, and landform. But irrigation was also subject to social contingencies including the ability of communities to coordinate labor for construction, operation, and maintenance, lay claim to and allocate land, water, and resultant food products, and mitigate inevitable disputes. As a practice that transformed human relationships with nature, and both modes and relations of production, irrigation also likely involved significant changes in sociocultural relations, identities, and understandings of landscapes. In light of this distinction devising analytical methodologies to identify and address the relative influence of environmental and social factors presents considerable challenges. The comparative dichotomy posed between environmental and social factors raises numerous important issues from climatic, hydrological, and demographic, to cultural, political, and ideological. As the methodological and analytical approaches chosen ultimately influence outcomes and conclusions, from the outset emphasis was placed on letting research interests determine the analytical techniques chosen rather than letting the technological tools available (e.g., GIS functionality) dictate research procedures.

Using the Wadi Sana watershed as a case study, the combination of archaeological survey, geomatics, and ethnoarchaeology devised for this research
provides for both quantitative and qualitative analyses of environmental and social factors. Environmental and social parameters of irrigation are not mutually exclusive; that is, irrigation developed in relation to both: 1) arid, rugged terrain with intermittent, abrupt runoff, and 2) sociopolitics, variable motivations, interests, and interactions of individuals and social groups. Although archaeological survey provides the basic means of discovery and data collection, the most suitable techniques for analyzing hydro-ecological versus socio-logistical and ideological parameters differ. To examine the influences of environmental contingencies, geomatics analyses are employed to evaluate the hypothesis that, in terms of type and location, the remains of irrigation structures are closely associated with quantifiable hydrological variables reflecting close behavioral ties to environmental conditions. If successful irrigation was primarily a techno-environmental obstacle closely governed by environmental contingencies, Wadi Sana’s prehistoric inhabitants would have directed substantial time and energy toward designing or remodeling structures, considering potential irrigation structure location options, and planning irrigation structure location choices. Alternatively, if irrigation was more primarily a function of social factors, less governed by environmental and hydrological contingencies, irrigation structures could (and therefore probably would) have been distributed in patterns less correlated with hydrological variables and Wadi Sana’s prehistoric inhabitants would have directed more time and energy (within the context of irrigation) toward addressing concomitant social obstacles, including how to stake and support claims to land and water, cooperatively or coercively mobilize labor for construction, operation, and maintenance activities, and mitigate inevitable disputes.

However, this hypothesis and the geomatics methods used to evaluate it conceive of the problem in predominantly in materialist terms, so it is important that the deficiencies of these methods are considered. Geomatics methods provide rigorous quantitative means of evaluating associations between environmental conditions and human behavior, but methodologically and analytically these techniques are particularly well suited to inclusion of environmental variables (such as landform and hydrological data) that are readily available and quantifiable in formats amenable to computer-based mapping. In contrast, geomatics techniques often tend to preclude consideration of social factors that are not always manifest spatially and are more difficult to quantify as maps. Who was involved in, and responsible for design, operation, and maintenance of irrigation facilities? How were these individuals or groups motivated and mobilized? How was irrigation connected to, and how did it shape, social landscapes? These social questions go beyond what quantitative GIS analyses can address, and are difficult to
consider with geomatics alone. To ameliorate this deficiency, ethnoarchaeological investigations provide for a more detailed appraisal of relevant social interactions within and among human groups. For this study ethnoarchaeology involves an ethnological overview of irrigation, synopses of typological and social aspects of contemporary irrigation in Yemen, and a preliminary field study of contemporary water-use in present-day Wadi Sana. Although geomatics can to some extent address social factors, and ethnoarchaeology can to some extent address environmental factors (indeed, the suitability of these methods varies dramatically according to specific types of evidence and research objectives), in this case a combined approach offers far more balanced means to consider both environmental and social elements of irrigation than either method in isolation.

4.1 Archaeological Survey

Archaeological survey was organized in conjunction with the Roots of Agriculture in Southern Arabia (RASA) Research Project. RASA Project investigations in 1998 and 2000 identified check dams, water diversion channels, and earthen-banked fields in a number of locales along the Wadi Sana drainage of Hadramawt Province, Yemen (Figures 1.1 and 4.1). Test excavations of two different check dams were completed in 1998 to examine sub-surface preservation and retrieve samples for dating. Although these efforts generated promising new evidence, and approximate dates for irrigation (McCorriston and Oches 2001), they raised important questions that could only be answered by additional survey. When (more precisely) did irrigation begin in the area; and how many other ancient structures were still preserved along the length the Wadi Sana? As RASA planned fieldwork for 2004 that would expand survey efforts up and down Wadi Sana from the middle Wadi Sana locale where intensive survey concentrated in 2000, a plan was devised to conjoin survey efforts for this dissertation. Since drainage basins provide particularly appropriate study areas for analyses of irrigation (e.g., Kelly 1983: 881), the 3600 sq. km Wadi Sana watershed was adopted as the primary study region for both RASA Project survey and survey conducted specifically for this dissertation. The bulk of survey that generated a sample of 174 irrigation structures was conducted during an eight-week field season from January to April 2004.

The survey methodology for this research combines systematic sampling techniques utilized by the RASA Project, with opportunistic sampling specifically designed for rapid discovery and recording of water management and irrigation. A program of judgmental, opportunistic sampling was conducted to generate data sufficient
for GIS analyses of irrigation structure distributions. Data from stratified random sample strips conducted by RASA were made available to provide a wider breadth of archaeological information and facilitate comparison with areas where survey did not identify irrigation. Small test excavations were dug in five locales to examine subsurface remains and retrieve samples for radiocarbon and Optically Stimulated Luminescence (OSL) dating.

During the course of general RASA survey ancient water management and irrigation structures were recorded wherever they were encountered (Appendix A). In 2000, the RASA team conducted intensive survey of an approximately two square kilometer area immediately surrounding a prominent triangular inselberg at the confluence of Wadi Sana and Wadi Shumlya known locally as the Khuzmum (see Figure 4.1; McCorriston et al. 2002). Using methods consistent for all RASA survey, these efforts involved 10-meter spacing between surveyors within survey units consisting of a single landform class delineated by GPS (Harrower et al. 2002). Major archaeological features were recorded as points, lines, and polygons using a Trimble Pathfinder Pro XRS backpack with real-time differential correction. In 2004, RASA expanded survey efforts up and down Wadi Sana to complete a total of fifteen 100-meter wide survey strips, twelve along the Wadi Sana main channel selected via stratified random sampling, and three judgmentally selected throughout the Ghayl bin Yumain basin (McCorriston et al. 2005a).

In addition to RASA survey, a recording approach was devised to specifically target water management and irrigation. This approach involved reconnaissance and recording of areas judgmentally identified based on inspection of LANDSAT and ASTER satellite imagery, and surveyors’ knowledge of potentially irrigable areas. The same Trimble GPS backpack used by RASA was used to record the locations of irrigation structures and associated remains. Reconnaissance forays were conducted by vehicle teams equipped with two-way radios. When areas with potential for preservation of ancient irrigation were encountered (i.e., areas beyond the currently active wadi channel where remnants of ancient water-borne sediments and gravels are preserved) surveyors covered them on foot at 30-meter spacing. Inclusion of random sampling data generated by RASA ensured coverage of areas where irrigation might not have been expected. Field teams were more widely spaced than those of RASA (30-meter spacing as opposed to 10-meter spacing) as irrigation structures are far larger and more easily identifiable

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4 Real-time differential correction was purchased as a separate satellite signal from Omnistar Inc. (www.omnistar.com).
from a distance in comparison with other remains such as lithic scatters and ancient hearths of more primary interest to RASA. Although survey was conducted primarily along Wadi Sana, a single day was also spent driving the length of Wadi Himiyyari where two areas of ancient irrigation were recorded. The southern reaches of Wadi Sana’s main channel (north of Qalat Habshiya) consist of a narrow canyon (150-250m wide) lined by cliffs hundreds of meters high (Figure 4.2). Surveyors can see throughout this canyon from a vehicle, and since neither the channel at the base of the canyon nor the cliff tops offer areas feasible for irrigation this area was covered predominantly by vehicle survey. To the north (starting approximately 14 km north of Qalat Habshiya), this canyon widens to 300-600 meters wide as it passes the Khuzmum (Figure 4.3). During approximately 2-weeks of survey, a sustained effort was made to cover this area as far north as time permitted. Ultimately this was accomplished throughout an approximately 15 kilometer strip stretching 11 km south and 4 kilometer north of the Khuzmum (an area for which RASA subsequently obtained a diagonal strip of high-resolution QuickBird imagery, Figure 4.4). Data for areas to the north of this area of concentrated survey, and south of Qalat Habshiya, were generated predominantly by RASA.

4.2 Geomatics Analyses

Geomatics techniques were first introduced for RASA research to facilitate basic navigation and mapping in a region where few pre-existing maps were available. As investigations progressed geomatics became an increasingly significant component of RASA research, particularly as a means of conceptualizing and visualizing the spatial distribution of archaeological remains (Harrower et al. 2002; McCorriston and Harrower 2005). Although LANDSAT satellite imagery was initially obtained to create study region maps and overlay GPS data, it was quickly recognized that such imagery could serve as a tool for landscape characterization that could be used to examine how archaeological remains were distributed across landforms. Prior to fieldwork in 2000 a series of 1:25,000 scale pseudo-color and LANDSAT landform classification image maps were produced for areas along the main channel of Wadi Sana (Harrower et al. 2002).

Building on techniques employed for RASA, this study applies a combination of geomatics methods to visualize, analyze, and model the distribution of irrigation structures. Four types of satellite imagery, MODIS, LANDSAT, ASTER, and QuickBird were used as tools for visualization and data generation (Table 4.1). A 250-meter resolution MODIS image was used for small-scale image mapping of the western
Arabian Sea region (Figure 1.1). One LANDSAT scene provided 30-meter resolution coverage of an area from the Arabian Sea coast to Wadi Hadramawt, while two ASTER scenes provided up to 15-meter resolution coverage for a 60 by 120 kilometer area slightly smaller than LANDSAT (Figure 4.1). Quickbird imagery was obtained for a 75 square kilometer portion of middle Wadi Sana offering 60-centimeter resolution coverage used to visualize local areas in detail (Figure 4.4).

Three principle geomatics modeling techniques, Digital Elevation Model (DEM) extraction, landform classification, and GIS hydrological modeling were used to generate data for analyzing the distribution of irrigation structures. A DEM consists of grid cells with associated elevation values, while a landform classification image consists of grid cells with associated landform category values. Digital Elevation Models are a primary means of representing terrain and topography in GIS, and are necessary for GIS-based hydrological modeling tools that use DEM values to calculate flow direction, flow accumulation, define channel networks, and watershed boundaries. Using the two stereo bands of ASTER imagery, a 15-meter resolution DEM was extracted for a 60 by 120 kilometer area covering the entire Wadi Sana watershed. The first 9 bands of ASTER and slope derived from the DEM were used to create a landform classification image for the same area. GIS hydrological modeling was conducting using the ArcHydro module for ArcGIS (Maidment 2002). Using the aforementioned DEM this module determines flow direction by defining for each grid cell the immediately adjacent cell with the lowest elevation value. Since each grid cell has 8 neighbors this method is known as the 8-direction pour point model (Olivera et al. 2002: 68-72). Once a flow direction grid was generated a flow accumulation grid was produced by determining how many cells would flow into any given cell in the study region. By setting a threshold number of cells (between 500 and 5000) channel network maps were produced and channel intersections were used to define flow catchments.

Once GIS data layers were generated, spatial modeling was conducted to quantitatively evaluate relationships between the environmental variables and the distribution of irrigation structures. These methods are based on those of archaeological predictive modeling with one critical difference. Rather than concentrating on predicting the location of undiscovered irrigation structures, modeling efforts concentrated on quantification and understanding variables that best account for the location of known structures. Archaeological predictive modeling generally involves two sequential steps: 1) identifying variables that are correlated with site locations and, 2) developing models based on those variables to predict site locations (e.g., Kvamme 1985, 1990a). A
A tremendous number of archaeological predictive modeling analyses have been conducted (see Judge and Sebastian 1988; Kohler and Parker 1986; Kvamme 1990a; 1999; Wescott and Brandon 2000; Wheatley and Gillings 2002: 165-182). But many modeling efforts have focused on the second step (predictive capacity) without critically examining if, how, and why particular variables are not only associated with but are casually responsible for site distributions. This can be attributed to a number of factors. Many modeling efforts are conducted for archaeological resource management, so that completion of the second step (predicting locations of undiscovered sites) is required so models can be used to weigh the archaeological potential of un-investigated locations and help mitigate damage to archaeological resources. Unfortunately in many cases it has not seemed to matter how or why models gain predictive capacity; only that they do. In cases that do not involve cultural resource management, researchers have still (in some instances) focused on predictive capacity as a means to evaluate the accuracy of modeling results. In effect it is tacitly assumed that if modeling results accurately predict site locations, then something about ancient behavior has been explained. Although numerous researchers have emphasized that prediction is not synonymous with explanation (e.g., Kohler and Parker 1986; Dalla Bona 1994) the complexities of predictive modeling have meant that explanation often becomes an afterthought rather than a primary analytical goal. In fact, predictive capacity can be the result of site preservation or site identification factors that have no relationship with ancient human behavior. The more explanatory first step (modeling known ‘site’ locations) with greatest potential to improve understanding of past human behavior and contribute to archaeological theory (cf. Church et al. 2000; Ebert 2000; Stancic and Kvamme 1999) deserves more exclusive emphasis.

Archaeological predictive modeling has been subject to vehement criticisms for positing relationships between human behavior and environmental conditions without critically evaluating them (see Wheatley and Gillings 2002: 179-181). These criticisms have been centered on two observations: 1) prediction is not explanation, and 2) predictive models include environmental data without adequately incorporating or addressing sociocultural factors. Although both criticisms are to some degree valid, they do not necessarily render predictive modeling outdated or theoretically bankrupt. The first criticism is relevant only to how predictive modeling has been applied in particular cases, not the tenets of the method as described by early proponents (see Judge and Sebastian 1988). That correlation is not causation, and prediction is not explanation, cannot be overemphasized, but this need not be an insurmountable flaw. The second
criticism emanates from theoretical differences of opinion about the relative efficacy of environmental versus social factors in shaping human behavior. Predictive modeling methods are often bias toward data that can be more easily quantified as maps, and for archaeology these data are often environmental. Predictive modeling alone is therefore not an adequate comparative test of whether environmental or social factors are more important. However, predictive modeling has demonstrated associations between environmental conditions and site locations, and can help isolate and understand environmental influences in ways that need not be blindly focused on environment alone. The term ‘spatial modeling’ is used for this study instead of predictive modeling not in a frivolous attempt divorce it from predictive modeling methods, but rather to emphasize first step modeling that concentrates on examining if, how, and why particular variables were implicated in ancient humans’ use of landscapes rather than merely prediction of site locations.

Beyond the pitfalls of equating prediction with explanation, and bias weighting of environmental versus social factors, The Modifiable Areal Unit Problem (MAUP) has even more important, less widely recognized, and more insidious ramifications for archaeological spatial analyses. Problems encountered when aggregating or categorizing observations into areal units of different shapes and sizes (therefore manipulating spatial scale) were identified by geographers conducting spatial analyses as early as the 1930’s. Explicit acknowledgment of similarities among these problems did not emerge until Openshaw and Taylor (1979) outlined the Modifiable Areal Unit Problem (MAUP) to describe them. The influences of MAUP on analytical and statistical outcomes have been described in most detail with reference to scale and data aggregation problems encountered when using modern census data (e.g., Openshaw 1983; Fotheringham and Wong 1991). Although the significance of MAUP for archaeological spatial analyses has been mentioned (Kvamme 1990a: 269; Lock and Harris 2000: xx-xxi) it has almost never been described in detail, nor explicitly considered as an encumbrance of archaeological spatial analyses (see McCorriston and Harrower 2005).

MAUP is closely related to a problem in geographic (spatial) analysis known as ‘The Ecological Fallacy’ (Robinson 1950). This issue should not be confused with assertions about the relative efficacy of environmental factors in human behavior; The Ecological Fallacy instead involves problems encountered when aggregating information about individuals. Goodchild (1996) offers a useful description:
For example, one might compare the level of unemployment in each county to the percentage of people in the county who have not completed high school. Robinson (1950) was among the first to draw attention to the fact that a positive correlation between these two aggregate measures is not necessarily evidence that individuals without high school graduation are more likely to be unemployed. The correlation indicates that unemployment and people without high school education are likely to be found in the same areas, but it does not indicate that they are necessarily the same people. It is an ecological fallacy to make a false conclusion about individuals from an observation about spatially aggregated data. (Goodchild 1996: 246)

Since archaeologists are almost always using aggregate data (not data about individuals) we therefore must be extremely cautious about equating spatial relationships among aggregate data with correlation, causality, or assertions about the behavior or less aggregate entities. Aggregation issues present problems not only for assertions about individual people but for any type of observational aggregation. For instance, circular tower tombs and irrigation agriculture both appear in many of the same areas of Hadramawt during the late 6th – early 5th millennium BP. Can we therefore assume that these arrivals were the result of agriculturalists who constructed tombs (cf. Orchard 1995: 149)? Not necessarily—one must look at the specific local contexts of tombs and irrigation, for instance, what artifacts are found in tombs versus sites occupied by peoples practicing irrigation. Indeed, tombs have been more carefully associated with nomadic pastoralists, not irrigating agriculturalists (Steimer-Herbert 2004). This example is not intended to resolve the complex archaeological issue, but rather illustrate the types of problems raised by The Ecological Fallacy. Namely, that one needs to be cautious when relying on observations of spatial association when using aggregate information.

Closely related to The Ecological Fallacy, The Modifiable Areal Unit Problem (MAUP) describes a type or category of capricious analytical results that occur because of discretionary (or arbitrary) data aggregation, categorization, and scale choices (Openshaw 1983). Investigations of MAUP demonstrate that choices of scale, object representation, and areal unit boundary delineation often have dramatic and insidious effects on the conceptualization of data and outcomes (including statistical outcomes) of spatial analyses (e.g., Dungan et al. 2002; Openshaw 1983). Arbitrary choices can produce correlation coefficients from almost zero to nearly one with the same data, categorized in different ways (Openshaw and Taylor 1979). These problems are magnified when using multivariate statistics, as MAUP issues for each variable are
compounded (Fotheringham and Wong 1991). Such issues are particularly crucial for spatial analysis with GIS because categorization is performed frequently and repeatedly at users’ discretion. These issues were recognized by geographers to a limited degree as early as the 1930’s, but researchers often ignored them or concluded that they were likely insurmountable (Openshaw 1983). Seldom recognized as MAUP, analogous problems encountered when aggregating and categorizing data for GIS analyses in archaeology have met a similar fate.

A simple example—associations between archaeological site locations and slope—illustrates how MAUP conflates archaeological spatial analyses (Figure 4.5). At a high level of spatial aggregation, where only two slope classes are used (slope > 30% and slope < 30%), it might appear that there is a very high correlation between slope and site locations (all sites fall within < 30% class). But at a lower level of spatial aggregation (with slope classes of 0-10%, 10-20%, 20-30% etc.), sites may appear to be only weakly correlated with slope because sites distribute across many slope classes. Although few researchers would choose to divide slope into only two categories, the problem—more subtle and insidious—still remains with less dramatic categorization changes and is compound when multiple variables are used such as in archaeological predictive modeling.

MAUP has been recognized not only as an analytical/statistical problem but also as an additional source of information (Larsen 2000). As scale and categorization choices are varied results often change. Determining which results are stable at multiple scales and/or with multiple types of categorization choices helps better illustrate spatial relationships. Results that vary according to scale may also do so for specific reasons that are important and informative. MAUP thus demonstrates the importance of multi-scalar research strategies that explicitly consider the impacts of scale, aggregation, and categorization, both positive and negative (McCorriston and Harrower 2005). The influences of MAUP and related sampling issues for spatial modeling of irrigation structure locations in Wadi Sana are discussed in Chapter 10.

4.3 Ethnoarchaeology

Ethnoarchaeological investigations for this dissertation pursue three primary alternatives for understanding ancient irrigation in Southwest Arabia: 1) cross-cultural evidence of small-scale indigenous irrigation worldwide; 2) evidence of irrigation in nearby regions such as the Levant, Mesopotamia, and Africa; and 3) evidence of contemporary and historic irrigation in Southwest Arabia. Such a combination of
generalizing and particularizing approaches has the advantage of gaining from what has been learned about irrigation and social relations generally (e.g., Downing and Gibson 1974; Mabry 1996a, 2000; Scarborough 2003), as well as evidence of similarities with runoff irrigation and water-use strategies in the Levant (e.g., Evenari et al. 1982; Lancaster and Lancaster 1999), technical and socio-organizational aspects of irrigation in Mesopotamia (e.g., Fernea 1970; Postgate and Powell 1988; Walters 1970), agro-pastoral irrigation in Africa (e.g., Gray 1963; Sheridan 2002), and practices unique to Southwest Arabia (e.g., Bujra 1971; Eger 1987; Serjeant 1988; Varisco 1982a). Since in each case there are likely to be similarities with respect to some aspects of irrigation and differences with respect to others neither of these alternatives is individually most appropriate. But comparisons can help identify methods for studying technical and social aspects of irrigation, and can help gain from results where ethnographic perspectives have assisted in understanding irrigation in other environmental and social contexts.

Irrigation involves environmental constraints in combination with competing interests and pathways of social differentiation in the midst of cooperation, competition, and conflict. A cross-cultural approach allows consideration of structural aspects that lead to general patterns, including scalar stress (Johnson 1982) encountered in organizing irrigation activities, such as design, construction, operation, maintenance, water and land allocation, and dispute resolution. Because recent changes can obscure past practices, analogs drawn from irrigation considerable distances from one’s immediate study area may provide better analogs than areas immediately nearby. Environments create constraints broadly applicable across regions as well as those specific to particular to areas, but since climates are constantly fluctuating looking wider than ones immediate study area is often instructive. Indeed, modern conditions in Dhofar (Oman) provide one of the most appropriate social/ecological analogs for ancient practices in Wadi Sana (see Chapter 11). Direct historical approaches can assist in tracing back circumstances from the present to the past to reveal connections deeply imbedded in cultural traditions.

Although they change through time in concert with changing residential, logistical, and cognitive territories of human groups, perceptual and ideological aspects can be maintained over long periods within complex webs of environmental and social relations in ways that may not be apparent when generalizing. As the detail with which cases are considered increases, the more instances of irrigation appear unique; when more general ethnological perspectives are pursed, general similarities among practices are more readily evident.
4.4 Summary

A range of environmental and social factors, including climate, hydrology, culture, politics, and ideology, combined to structure irrigation’s origins in Southwest Arabia. Using the Wadi Sana watershed as a local example of regional patterns, the archaeological survey, geomatics, and ethnoarchaeological methods devised for this study provide an analytical combination for comparatively examining and integrating multiple environmental and social lines of evidence. Archaeological survey and test excavation serve as basic means of discovery and documentation. Geomatics tools, namely satellite remote sensing, Global Positioning System (GPS), and Geographic Information System (GIS) technologies, are adapted for spatial modeling of associations between irrigation structure locations and hydrological circumstances. Ethnoarchaeological analyses, including a cross cultural overview of irrigation, synopses of typological and socio-logistical aspects of contemporary irrigation in Yemen, and a preliminary study of water-use throughout the Wadi Sana watershed, facilitate understanding of social parameters that shaped development of incipient systems. These complementary methods are applied to examine irrigation’s origins in Southwest Arabia and evaluate the relative, interconnected influences of environmental and social factors.
Figure 4.1: ASTER satellite image of the Wadi Sana watershed (black outline designates watershed boundaries, ASTER bands 5:10:1, two mosaicked scenes orthorectified to UTM Zone 39N, WGS 84).
Figure 4.2: The Wadi Sana main channel just north of Qalat Habshiya (approximately 13 kilometers north of Ghayl bin Yumain).

Figure 4.3: The middle Wadi Sana landscape looking north toward the RASA Project’s fieldcamp.
Figure 4.4: Quickbird image of middle Wadi Sana showing the Khuzmum inselberg area where Wadi Sana and Wadi Shumlya intersect.
Figure 4.5: Two categorizations of slope for the Khuzmum area derived from the same 15-meter resolution Digital Elevation Model (DEM). Slope values are grouped into two classes in the left image; the same values are grouped into ten classes in the right image. If archaeological site distributions are compared with such images in GIS results can differ dramatically depending on the number of classes used, and method of categorization employed.

Table 4.1: Types of satellite imagery used for this study.

<table>
<thead>
<tr>
<th></th>
<th>Spatial resolution (pixel size)</th>
<th>Singe scene coverage area</th>
<th>Bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS*</td>
<td>250m, 500m, 1km</td>
<td>2330 x 2030 km</td>
<td>36</td>
</tr>
<tr>
<td>LANDSAT 5</td>
<td>30m, 120m</td>
<td>185 x 170 km</td>
<td>7</td>
</tr>
<tr>
<td>ASTER</td>
<td>15m, 60m, 90m</td>
<td>60 x 60 km</td>
<td>15</td>
</tr>
<tr>
<td>QuickBird</td>
<td>60cm, 2.4m</td>
<td>16.5 x 16.5 km</td>
<td>4</td>
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*Many MODIS data products are available, the MOD02QKM product consisting of the first two MODIS bands (250m resolution) was used for this study.
CHAPTER 5

ETHNOLOGY OF IRRIGATION

Water management and irrigation have played important economic and social roles for numerous ancient human populations, from hunter-gatherers, pastoralists, and incipient agriculturists, to states and civilizations. Water is arguably the single most important substance required for human survival. Humans can live only a very short period without it and the plants and animals on which humans depend similarly require it. Although irrigation is by far the most commonly recognized type, water management occurs in a great variety of forms for a multiplicity of reasons, including transportation, defense, drainage, flood control, ritual, symbolism, provisioning of animals, and most obviously, for human consumption (Scarborough 2003: 79-89). Indeed, water and human manipulation of water resources have long remained a theme of cross-cultural interpretations of ancient societies, from the early investigations of Steward (1949), Wittfogel (1957), and Raikes (1967), to the more recent contributions of Issar (2003), and Scarborough (2003). Archaeological studies of irrigation, however, encounter substantive challenges. Irrigation structures are often distributed widely across landscapes offering a more diffuse category of evidence compared to much higher densities of remains found at settlements, where archaeologists frequently concentrate their efforts. Irrigation structures are subject to damage due to subsequent agricultural and settlement landuse, and are often preserved as isolated fragments of larger systems that are difficult to date. Nevertheless, studies of ancient irrigation have illustrated important connections between human societies and their environments (e.g., Butzer 1976), have led archaeologists to postulate causal connections between irrigation and sociopolitical relations (e.g., Wittfogel 1957), and have demonstrated irrigation’s significance as a pre-industrial mode of agricultural intensification (e.g., Adams 1965; Sanders and Price 1968).
A brief cross-cultural overview of irrigation (as a category of water management) provides an informative starting-point for considering the origins and early development of techniques in Southwest Arabia. Since evidence of irrigation in ancient Southwest Arabia is presently dated as early as macrobotanical evidence for agriculture (see Chapter 7), a cross-cultural perspective provides means to consider whether irrigation could have first been practiced by foragers or pastoralists who irrigated wild plants. Irrigation practices among small and large-scale agriculturists also helps illustrate types of irrigation and how particular systems operated and were managed. The comparative review below draws on a variety of ethnographic and archaeological examples focused on small-scale systems, evaluations of the hydraulic hypothesis, and more on Old World regions near Southwest Arabia than far distant New World technologies. Although an ethnological perspective inevitably emphasizes similarities that mask underlying diversity, general parallels exist among widely disparate cases.

Studies of ancient irrigation have long revolved around the hydraulic hypothesis; namely, the contention that coordination required for large-scale irrigation prompted centralized political organization and spawned the world’s earliest states. Given the wide prevalence of irrigation among many of the world’s first civilizations it is not surprising that irrigation has been considered as a factor that may help account for their origins. Although the beginnings of the hydraulic hypothesis appeared in Wittfogel’s (1926) studies of ancient China, and was more specifically formulated by Steward (1949, 1955b), the hydraulic thesis was most vehemently argued and is most frequently associated with Wittfogel’s (1957) *Oriental Despotism: A Comparative Study of Total Power*. A seminal contribution to the study of irrigation, *Oriental Despotism* deterministically emphasized large-scale hydraulic works as the singularly most crucial factor in the history of ancient complex societies. Although subsequent analyses have revealed a far more complex, nuanced picture, the hydraulic hypothesis was important in prompting researchers to consider irrigation’s effects on forms of society (and reciprocally) societies’ effects on forms of irrigation (Steward 1977). As Downing and Gibson (1974: ix) noted in the preface to their monograph “Irrigation’s Impact on Society”, their book may have just as suitably been titled “Society’s Impact on Irrigation” or “The Impact of Society and Irrigation on One Another”. Now that the hydraulic hypothesis has aged, and has been discredited on a variety of grounds (e.g., Scarborough 2003: 17-19), analyses of irrigation require new frameworks that move beyond uni-causal determinism. Although a number of methodological avenues for continued research on irrigation have been proposed (e.g., Kelly 1983; Mabry 1996b; Mitchell 1973;
Scarborough 2003) none has yet gained widespread prevalence. Resolving discrepancies among them still involves identifying precisely where the hydraulic hypothesis went wrong to determine how more appropriately to proceed (Mabry 2000).

In general irrigation techniques can be characterized along a scale of increasing water manipulation intensity according to four broadly defined subsistence types: 1) foragers who dig wells and sometimes divert water to promote the growth of desirable plant species, 2) pastoralists and agro-pastoralists who practice a variety of water harnessing techniques to provision animals, and sometimes cultivate crops to supplement predominately herding economies, 3) small-scale agriculturists who produce food primarily for household or local group consumption and frequently settle and cultivate in water-rich locales such as alluvial floodplains or seasonally inundated areas, and 4) large-scale agriculturists who practice more complex and labor-intensive forms of irrigation that generate food for redistribution and exchange in addition to household consumption. Although these general categories provide a useful means to consider irrigation strategies, they are simplified heuristic divisions rather than mutually exclusive types. Indeed, manipulation of water for agriculture falls along a continuum of variability, from digging wells and cisterns, exploiting hillslope runoff or flood-recession waters, to flash-floodwater or spate irrigation, terraces, dams, canals, and underground infiltration galleries. In the case of any particular human population, techniques vary in a complex manner according to terrain, climate, environment, social, cultural, and political factors, and therefore cannot be deterministically predicted.

5.1 Foragers

For hunting and gathering populations water availability is crucial for a number of reasons, most importantly for human consumption and particularly in arid regions because it fosters vegetation and tends to attract game. Ethnographic research among Australian and African foragers has demonstrated, for example, the importance of proximity to water in influencing residential mobility (e.g., Kelly 1995: 126-127); and archaeological predictive models developed for ancient North American foraging populations frequently identify proximity to water as a primary determinant of settlement and activity locations (e.g., Kvanme 1985). Since these associations demonstrate that water was undoubtedly a matter of important concern, it is not unexpected that some foraging populations took important steps beyond passive reliance on water availability and devised water diversion techniques to promote the growth and/or ensure the success of plants upon which they relied.
The Northern Paiute of Owens Valley, California are probably the most widely known example of irrigation among a group that are generally considered foragers. As reported by Steward (1930, 1933) the Paiute used small ditches and earthen channels to divert water toward plots of seeds and tubers. As he describes, “They did not till the soil, plant or cultivate. They merely intensified by irrigation what nature had already provided” (Steward 1930: 150). Recognizing its relevance to explanations of agricultural origins, Steward took interest in the topic, particularly as it pertained to the contention that irrigation was involved in the world’s earliest cultivation and domestication of plants (Steward 1930: 149). Although irrigation among the Owens Valley Paiute is important to models of agricultural origins (as it provides a unique example of irrigation prior to agriculture) after more than 70 years the case has received relatively little research attention. Steward discussed a number of means that might account for the presence of irrigation in Owens Valley, including: 1) a local, independent origin (Steward 1930: 156, 1933: 249), 2) survival of a practice that preceded cultivated plants in the Southwest (Steward 1930: 154, 1933: 248), and 3) ancient or historic stimulus diffusion in which irrigation was adopted from the Southwest but not cultivars themselves (Steward 1930: 154, 1933:248). Although conclusively evaluating these alternatives still presents substantive challenges (beyond the scope of this analysis), a more recent reappraisal by Lawton and colleagues greatly clarified many of Steward’s findings (Lawton et al. 1976). Drawing on ethnographic and linguistic evidence, historical accounts, and land survey records, Lawton et al. found that irrigation in Owens Valley was far more widespread than Steward recognized, and was likely not an isolated instance resulting from protohistoric contact with Europeans. Although Lawton and colleagues were unable to determine how far such practices extended into prehistory, they identified ten, 19th century instances of Paiute irrigation distributed along a 57 mile long stretch of the Owens Valley and concluded that irrigation likely existed since at least the 1820’s. (Lawton et al. 1976: 27, 32). Although Lawton et al. maintain that the Paiute were by definition engaged in agriculture (Lawton et al. 1976: 15) they provided no explicit definition of factors they believe should constitute ‘agriculture’, and their conclusion certainly depends on the specific definition one applies. While Lawton and colleagues argued that planting (or at least leaving tubers in the ground) was likely practiced, Steward did not identify planting (in fact he explicitly stated it was not the practice). Without direct observations or experimental evidence, it therefore remains difficult to determine precisely what techniques were or were not involved.
Foraging populations other than the Owens Valley Paiute may well have practiced incipient forms of irrigation, but the record of such practices is exceedingly sparse. The only other published example identified for this research comes from grass seed gathering populations of Australia who employed somewhat similar water manipulation techniques. According to Tindale (1977: 345, 347) two Australia groups, the Iliaura and the Wanja, reportedly blocked runoff channels leading from periodically flooded areas to encourage water retention and promote the success of gathered grasses. Although these practices may provide a potential analog for strategies among incipient agriculturists elsewhere, it is highly unlikely that such temporary structures would be preserved archaeologically.

In many ways it is not surprising that irrigation without domestication is rare. One of the crops irrigated in the Great Basin for instance, yellow nut-grass (*Cyperus esculentus*), is known as a historic cultivar in numerous regions including Egypt but never became a domesticated staple (Lawton *et al.* 1976: 37-39). One would expect that given the labor necessary to irrigate a plot of land, other methods of promoting plant success, such as reserving seed for sowing, would be feasible and worthwhile. But numerous important questions still remain. Under what conditions can irrigation without planting remain a feasible or efficient strategy; and how long and how intensively can irrigation continue without inducing domestication? Although the latter question certainly depends on specific harvesting practices and the biology of plant species involved (e.g., Hillman and Davies 1990), considering the limited nature of evidence gleaned to date, irrigation among foraging populations remains an informative but sparsely documented topic.

5.2 Pastoralists

In comparison with foragers, water acquisition strategies take on added significance for pastoralists who must ensure an adequate supply for both themselves and their animals. Particularly in arid locales, water provisioning for animals was a demonstrably important factor influencing logistical and residential mobility choices from the very appearance of animal husbandry during the early Holocene. Wendorf and colleagues have argued, for instance, that some type of water provisioning must have been practiced in Egypt since the 10th millennium BP because without human assistance, survival of cattle in the Western Desert would have been highly unlikely (Close and Wendorf 1992; Wendorf and Schild 1994, 1998). Since water availability depends on a complexity of factors (including topography, landforms, vegetation, and isolation) absolute statements about annual precipitation required to sustain particular domesticated
animals are impossible; but cattle husbandry generally requires approximately 400mm of precipitation per annum, sheep and goats 200mm, while camels can be sustained with as little as 100mm (cf. Zarins 1992b). In more arid regions or during times when less precipitation occurs, herds can still be maintained, but a supplementary source of water, such as rivers, springs, or specialized water procurement techniques are required. A variety of techniques, such as digging water holes to access shallow ground water, are known among pastoralists, including the Nuer (Evans-Pritchard 1940: 57-59). Lancaster and Lancaster (1999: 129-167) provide a detailed review of water acquisition methods among Bedouin pastoralists of the Levant who construct cisterns and dig specialized pits including ghudrân, where natural depressions along wadi channels are dug out and expanded (Lancaster and Lancaster 1999: 133), and thumaila in which pits along areas of periodic flow are lined with rock slabs to allow entry from the surface and via infiltration (Lancaster and Lancaster 1999: 138). In locales receiving less than 100 mm per annum, remarkably conservative techniques are known. Harasiis pastoralists of Oman, for instance, collect moisture by laying blankets over, and/or shaking vegetation after dew accumulates at night (Janzen 1986: 81; Reader 1988: 106-107). They derive fluid for human consumption predominately from camel and goat milk and under particularly extreme conditions obtain water from the half-digested stomach contents of camels, or slaughter them to access their stomach storage bladder (Janzen 1986: 81).

In addition to water acquisition and provisioning, agro-pastoralists who pursue mixed herding-cultivating strategies often inhabit areas where more than direct precipitation on fields is required. Although agro-pastoralists frequently obtain plant foods via trade, cultivation is often practiced to supplement herding, to provide a subsistence fall-back during times of shortage, and because cultivation by-products can be used as fodder. Flood-recession and spate cultivation techniques are common among African agro-pastoralists, including: 1) the Bisharien of Eastern Sudan who capture water for sorghum cultivation from hillslopes and wadis (Egemi 2000), 2) the Nuer of Southern Sudan who grow millet along seasonally flooded riverbanks (Evans-Pritchard 1940), and 3) transhumant pastoralists of the Sheeb region, Eritrea who use tree branches and boulders to build small spate-water diversion structures (Tesfai and de Graaff 2000; Tesfai and Sterk 2002; Tesfai and Stroosnijder 2001). Irrigation techniques among agro-pastoralists are (in general) less labor intensive and frequently less critical to survival than strategies employed by agriculturists who are more exclusively dependant on cultivation. Seasonal transhumance to ensure animal graze often necessitates patterns of mobility that make heavy reliance on cultivation impractical. Comments of Bedouin
pastoralists of the Bilâd ash-Shâm anecdotally illustrate opportunistic cultivation:

> We were never here all the time, or all of us together; we were out herding in the *harra*, this was a place we liked to be in the summer. But we weren’t here every summer or all of a summer. Sometimes we went up to Mlah or other places in the Jabal al-Arabi. But we always got something from the farm even if it was only grazing the crop we’d planted, and we had the stored water for us and the animals (Lancaster and Lancaster 1999: 147).

Water acquisition and provisioning was (and is) undoubtedly an important matter of concern in the lives of pastoralists and the search for water probably contributed to experiences with water manipulation that in some cases provided bases for cultivation. Interestingly, no agro-pastoralist population identified during the course of this research irrigates either wild plants or domesticated crops exclusively to provide fodder for animals without consuming irrigated plants as food for themselves. Given the trophic energy losses involved in producing crops exclusively for fodder and then consuming resultant meat, milk, or blood (rather than crops themselves), it is not surprising that irrigated crops are only used for fodder after they have provided humans with food. Indeed, animals provide an effective use for crop by-products so it makes sense for humans to consume primary products, and provide secondary products to animals. Although the issue has received relatively little attention, it remains an open question whether there are circumstances where irrigating exclusively for animals is an effective strategy. Importantly, one might expect that mixed cultivation-herding strategies would hold increased importance when reliable trade for plant foods was not an option, or when foraged human plant food availability was declining because over-exploitation or aridity.

5.3 Small-Scale Agriculturists

Although irrigation may not be exclusively restricted to agriculturists, it is predominately among groups with cultivation-based economies that irrigation becomes a prominent aspect of subsistence. In comparison with foragers, small-scale agriculturists are generally more sedentary, and because of intensified relationships with particular plants, are often more reliant on a smaller number of food staples for the bulk their subsistence needs (Harris 1989). Agriculture therefore marks a substantial turning point from reliance on wild plants and animals that propagate largely independent of human intervention, to reliance on crops that thrive because of (and in some cases require)
human assistance (Rindos 1984). As humans become more reliant on a handful of cultivated plant staples, they become concomitantly dependent on conditions those plants require for survival, including suitable relief, arable soils, amenable (e.g., seasonal) patterns of temperature and moisture availability. Of these, moisture availability is one of the most variable, and as Wittfogel (1957: 13-15) recognized, the fluid nature and spatial diversity of surface flow make water the most malleable of necessary conditions. Agriculture creates circumstances where humans become agents who choose conditions on behalf of plants (Rindos 1984), and some of the first choices many populations made involved ensuring adequate soil moisture.

The study of ancient agriculture has long been shaped by the implicit view that irrigation-based modes of agriculture are descendant strategies that developed from preexisting forms of rainfed cultivation. However, this supposition has not been demonstrated and in many (perhaps most) regions of agricultural origins is not necessarily warranted. In an overview of early cereal cultivation Sherratt (1980) argued, although rainfed techniques are often considered an agricultural norm, most early strategies relied on ground and surface water. Rainfed or dry-farming strategies, he contended, are in fact less usual and comparatively more recent techniques that mark the spread of agriculture into regions such as Europe and the tropics rather than its origins. Sherratt’s arguments were couched within a framework of other important observations and he provided only a handful of examples centered on the Near East and Europe. Although Sherratt’s contention ultimately needs to be evaluated on a case-by-case basis, there is considerable evidence that many of the world’s earliest cultivation techniques were not dependant on direct rainfall alone but targeted water-rich locales such as alluvial floodplains or seasonally inundated areas. Water is a factor significant to the location of numerous aceramic Neolithic sites in the Levant, which are often found: a) near springs, such as Jericho (Bar-Yosef 1986) and Dhra, b) in areas where runoff concentrates because of topography, including Beidha (Miller 1980: 332) and Netiv Hagdud (Bar-Yosef et al. 1991: 406, 407), and c) near annually flooding perennial rivers such as Abu Hureyra and Mureybet (Moore et al. 2000). In her recent analyses of archaeobotanical remains from Levantine sites, Colledge (2001: 190-191) noted that at Neolithic sites where cultivation was underway assemblages were dominated by wet-ground taxa, and she thus concluded that cultivation likely took place in locally water-rich locales. Décrue techniques where cultivation is practiced along intermittently flooded margins of lakes and rivers, was a similarly primary mode of early African agriculture (Harlan 1992). Water is an indisputably important element of one of East Asia’s earliest domesticates,
rice, and early strategies may have involved entrapping water to extend natural rice habitats (Smith 1998). Evidence from Oaxaca points to well-watering, cultivation in high water table (tierra de humedad) areas, and along drainage corridors (barrancas) as methods important to incipient Mesoamerican agriculture (Flannery and Marcus 2003 [1983]: 323-339). Dillehay and colleagues have found small Preclassic irrigation ditches in Zana Valley, Northern Peru (Dillehay et al. 1989: 750; 1997: 54; Piperno and Pearsall 1998: 207), and recent findings in the Norte Chico region further strengthen the view that irrigation was important very early in the history of ancient Peruvian agriculture (Haas et al. 2004). Finally, as Smith (1992) argued, Archaic sites in the Eastern Woodlands of North America were often associated with riverine locales where foragers became engaged in co-evolutionary relationships with floodplain adapted species.

Although the aforementioned examples provide only an extremely brief overview, regions of early cultivation including Southwest Asia, Africa, East Asia, Meso, South, and North America each yield evidence that naturally water-rich areas were targets of early cultivation, and therefore, that incipient irrigation may not be as dramatic a departure from initial cultivation strategies as is commonly supposed. Given that populations of the Levant, for instance, had been gathering cereals such as wheat and barley for many millennia prior to domestication, they would have well understood the conditions these plants required to thrive (Kislev et al. 1992; Kislev et al. 2004), and it is hardly surprising that they may have targeted areas for cultivation that were naturally most productive.

Relationships between water and agriculture become considerably more complicated as one moves along a scale of water-use intensity from targeting naturally water-rich areas such as springs and alluvial fans to increasingly labor-intensive forms of water manipulation. Once naturally water-rich areas are occupied (and the production advantages of these locations realized) early farmers in arid areas are pressured either to cultivate comparatively less productive land or devise means to capture and divert water (cf. Stone 1996). Although the range of potential options is considerable, small-scale agriculturists in widely disparate settings practice many similar forms of water manipulation. Some techniques likely diffused with crops themselves while other techniques developed independently. Although the origins of particular techniques requires unraveling with reference to specific cases, some basic patterns are recognizable.

Small-scale flood recession, or décrue cultivation, is one of the least labor-demanding forms of water-reliant cultivation; but small-scale flood-dependent systems
are among the most risky because the areal extent of flooding can vary dramatically from year-to-year. When demands for seasonally flooded land are low, farmers can choose areas for planting based on the magnitude of floods; but as local demands for land increase, maintaining claim to particular plots (that may or may not flood) makes reliance on floodland cultivation precarious. While Besteman (1996) describes a ‘first-to-arrive’ system of claiming inundated land in Somalia; Park (1992) reports a system in Senegal where inundated land was redistributed each year based on which areas flooded.

The use of wells and cisterns for direct watering of crops is a relatively simple form of irrigation that likely developed from use of water-holes for drinking water. Wells are found among hunting and gathering populations of Mesoamerica during the early Archaic (Caran et al. 1996), and were subsequently used in Oaxaca for pot-watering crops (Flannery and Marcus 2003 [1983]: 325-326). Pre-Pottery Neolithic wells have also been discovered in Cyprus and may have helped facilitate the spread of early Levantine agro-pastoralists (Peltenburg et al. 2000).

The terms hillslope or surface runoff best describe a variety of irrigation techniques that can be used on undulating to rugged terrain, including water diversion from alluvial fans, and agricultural terraces. Although disagreements often arise about whether terraces are intended to hold soil or retain water (see Donkin 1979: 33-34; Wilkinson 2003: 189), reasons can vary dramatically according to setting. For pond-field agriculture in Bali (Lansing 1991) terraces were obviously constructed to hold water; while in Eastern Tigray, Ethiopia (where historic hillside erosion has been particularly detrimental, see Kloos 1991) farmers report constructing terraces to reduce erosion. For many terrace systems a single, exclusive purpose is challenging to demonstrate, and some may have been constructed for more than one reason. Based on a long history of experimental research, Shanan (2000: 99-100) argued that ancient terraces in the Negev, for instance, were used to both stabilize soils and collect water. Instances of hillslope diversion and terrace agriculture are numerous, examples near Yemen include: runoff farms in the Negev (Evenari et al. 1982; Shanan 2000), ancient terraces in Jordan (Schnurrenberger and Cole 1997; Barker 2000), and hillslope/alluvial fan irrigation in Iran (Neely 1974, Oates 1969, 1982, Prickett 1979, 1985).

Compared to hillslope systems, canal and spate water irrigation commonly divert even greater quantity and velocity water flows. Temporary barrages that are periodically destroyed and rebuilt provide relatively simple means of perennial flow and spate-water

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5Research on agricultural landuse, including terracing and irrigation, in Eastern Tigray, Ethiopia (conducted with the Gulo Makeda Research Project) was commenced by the author in early 2005.
capture. Temporary brush and stone structures have been reported in a wide variety of ethnographic and historic contexts including, Eritrea (Tesfai and Stroosnijder 2001: 53-54), the Philippines (Coward 1979: 29), Mesoamerica (Flannery and Marcus 2003 [1983]: 337), and Hawaii (Earle 1980: 18). Although intermediate-scale canal systems are often obscured by later counterparts, early canal systems supported, for instance, Early and Middle Bronze Age settlements in the Balikh Valley, Syria (Wilkinson 1998b). Experiences with surface runoff techniques, and knowledge of how and where to construct barrages and canals for perennial flow and spate water control, were likely prerequisite to larger, more difficult to engineer systems.

5.4 Large-Scale Agriculturists

As a primary means of agricultural intensification, irrigation figured prominently in ancient transitions from subsistence-scale practices to strategies that (in addition to sustenance for farmers and their associates) produced food for redistribution by persons of authority and exchange in market economies. Irrigation among societies traditionally deemed chiefdoms and states includes each of the aforementioned small-scale practices, as well as more labor-intensive and technologically complex forms, including large flash-floodwater (spate) systems, extensive networks of dams and canals, floating gardens, and underground infiltration galleries. Although practices worldwide are so diverse that a comprehensive review is an enormous undertaking (cf. Scarborough 2003), studies of large or larger-scale irrigation, including evaluations of the hydraulic hypothesis, offer many important insights for understanding irrigation’s economic and social influences.

Due in part to a long history of scholarship that has considered irrigation as a factor potentially responsible for the emergence of states, numerous studies have examined irrigation among chiefdoms. Notwithstanding caveats necessary when utilizing evolutionary classifications (cf. Yoffee 1993), among societies that fall between the range of groups traditionally known as tribes and states, irrigation played an important role in boosting production to generate food products for consumption beyond immediate kin and reciprocal exchange. In examining political economies among chiefdoms, Earle (1997) discussed societies of three areas, two of which, Kaua’i, Hawai’i (AD 800-1824) and Mantaro Valley, Peru (AD 500-1534) relied on irrigation. Although Earle emphasized the greater productive capacity of irrigation and the potential for elites to use food surpluses as avenues of power, he considered irrigation only one (and not the most important) pathway of social inequality. Earle’s conclusion that irrigation was an important mode of staple finance, but not necessarily the central factor responsible for
sociopolitical change, holds true for societies of Polynesian generally, and for the American Southwest—two of the best known regions of irrigation among pre-state complex societies.

Although various forms of water diversion were important throughout the American Southwest (e.g., Fish and Fish 1994; Vivian 1974), Hohokam systems consisting of hundreds of kilometers of canals along the Gila and Salt rivers have been most extensively studied (e.g., Masse 1981; Neely 2001a; Woodbury 1961). Particularly since Hohokam systems irrigated thousands of hectares, there has been considerable interest and debate about how irrigation was organized. Since ethnographic populations in the area never constructed irrigation systems on the scale of the Hohokam, Hunt et al.’s (2005) use of an ethnological perspective helps ameliorate some of the controversy. Using a wide range of cross-cultural examples, Hunt et al. (2005) argued that Hohokam irrigation must have required non-acephalous coordination, not necessarily central coordination as a single basin-wide system, but more plausibly some form of communal canal-level management (Hunt et al. 2005: 451-452).

Polynesian agricultural strategies, including pond-field irrigation, have also received considerable research attention (e.g., Earle 1980; Kirch and Lepofsky 1993). Kirch’s (1994) *The Wet and the Dry: Irrigation and Agricultural Intensification in Polynesia* shed important new light on irrigation’s purported role in sociopolitical change. Applying archaeological, ethnographic, and historical information, Kirch traces the history and human geography of swidden versus pond-field cultivation and concludes that intensification of short-fallow shifting cultivation, rather than irrigation, contributed to increases in sociopolitical complexity.

Early states in regions worldwide elaborated from (in some cases) millennia of experience with small and intermediate-scale irrigation, to develop a vast array of floodplain cultivation and irrigation technologies that dramatically increased agricultural outputs. In Egypt along the Nile (e.g., Butzer 1976; Hassan 1997), in Mesopotamia along the Euphrates and Diyala Rivers (e.g., Adams 1965, 1974, 1981; Postgate and Powell 1988), in South America along major rivers including the Moche (e.g., Billman 2002; Farrington 1974, 1980; Kolata 1991; Park 1983), and throughout Mesoamerica (e.g., Doolittle 1990; Neely 2001b; Scarborough and Isaac 1993; Woodbury and Neely 1972) early complex societies developed not only in areas with most productive dry-land agriculture (Wilkinson 1994) but in locales where irrigation could far surpass the productivity of direct rainfall dependant strategies. Details of agricultural production among complex societies of South Asia and China, including floodplain techniques along
perennial rivers of the Indus watershed, and cultivation strategies along the Yellow and Yangtze rivers are less well-known (for general overviews see Maisels 1999: 206-214; Scarborough 2003: 140-146; Trigger 2003: 287-289). But these societies similarly required food not only for farmers and their associates but for craft specialists, bureaucrats, armies, and temple economies, for which irrigation played significant roles.

In Mesopotamia, for instance, the Euphrates was naturally higher than surrounding alluvial plains offering many convenient opportunities for irrigation (Postgate and Powell 1988). Although early systems in southern Mesopotamia do not appear to have been initially coordinated by state authorities (R.M. Adams 1981), by Babylonian times state leaders and bureaucrats played crucial roles in funding and organizing construction, operation, and maintenance (Walters 1970). But as Fernea (1970) demonstrated in a detailed ethnographic study among the El Shabana of southern Iraq, Mesopotamian canal systems do not necessarily require state intervention, and can instead develop by accretion according to the initiatives of local farmers and tribes.

5.4.1 Evaluating the Hydraulic Hypothesis: Given the near ubiquitous presence of water exploitation as a productive force among early states, it is hardly surprising that irrigation was postulated as a primary factor responsible for the emergence of complex sociopolitical hierarchies, and has held a prominent position in analyses of ancient civilizations for nearly half a century. Whether or not irrigation had significant economic and social ramifications among early states is no longer a primary matter of dispute. Rather, the nature, extent, and precise influences of irrigation among ancient societies and their complex trajectories are more predominately issues of controversy. Although the hydraulic hypothesis as Wittfogel formulated it is clearly defunct, it has so defined studies of irrigation that it remains important to look back at what has been learned to help determine how future studies might proceed (Mabry 2000).

During the 1950’s Wittfogel (1955, 1957) and Steward (1949, 1955b) emerged as key proponents of the assertion that large-scale irrigation projects, which required central administrative coordination, were a primary impetus, or cause, in the emergence of states. Wittfogel’s Oriental Despotism: A Comparative Study of Total Power (1957) elaborated from Marx and Engels’ notion that means of production were crucial in shaping relations of production and that among pre-industrial societies of Asia production frequently involved irrigation (see Wittfogel 1972). Recognizing that early societies in the New World also developed sophisticated means of water control, Wittfogel (1957) introduced the term “Hydraulic Societies” to replace Marx’ “Asiatic Societies”. Steward, who was
motivated by a desire to develop law-like generalizations to explain change among early societies, took a more moderate view considering the contention that large-scale irrigation required bureaucratic coordination as a potential cross-cultural parallel worthy of further examination (Steward 1949, 1955b).

Particularly following Wittfogel’s book, postulated connections between irrigation and the rise of centralized political authority became a hypothesis frequently evaluated for the emergence of states (see Adams 1966; Downing and Gibson 1974; Hunt and Hunt 1976; Mitchell 1973; Sanders and Price 1968). Although Wittfogel was trained as a historian/sinologist and his arguments were based predominantly on secondary sources rather than on first-hand observation, that his work has remained influential suggests his assertions hold at least some utility for understanding ancient societies (Mabry 2000). Wittfogel was clearly correct in identifying irrigation as an important aspect of production with significant socio-organizational challenges. However, serious problems have been exposed in his deterministic conceptualization of irrigation’s influences on social relations. Wittfogel’s hydraulic hypothesis can be divided into three primary assertions: 1) large-scale irrigation requires centralized coordination; 2) the need for centralized coordination of large-scale irrigation led to the development of state-level political hierarchies; and 3) the nature of political authority among early irrigating societies was fundamentally despotic. Attempts to evaluate these assertions have dramatically clarified relations between irrigation and society. Although some of Wittfogel’s assertions are supported to a limited extent, subsequent case studies have revealed a far more complex picture than he postulated. Because each assertion could be independently or partially accurate even if the others are not, I will briefly address each in turn.

A broad range of both individual case studies and cross-cultural analyses have evaluated the contention that large-scale irrigation requires centralized coordination (e.g., Downing and Gibson 1974; Fernea 1970; Hunt 1988b; Hunt and Hunt 1976; Kelly 1983; Lees 1994; Mabry 1996a, 2000; Million 1962; Mitchell 1973, 1976; Price 1994; Scarborough 1991). A range of agronomic studies of irrigation management (although they do not explicitly address the hydraulic hypothesis) also provide insights for understanding organization and coordination issues (e.g., Bolin 1990; Coward 1977, 1979; Holbrook 1997; Levine 1977; Martinez-Fernandez et al. 2000; Trawick 2001; Uphoff 1986). As evidence from widely disparate regions of the world has accumulated, the complexity and diversity of irrigation management systems has become increasingly evident. Although there is a tendency toward centralization of authority as scale
increases, this tendency is subject to a variety of case-specific particularities, so that no 
simple deterministic relationship holds between scale and centralization (Hunt 1988b). 
Identifying and measuring relevant variables—including what is meant by ‘large-scale’ 
and ‘centralization’—has proven a challenge (Hunt 1988b). Scale can be defined as the 
size of area controlled by an irrigating society, the size area actually irrigated, the number 
of people served by the irrigation system, or the number or irrigators involved. While 
centralization is sometimes taken to mean the highest level of political authority of a 
society (Kappel 1974), it is important to distinguish general sociopolitical authority from 
that directly involved in management of irrigation (Hunt and Hunt 1976). Particularly in 
historic and archaeological cases, scale and centralization (however they are defined) can 
be difficult to determine, or even estimate. Although water allocation authority has been 
employed as representative of centralization (Millon 1962), irrigation management 
voyles a variety of tasks including design, construction, operation, and maintenance 
(see Section 5.5) that can be simultaneously managed at different sociopolitical scales. A 
significant distinction is to be made between tasks that occur infrequently that involve 
comparatively more substantial labor and thus tend to be associated with more centralized 
coordination (such as construction and maintenance); versus those that occur more 
frequently (such as water distribution) and tend be organized on a more local level (Hunt 
and Hunt 1976). Although labor inputs for large-scale systems are rarely measured and 
are often assumed to be substantial, as Farrington (1980: 288) recognized, they do not 
necessarily surpass those of slash-and-burn agriculture, which is frequently organized 
without centralized authority. Labor can be mobilized by intra-group-pressure and 
maintenance can be accomplished by a small number of people working over a long 
period of time. Numerous groups within modern states manage their systems 
predominately at the community level without (or with very little and/or highly 
intermittent) involvement of central or provincial governments (Hunt 1988b; Lees 1973). 

Collectively, ethnographic studies of irrigation management illustrate a wide 
diversity of organizational circumstances, and demonstrate that Wittfogel was only “half-
right” in contending that large-scale irrigation requires centralized coordination (Mabry 
2000). Although analyses that explicitly compare cross-cultural cases have failed to 
confirm deterministic associations between scale and centralization (e.g., Hunt 1988b; 
Millon 1962), this certainly cannot be taken as evidence that no relationships exist 
between forms of irrigation and forms of its organization. Irrigation is fundamentally a 
group activity that requires group coordination, and logistical requirements do exert 
influences on social relations. Although irrigation is often considered a homogenous
category, differences in climate, timing of precipitation, topography, crops, and the technical aspects of the particular irrigation techniques induce a wide variety of operational (socio-logistical) challenges. It is not simply the scale of irrigation but specific logistical and managerial needs that have important influences on social relations. Although individual cases are subject to specific particularities, as the scale and technical complexity of irrigation systems rise, the complexity of social arrangements and institutions required to control and organize them tend to correspondingly increase. Scalar stress (Johnson 1982) is an important consideration. That is, as the number of people involved with irrigation increases, consensus based management systems become increasingly less effective. Given larger numbers of people and larger areas to be irrigated, management necessarily tends to shift from consensus systems arranged by an entire group of irrigators, to increasingly hierarchical and multi-level systems of management (Mabry 1996b). As modern development studies illustrate, motivations of different individuals and social groups (including farmers themselves) are not necessarily synonymous with those at higher levels of political authority (Levine 1977). Competing interests often prevent centralization of control, limiting political authorities to intervention when other means of management are ineffective. Ultimately large-scale forms of irrigation do not necessarily mandate any particular forms of organization. Given very different environmental and social circumstances, organizational needs are (at least to some extent) unique.

Though large-scale irrigation in some instances may encourage centralized coordination, an even more controversial assertion of the hydraulic hypothesis is the causal connection it posits between irrigation and the rise of ancient states. Probably the most challenging obstacle to evaluating this assertion lies in unraveling the temporal chain of events required to establish causation. Forms of ‘small’ or at least ‘medium’ scale irrigation appear long before the rise of complex hierarchies in every region of primary state formation. At what juncture was central coordination required? Does encountering and surmounting that juncture recognizably correspond with a substantive increase in sociopolitical complexity?

If irrigation was the primary causal factor responsible for the rise of states, centralized authority could not have appeared long before large-scale irrigation because it then would have been the result of some other factor or set of factors; and it could not have appeared long after large-scale irrigation because (according to the hydraulic hypothesis) centralization would have been required to make large-scale irrigation possible. To verify the hydraulic hypothesis, centralization of authority would have to
occur virtually simultaneously (or nearly so) with large-scale forms of irrigation.

Mitchell (1973; 1976) has critiqued notions that confirmation of the hydraulic hypothesis requires a precise temporal chain of events. He suggests reformulating the hydraulic hypothesis to state, “if there is centralized direction of irrigation activities in an arid or semiarid environment, then there will be a corresponding increase in centralized political power in other areas of social life” (Mitchell 1973: 534). However, this reformulation conflates the causal processes Wittfogel postulated with substantially different issues. Few might dispute that centralized control of irrigation would have ramifications in other domains of life, and these are critically important, but they are not the hydraulic hypothesis. The primary issue (if one aims to evaluate the hydraulic hypothesis) is not how irrigation affects society after centralized authority had developed, but rather, whether or not irrigation prompted centralization of authority in the first place. Was irrigation at the leading edge of sociopolitical change, or did irrigation merely reflect changes in political organization that were initiated in other domains of life?

Problems in establishing an accurate temporal chain of events pose the most fundamental challenge to evaluating the causal connection postulated by the hydraulic hypothesis. The cause and the effect must be situated at least near each other in time. As Adams phrased the question, “Were they [irrigation systems] sufficiently large in scale or complex in managerial requirements during the periods in which we are dealing to have served as a stimulus to the growth of specialized political bureaucratic elites” (Adams 1966: 67). Such temporal issues are difficult to resolve. They depend not only on how the terms large-scale irrigation and centralized political authority are defined, but additionally require that these variables can be identified and measured through time. Most ethnographic case studies generate static frameworks that rarely allow comparison of irrigation and social relations over long periods of time (Millon 1962). Archaeological irrigation systems are subject to destruction due to subsequent land-use. While household refuse (e.g., sherd scatters) can help define ancient field areas, continual deposition and redeposition make changes in areal extent of fields during different periods very challenging to reconstruct (cf. Wilkinson 2003: 52-57). Even if one can determine that an irrigation system of specific extent was in use during a particular period of time, it is still difficult to know whether construction was necessarily a short-term project directed by central authorities or whether the system developed by accretion over a longer interval according to the motivations of individuals or small groups of collaborating farmers.
That it has proven challenging to place substantive increases in the scale and/or complexity of irrigation precisely together in time with substantive increases in social complexity suggests that, although irrigation was important, it was not the singular or even central cause Wittfogel envisioned. For Mesopotamia, Adams (1966: 66-76) recognized relationships between irrigation and social relations but argued that sociopolitical hierarchies preceded rather than followed large-scale irrigation. Nissen (1988: 60) emphasized the role of irrigation in boosting agricultural production in Mesopotamia but similarly rejected the hydraulic hypothesis. Butzer recognized the crucial importance of irrigation in ancient Egypt but concluded, “there is no direct causal relationship between hydraulic agriculture and the development of the Pharaonic political structure and society” (Butzer 1976: 110). Sanders and Price (1968) offered a more favorable appraisal of the hydraulic hypothesis for Mesoamerica emphasizing the managerial requirements of large-scale irrigation and the role of elites in conflict resolution. But Sanders and colleagues later presented irrigation as only part of the explanation along with a range of other factors including: ecological conditions, economics, trade, warfare, and above all, population growth (see Sanders et al. 1979).

While some pronounce the hydraulic hypothesis dead (Butzer 1996), others defend it (Price 1994), and still others take intermediate positions (Mabry 2000), most now agree that irrigation was not the primary factor responsible for the origins of states (see Scarborough 2003: 17-19; Trigger 2003: 676).

The third assertion of the hydraulic hypothesis as formulated by Wittfogel involves the nature of political authority among ancient states. Wittfogel (1957) depicted the need for centralized management of large-scale irrigation as a means used by elites to concentrate and monopolize power. Although ancient states were in many cases less equitable than (some) modern nations, labeling them despotic or totalitarian is a value judgment difficult to evaluate. Nevertheless, Wittfogel’s depiction of political power prompted interest in the nature of power, including relative elements of exploitation versus cooperation. In contrast with Wittfogel’s view that largely dismisses the role of cooperation (Mitchell 1973), ethnographic research yields considerable evidence of collective and coercive action in tandem with traditions that specifically limit the ability of individuals or social groups to gain autocratic control (Hunt 1988b; Lees 1973, 1979; Trawick 2001). The nature of authority in irrigation management is not always despotic or coercive (Mabry 2000). In both medieval Valencia (Glick 1970) and Bali (Geertz 1980; Lansing 1991), management involved significant “consensual authority” (Scarborough 2003: 21). In the al-Ahjur region of North Yemen, for example, Varisco
(1982a) describes a peer-pressure system of labor mobilization that did not necessarily involve direct sanctions against workers even when they failed to participate.

5.5 Beyond the Hydraulic Hypothesis: New Frameworks for Studying Irrigation

As more detailed understandings of irrigation have emerged, evaluations of Wittfogel’s hydraulic hypothesis have waned and researchers have come to favor less deterministic explanations (see Scarborough 2003: 154-156). Even by the 1970’s Steward recognized that irrigation must be considered as both a cause and a consequence of societal change (Steward 1977). But as he noted, “it is safe to say that even Wittfogel’s most vigorous critics have advanced our understanding of the role of irrigation precisely because their interest had been directed to the subject and they had a theory which could be tested” (Steward 1977: 88). Evaluations of the hydraulic hypothesis have shown that: 1) there is no simple, deterministic correlation between scale and centralized coordination; 2) irrigation was not the singular factor responsible for the emergence of states; and 3) social organization of irrigation often involves elements of mutually beneficial cooperation in conjunction with authoritarianism, coercion, and conflict. Although the details of irrigation’s influences among ancient societies are still far from resolved, they require new frameworks that move beyond the rigid confines of the hydraulic hypothesis.

As a domain of human behavior, irrigation involves a wide range of activities and associated social relations. Loci of decision-making, status, power, and authority are often dispersed throughout complex milieus of social differentiation. Even though central bureaucracies coordinate some large-scale systems, decision-making and labor-coordinating authority is often found at multiple local, regional, and national levels. Rather than a scenario where managers or administrators dictate decisions, the authority of leaders at any level is invariably subject to checks and balances. Pressing questions include; what social arrangements do particular irrigation techniques involve at the incipient level, and how do these arrangements change as the scale and complexity of particular systems increases? A seldom recognized but fundamental problem is the manner in which irrigation is treated as an independent variable (Varisco 1982a: 8-10). Irrigation is not independent and develops within complex social frameworks that make isolating it as an autonomous factor difficult to impossible.

The wealth of evidence now available shows that irrigation and society have interacting rather than uni-directional relationships in which forms of irrigation determine forms of society or vice versa. From an economic-materialist perspective it was not
irrigation *per se* that was most important but advantages conferred by increasingly productive forms of agriculture that could support, or facilitate, burgeoning populations (*cf.* Boserup 1965). From a social-idealistic perspective it was not necessarily the greater productivity irrigation offered, but its capacity for elites to dominate (and in some cases position themselves as the cosmological authorities of) food production that make irrigation so crucial.

A number of scholars have suggested refinements of terminology used in studies of irrigation and have suggested new directions for research (Kelly 1983; Mabry 1996b, 2000; Mitchell 1973; Scarborough 1991, 2003). Since “scale” and “centralization” are vague and problematic terms that pertain to a wide variety of activities, Mabry (1996b: 9-11) suggests that scale be more explicitly defined as the size area irrigated and/or number of irrigators. One commonly suggested means of better addressing social organization of irrigation (including issues of scale and management centralization) involves dividing irrigation into a series of practical or logistical tasks. Numerous analysts have pursued task-based approaches, including Hunt and Hunt (1976) who examined tasks involved in canal irrigation, and Kelly (1983) who examined four phases of irrigation (water source control, water delivery, water use, and water drainage), and Scarborough (2003) who compared labortasking, technotasking, and multitasking based systems. With the aim of understanding irrigation management alternatives for modern development projects, Uphoff (1986) discussed 12 different task categories. But many of the categories he defined (*e.g.,* decision-making, communication, and conflict management) are not physical or logistical tasks but are abstract elements of dialogue and power among irrigators that are difficult to examine archaeologically. If the categories Uphoff distinguished are restricted to those he described as ‘water control’, namely, design, construction, operation, and maintenance (*cf.* Mabry 1996b: 14-19), they provide a more manageable basis for considering physical tasks required to operate particular ancient systems. Each presents a specific set of physical challenges; while decision-making, communication, labor mobilization, water and land allocation, and dispute mitigation span a range of these more simplified task categories. Importantly, this physical task approach allows more explicit consideration of challenges specific practices involved, who was involved in particular tasks, and who benefited from the resultant agricultural products.

A long history of ethnographic studies and cross-cultural comparisons has made some of irrigation’s context-dependent management complexities apparent. As the size area irrigated and number of people involved increases, management challenges
correspondingly increase. While irrigation on a very small-scale can be organized at the household or extended family level, there are invariably thresholds after which management can no longer remain entirely acephalous. Although these thresholds vary depending on social context and the types of tasks involved, drawing on an extremely wide range of examples, Mabry (1996b, 2000) tentatively identifies 100 hectares as a potential “cross-cultural threshold between democratic and bureaucratic management capacities” (2000: 290). As Mabry emphasizes, organizational challenges and scalar stress emerge with as few six people (Johnson 1982), and these challenges generate context-dependent thresholds beyond which systems become very difficult to manage by consensus.

Ethnographies of irrigation point to a number of management options beyond acephalous negotiation among an entire group of irrigators. Managers appointed or elected by irrigating communities, and water users associations have both been identified in a wide variety of independent cases (e.g., Hunt 1989; Coward 1977). Steward (1933: 247) describes honorary, elected irrigation managers (tuvaijü’) in the Owens Valley. Coward (1979) describes irrigation headmen (panglakayen) in the Philippines who served in systems from 15 to 70 hectares with 15 to 30 farmers and are subject to replacement. Trawick (2001:8) describes water officials in Peru who are elected by community assemblies known as campos. Based on her dissertation, Lees describes the role of irrigation managers in Oaxaca, Mexico and notes that, “on the whole, community members saw public service as a duty, a heavy burden, and did not seek such public honor” (1979: 271). While the roles of irrigation managers among these cases are diverse, it is clear that appointed or elected managers or supervisors provide one of the primary management options as systems move beyond household or acephalous management scales. Water users associations or village council irrigation management systems have also been identified in a wide variety of cases, including wenamiji village council management among the Sonjo of Tanzania (Gray 1963), and the subak water-temple coordination in Bali (Lansing 1991). Interestingly, khiyyl irrigation managers are also known among intermediate-scale irrigation systems of the Hadramawt, Yemen (Rodionov 1999), and thus provide an informative avenue to consider potential management alternatives among ancient Southwest Arabian systems (see Chapter 9 and Section 10.5).
5.6 Discussion: The Relevance of Ethnology for Understanding the Origins of Irrigation in Southwest Arabia

General parallels between irrigation practices among foragers, pastoralists, small and large-scale agriculturalists have crucial importance for understanding the origins of irrigation in Southwest Arabia. Since we still know relatively little about Southwest Arabia’s earliest irrigating/cultivating societies, irrigation practices elsewhere can help consider potential operational alternatives and help reconstruct irrigation’s development.

Cross-culturally, irrigation by foragers, or by pastoralists exclusively to produce fodder for animals, is rare and therefore arguably unlikely in ancient Southwest Arabia. Steward’s (1930) provocatively titled paper, *Irrigation without agriculture*, drew attention to irrigation among foragers. But documented cases of irrigation without cultivation are limited, and even in the Great Basin there remains uncertainty about whether irrigators were in fact planting crops and should therefore be considered agriculturists. Irrigation by pastoralists exclusively to produce fodder for animals (without consuming irrigated plant foods themselves) is probably also unlikely. Although pastoralists sometimes irrigate, in every case identified for this research they consume primary products themselves and supply the by-products as fodder for animals (and therefore are best described as agro-pastoralists). Although it remains possible that mid-Holocene Southwest Arabian foragers or pastoralists irrigated wild plants (see McCorriston et al. 2005a: 8), given the labor demands of irrigation, and the fact that crops were present in the region at the time, it seems a minor stretch from irrigation to actively planting and harvesting.

Roberts (1977) long ago argued that the southern Levant down the coast of the Red Sea to Southwest Arabia was a zone of runoff agriculture. Although Raikes (1978) disputed some of Roberts’ findings he agreed that water-rich areas and irrigation were likely integral to agriculture’s origins in the region (Raikes 1987). Due in part to challenges of accessibility, Roberts’ arguments suggesting that runoff diversion might have been necessary for agriculture in Southwest Arabia have yet to be conclusively resolved. Although rainfed cultivation is today feasible in many areas of highland western Yemen, one cannot assume that rainfed cultivation strategies necessarily preceded cultivation in water-rich locales or incipient irrigation.

Efforts to evaluate and refine the hydraulic hypothesis have generated findings crucial for understanding irrigation’s origins and development in Southwest Arabia. Although relationships between irrigation and societies are diverse and complex, as the size areas irrigated and number of irrigators increase, there is a general need for more
intricate management practices. Small-scale systems are often managed at the household or extended family level, but at some point thresholds are reached beyond which acephalous, consensus management systems become difficult to sustain. Irrigation managers who are appointed or elected but hold little official political power and water users associations are two of the most widely prevalent intermediate-scale management options. As increasingly sophisticated large-scale forms of irrigation develop, control of food products and manipulation of ideologies of agriculture provide avenues for aspiring individuals (whether despots or not) to gain power, authority, and prestige. In regions of primary state formation, early complex societies developed sophisticated means of water control that dramatically increased agricultural outputs, but centralized management of these systems was not a singular cause, nor a necessary consequence of state sociopolitics. Southwest Arabia offers a wide range of opportunities to further investigate relations between irrigation and societies, including potential to both evaluate and refine cross-cultural observations. The following chapter thus outlines a typology of traditional irrigation practices in Yemen as an avenue to facilitate consideration of irrigation’s origins.
A considerable history of research on traditional Southwest Arabian irrigation has generated information sufficient to devise a general typology. Although nearly 80% of modern cultivated land in former North Yemen (YAR) is rainfed (qagar) rather than irrigated (Taha 1988: 14; Varisco 1996: 239), former South Yemen (PDRY) is far more arid and irrigation in most areas is required. Regardless, the vast majority of both the former YAR and PDRY receive less than 800 mm of precipitation per annum (see Chapter 8), so spring, surface runoff, well, and floodwater (spate) irrigation are utilized (to some extent) in almost every region possible. Two researchers, R.B. Serjeant (1964, 1988) and Daniel Varisco (1982a, 1983a, 1983b, 1996), have contributed a wide range of information on types of traditional Southwest Arabian irrigation. A number of other studies also record technical details important to typologies. Moving from east to west, Abdul fattah (1981) studied highland irrigation in the ‘Asir region of southwestern Saudi Arabia. Eger (1987) completed a technical-hydrological study of runoff systems in Yemen’s western highlands. One of Serjeant’s students, A. Maktari published a study on water-rights and water-laws in Lahj near Aden that includes a technical description of irrigation systems (Maktari 1971: 49-70). Bujra (1971), Ba-Qhaizil et al. (1996), and Al-Khanbashi and Badr (n.d.) provide details on irrigation in the Hadramawt. Although they are far more common in Southeast than Southwest Arabia, a number of studies have also focused on underground water supply systems in Yemen (Hehmeyer et al. 2002; Lightfoot 2000a, 2000b). General information on sociocultural and agricultural development issues is also available from a variety of sources (e.g., Barnes 1993; Carapico and Tutweiler 1981; Donaldson 2000; Nugent 2003; Serjeant 1974, 1983; Varisco 1982a, 1985, 1990, 1997, 2000; Vogel 1988), but most offer few operational details pertinent to typologies.
Although a variety of systems could be devised to categorize irrigation in Yemen, for the purposes of this study a typology that facilitates consideration of irrigation’s origins is most appropriate. Wilkinson (2003: 45-52) used a system to categorize water supply techniques throughout the Near East that divided them according to water-source, including groundwater (e.g., water collection pits, wells, and underground infiltration galleries), perennial flow (e.g., canals), and episodic flow (e.g., flashflood diversion and runoff farm) systems. This classification was presumably employed because it provides a simple three category scheme that encompasses a tremendous variety of techniques. However, it complicates examinations of how particular techniques originated because groundwater systems, for instance, include both very simple systems such as water collection pits, often used by foragers and pastoralists for non-agricultural purposes that probably developed very early, with hydraulically complex systems like underground infiltration galleries (*qanāts*) that developed much later. Below, the scheme developed for Yemen by Varisco (1982a, 1996) is augmented and discussed in sequence of increasing engineering complexity and labor intensity from use of naturally occurring springs, to large flashflood water diversion dams and *qanāts*. Although one cannot assume that systems necessarily developed in this chronological sequence, given the progressive succession of labor intensities and management complexities involved, there are good reasons to suspect that less complex and less labor-demanding forms developed before systems that required sophisticated knowledge to construct and operate.

6.1 *Spring Flow* (*‘ayn* and *ghayl*)

Often one of the least labor-demanding forms, irrigation using naturally flowing springs is widely prevalent in Yemen. The general Arabic term for spring (*‘ayn*) is most commonly used to describe relative modest spring flows while the term *ghayl* (pl. *ghuyūl*) is reserved for greater volume flows. Both flow types are utilized throughout Yemen. Like *‘ayn* and *‘bir* (well), the term *ghayl* is used for place names (e.g., Ghayl Umar and Ghayl ba Wasir in Hadramawt Governate). Varisco (1982a) conducted a detailed and enlightening study of water allocation focusing primarily on *ghayl* flow in the valley of al-Ahjur. Although his argument that “tribal political organization is an adaptive response to highland spring flow allocation in Yemen” (Varisco 1983b: 365) may slightly overestimate its importance (since even in al-Ahjur most land is dry-farmed), spring-flow irrigation was and is crucial throughout most parts of Yemen.
6.2 Surface Runoff (mudarrajāt and shrūj)

The category surface runoff distinguishes a wide variety of irrigation methods, including hillslope diversion, runoff farms, and terraces that alter waterflows. These forms are often more technically sophisticated relative to spring-flow systems because they require that irrigators anticipate flow volumes and sheetwash on slopes. They also frequently require more labor than spring flow systems because longer diversion channels are required to deliver water from catchment areas rather than a single source. Terraces (mudarrajāt) and other surface runoff methods are nearly ubiquitous in highland western Yemen, a region known for its picturesque terraced landscapes. In a study of runoff systems in Yemen’s western highlands, Eger (1987) describes a variety water harvesting and runoff capture techniques including terraces, small dams in valley bottoms, and diversion channels. The labor required to construct and maintain these systems is considerable; since the 1970’s lower-cost imported food along with emigration of working age men has caused terraces in many areas to fall into disrepair (Vogel 1988). Terraces are not an option throughout much of the Hadramawt where hillslopes are often rocky and completely devoid of sediment. A variant of hillslope diversion known as shrūj was used in the Hadramawt during ancient and historic times, although it is far less frequently employed today (see Section 10.5).

6.3 Wells and Cisterns (bi’r, birkah, ma’jil, sināwa)

Wells are a common means of irrigation in Yemen, where they are often referred to using the common Arabic term for well, bi’r. Depending on depth of watertable, labor required to dig wells can be considerable, and in many parts of Arabia specialist well-diggers are known (Birks and Letts 1976; Varisco 1996: 244). Although raising water from wells is today most often accomplished with diesel pumps, wells often go by different names according to traditional water-raising method including the term sināwa that refers to a wooden pulley structure used to haul water, rather than the well itself. A wide variety of water collection features similar to wells either tap groundwater or collect runoff. Pits in wadi channels, including those described by Lancaster and Lancaster (1999: 135) and Vidal (1978) in the Levant and Saudi Arabia respectively are roughly similar to types traditionally used in the Hadramawt (Serjeant 1964: 52). In less arid areas of Yemen, tanks or cisterns (birkah or ma’jil, Varisco 1996; Kirchner 2003) are often used to store water, including the famous Aden tanks studied by Norris and Penhey (1955).
6.4 Flash Floodwater (sayl)

Flash floodwater or spate irrigation systems divert sudden, massive discharges that occur in desert regions with limited (~20-200mm/annum) precipitation. Sparse vegetation, little soil development, and therefore low-water-holding types of landcover with low infiltration/absorption contribute to abrupt flows in arid regions (Shanan 2000). Spate waters are generally diverted rather than impounded, and in addition to water have the advantage of distributing soil nutrients. Spate systems (known as sayl) are common in Yemen (UNDP 1987; Varisco 1983b), and were the primary agricultural basis for Southwest Arabia kingdoms that emerged during the late 4th through 3rd millennia BP (see Chapter 7). Spate systems are thought to have diffused from Yemen to Eritrea and Ethiopia. Although some speculatively place this diffusion during either recent (e.g., Tesfai and de Graaff 2000: 363) or ancient times (e.g., Bard 2000: 75; Butzer 1981: 477), dissemination of sayl techniques probably occurred many times throughout ancient and recent history. In addition to examples studied in Eritrea (Tesfai and Sterk 2002; Tesfai and Stroosnijder 2001), modern spate irrigation is found in a wide variety of regions including Pakistan (van Steenbergen 1997), Libya (Gale and Hunt 1986), and Oman (Costa 1983; J.C. Wilkinson 1977).

6.5 Underground Infiltration Galleries (qanāts and aflaj)

Underground infiltration galleries tap water from aquifers using a horizontal shaft connected to a series of vertical access shafts. In the Middle East, North Africa, and Central Asia infiltration galleries go by a variety of different names including kariz, khattara, fogara, qanāt, and aflaj (Beaumont et al. 1989). They most probably originated in Persia, where they are known as qanāts, and diffused to Southeast Arabia during the 3rd millennium BP (Lightfoot 2000a, 2000b; J.C. Wilkinson 1983a). They are most commonly referred to in Southeast Arabia using the term aflaj and have been the subject of many studies on construction, operation, and labor organization (Birks 1984; Costa 1983; Dutton 1989; Mershen 2002; Sutton 1984; J.C. Wilkinson 1977; T.J. Wilkinson 1975, 1976, 1977). Importantly, the term aflaj refers to wide variety of water capture methods some of which are not technically underground galleries and sometimes capture water directly from wadi beds (al-Tikriti 2002: 136-137).

6.6 Summary

A basic typology of traditional Southwest Arabian irrigation provides an informative starting-point for considering how different techniques first developed.
Systems that are less difficult to design and less labor-intensive to construct and operate likely developed before systems that are hydraulically complex and operationally labor-demanding. Exploitation of water-rich areas that in Yemen include springs and areas naturally watered by seasonal floods provide some of the least complex and least labor-intensive cultivation options. But springs are only available in fortuitous areas and can only irrigate a small fraction of available land, and floodwaters (without some form of capture or control) cannot necessarily be relied on to flow at the same magnitude from year-to-year and consistently water areas desirable for cultivation. Surface runoff methods are considerably more difficult to devise and more labor-demanding, particularly terraces that in many areas of western Yemen stand up to two meters high and if not constantly repaired are nearly impossible to rebuild (Vogel 1988). Springs and surface runoff methods were among Southwest Arabia’s earliest irrigation technologies; a surface runoff technique known as shrūj irrigation used in eastern Yemen and along rocky hillslopes of ancient Wadi Sana is a primary focus of this study. Wells are somewhat more labor-intensive to dig and utilize since water needs to be raised and sometimes delivered by hand. Flash floodwater (sayl) and underground infiltration galleries are generally the largest in areal scale, most complex to engineer, and most productive of traditional systems. Large sayl systems supported the rise of Southwest Arabia’s earliest kingdoms along the Ramlat as-Sab’atayn Desert’s margins as early as the late 4th millennium BP and underground infiltration gallery technologies are thought to have diffused from Iran to Southeast Arabia during the 3rd millennium BP. While research to date helps outline a general descriptive typology, relatively little is known about the ancient environmental and social contexts within which different techniques first appeared and developed.
CHAPTER 7

CONTEXTS FOR THE ORIGINS OF IRRIGATION: AN OVERVIEW OF SOUTHWEST ARABIAN PREHISTORY

Southwest Arabian societies followed unique trajectories from foraging to pastoralism and plant agriculture throughout which water availability and water management were crucial. This chapter reviews the basic chronological sequence of technological, economic, and social change to assist in examining the context(s) in which irrigation developed. Since archaeological evidence available for Southwest Arabia is limited in comparison with what is known of regions such as the Levant, Mesopotamia, and Egypt, investigations of ancient irrigation are usefully situated within a framework of what has been learned about concurrent societies and irrigation practices among the inhabitants of adjacent regions. This certainly does not mean that developments in Southwest Arabia are less important than findings in adjacent regions, rather new understandings of the ostensive periphery hold arguably as many new insights as continued research in locations where chronologies and mechanisms of change are better established.

The archaeology and culture histories of Southwest Arabia have traditionally remained far more sparsely known than chronologies of surrounding regions. Until the 1980’s archaeologists still pondered whether there was a substantial human presence in Southwest Arabia prior to the 5th millennium BP (see de Maigret 1986), and many explanations posited diffusion from Mesopotamia and/or Egypt as the primary mechanism responsible for the emergence of Southwest Arabian states (see Ghaleb 1990). As archaeologists have progressively expanded their searches beyond prominent city-states a far more detailed picture of ancient Southwest Arabia has become available. In contrast with the pre-1980’s view that Southwest Arabia was largely barren prior to the 5th millennium, archaeologists now recognize substantive early fortified settlements.
across the southern Arabian Peninsula (Cleuziou 2002; Edens and Wilkinson 1998; Edens et al. 2000; Frifelt 2002; Wilkinson et al. 2001; Potts 1990, 1993). While attempts to explain the origins of qanat or aflaj irrigation have sometimes envisioned developments in Southern Arabia as largely independent of other locales (e.g., Orchard 1995; Hehmeyer et al. 2002), the origins of irrigation technologies most plausibly involved neither wholly diffusion nor fully independent invention. Traditional understandings of irrigation’s origins require refinements that postulate neither simple transfers of pre-existing techniques, nor independent invention of superficially peculiar technologies, but instead acknowledge Southwest Arabia’s unique environmental, social, and political circumstances in tandem with the substantive technological and cultural influence of surrounding regions.

The extent to which irrigation technologies developed independently in Southwest Arabia or were the result of wide inter-regional contacts remains a crucial issue that can only be addressed via analyses that discuss developments in surrounding regions. Irrigation in Yemen may have been prompted, or influenced by, analogous means of agricultural intensification in adjacent regions including the Levant, Mesopotamia, Egypt, Iran, or South Asia. By the time irrigation appeared in Yemen during the 6th millennium BP, substantial scale irrigation was well underway, for instance, in Egypt (e.g., Butzer 1976) and Mesopotamia (e.g., Adams 1965). However, Southwest Arabian environments and social contexts posed unique challenges (see Chapters 8 and 9), so one cannot assume that irrigation diffused. In this chapter two lines of material evidence are applied to address diffusion/independent invention issues: 1) material evidence for transfer, exchange, or diffusion of technologies, raw materials, goods, or domesticates (including stone tool technologies, obsidian, ceramics, and crops with regions that had previously developed irrigation), and 2) irrigation techniques or elements of irrigation design and form that are either likely or unlikely to have developed independently. Attention is paid not only to when and how irrigation diffused but also to when it could have but did not. While Potts (1993) rightfully questions the use of foreign chronological sub-divisions, general terms such as Paleolithic, Mesolithic, and Neolithic can be useful as long as it is recognized that South Arabian populations experienced different trajectories of change and the timing of shifts between chronological subdivisions is not a priori the same as other regions. Radiocarbon calibration curves that are frequently updated and the marine reservoir effect introduce significant problems in establishing chronologies. All radiocarbon dates below are reported in calibrated years BP using CALIB v5.0.1 and are listed as a single median probability date (rather than a range, or set of intercepts) to
simplify comparison.

7.1 Paleolithic: The Earliest Foragers

The arrival of hominids in southern Arabia can be tentatively placed as early as the Lower Paleolithic (Zarins 2001: 33-34; Inizan et al. 1997; Inizan and Ortlieb 1987). Both geographically and temporally early foragers were sporadically distributed. Although Potts (1990) questioned the existence of any pre-Holocene populations in Southeast Arabia, and Zarins (2001: 33) agrees that some early reports of Paleolithic sites in eastern Saudi Arabia, Qatar, and UAE were erroneous identifications, recent work in Oman better confirms the presence of Pleistocene populations (e.g., Rose 2004). Reports of Oldowan and Acheulean-type tools are traditionally more conclusive and numerous throughout Southwest Arabia (e.g., Amirkhanov 1994; Inizan and Ortlieb 1987; Inizan et al. 1997; van Beek et al. 1963; Whalen and Pease 1991; Whalen and Schatte 1997; Zarins 2001) than Southeast Arabia. Based on the work of the Soviet-Yemeni expedition, Amirkhanov (1994) reports 53 Lower, Middle, and Upper Paleolithic sites from Mahra and Hadramawt Provinces. Unfortunately current findings are based almost exclusively on surface finds without chronometric dates. It therefore remains difficult to be certain about the age of tools that mimic types more precisely dated throughout Africa and the Levant. Levallois-technique materials have been reported from upland plateaus of the Hadramawt (Caton-Thompson 1953; Inizan and Ortlieb 1987; van Beek et al. 1963; Zimmerman 2000) and have been identified along plateaus of Wadi Wa’shah and Wadi Sana (Crassard 2004; Crassard and Bode 2004). Without better understanding of local technologies, assigning them a date more precise than a general Middle Paleolithic range between 500,000 and 50,000 BP is challenging, and it is difficult to exclude the possibly that Levallois-like techniques extended into the terminal Pleistocene or beyond. If accepted, the recent discovery of inundated Middle Stone Age lithics along the coast of Eritrea (Uranium-Thorium dated to ~125 thousand years ago) supports speculations that Pleistocene populations could have crossed the Red Sea near the Bab el-Mandab (R. Walter et al. 2000). Indeed, climates of this time during the Eemian interglacial (substage 5e) were warm, moist and somewhat analogous to those of the early Holocene, making Yemen ripe for human expansion (Burns et al. 1998). The general lack of chronometrically dated evidence, however, makes evaluating the timing and nature of pre-Holocene population dispersals difficult.
7.2 Mesolithic: Holocene Foragers

Relatively few South Arabian sites have been conclusively dated to the first few millennia of the Holocene (12.3 to 9.0 cal yr BP). Both regionally and throughout particular locales, the density of foragers probably remained low, even compared with arid areas such as the Negev and Sinai. Based on postulated affinities with Levantine counterparts, early Arabian blade and bladelet industries may date to as early as the late Pleistocene but more likely fall during the 10-8th millennium BP (Edens 2001; Edens and Wilkinson 1998: 62). Many desert sites consisting of scatters of lithics and bone have been found along the ancient shorelines of early Holocene playa lakes (Inizan et al. 1997; Lezine et al. 1998; McClure 1976; 1984). When water suitable for humans or animals was available at playa lakes, they undoubtedly served as attractive short-term encampment points, but the precise age of surface materials found at these sites is difficult to determine, and in many cases can only be dated sometime during the early Holocene humid interval of lake formation (~12.3 to 8 cal yr BP). A handful of dates also document early Holocene foragers in coastal and highland areas, including the earliest date from Wadi Wuttayya, Oman (10,951 cal yr BP\(^6\)), from Habarut on the Oman-Yemen border (9,493 cal yr BP\(^7\)), an early date from Zebrit 68 in Dhofar (10,509 cal yr BP\(^8\)), and two nearly identical dates from Wadi Markha, Yemen (9,453 cal yr BP\(^9\)). Although little can be stated with certainty regarding economic orientations, gazelle, ibex, equids, and cattle remains identified along the margins of ancient lakes suggest these fauna would have been important hunting targets (Edens and Wilkinson 1998: 69).

While foragers slowly established themselves throughout Southern Arabia during the 11th through 9th millennia, the origins and spread of agriculture across the Fertile Crescent (Levant-Taurus-Zagros) initiated unparalleled changes over an extremely wide geographic area (e.g., Bar-Yosef 1995; Bar-Yosef and Belfer-Cohen 1992; Perrot 2001). From the Anatolian Plateau to the Sinai Peninsula, the beginnings of plant and animal agriculture (first involving domesticated wheat, barley, rye, sheep, goat, cattle, and pigs) dramatically altered the lives of not only those who had begun to inhabit sedentary settlements but also those of arid-zone foragers who continued hunting and gathering throughout increasingly circumscribed territories (Bar-Yosef and Belfer-Cohen 1989; Kuijt and Goring-Morris 2002). A variety of explanations emphasize a range of factors

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\(^6\) 9,615 +/- 65 \(^{14}\)C yrs BP, Uerpmann 1992: 69, 88
\(^7\) 8,470 +/- 40 \(^{14}\)C yrs BP; although there other substantially earlier dates obtained on shell they are less reliable because of potential carbon uptake, Amirkhanov 1996: 138.
\(^8\) 9,280 +/- 210 \(^{14}\)C yrs BP, on shell Zarins 2001: 50
as responsible for Levantine agricultural origins, including climatic/ecological changes (e.g., Bar-Yosef 1996; Hillman 1996; McCorriston and Hole 1991; Moore and Hillman 1992; Wright 1993), demographic stress (e.g., Lieberman 1993; Rosenberg 1990, 1998), and/or shifting social and ideological relations (e.g., Cauvin 2000; Kuijt 2000). Competing explanations for the Neolithic Revolution in the Levant certainly cannot be transposed unmodified to explain much later Mesolithic-Neolithic transitions in Southern Arabia. But given the profound sociocultural, technological, and economic changes taking place in the Levant, it is not unreasonable to postulate that these changes may have indirectly influenced the lives of Southwest Arabian foragers. The central Arabian Peninsula remains one of the primary geographic gaps in regional culture histories. Synthetic reviews that integrate evidence from southern Jordan, the Sinai, and Saudi Arabia grapple with challenging issues of potential diffusion and/or intermittent emigration (e.g., Zarins 1990a; 1992a; 1998). Purported connections between lithic technologies provide the earliest potential evidence of contacts between the Levant-Mesopotamia and Southern Arabia. Similarities between Levantine Pre-Pottery Neolithic B (PPNB) stone tool types and those originally identified and labeled Qatar B by Kapel (1967) have long remained a point of interest that is commonly mentioned in regional overviews (e.g., Edens and Wilkinson 1998: 62; Inizan 1988; Cleuziou and Tosi 1998: 123; Potts 1990: 32-35, 1993: 170-173; Uerpmann and Uerpmann 1996: 133). However, Kapel’s earliest date for Qatar B (7,804 cal yr BP\(^{10}\)) falls almost 500 calibrated years after the Final PPNB/PPNC (Kuijt and Goring-Morris 2002: 366). The earliest date for the Wadi Wuttayya facies ‘roughly contemporary’ with Qatar B (8,077 cal yr BP\(^{11}\)) falls almost 250 years after the Final PPNB/PPNC, and dates for Fasad projectile points (commonly associated on stylistic grounds with the Qatar B) place them during the middle 7\(^{th}\) millennium BP (Charpentier 1996) almost two thousand years after the end of the Final PPNB/PPNC. Although some South Arabian stone tools bear significant stylistic similarities with Levantine counterparts (Edens 1988), chronometric dates presently available make alleged connections with the PPNB tenuous. More detailed analyses of production sequences along with new radiocarbon assays will undoubtedly be required to better confirm or refute long-purported, inter-regional contacts.

In terms of irrigation, there is provisional evidence that some Levantine Pre-Pottery Neolithic populations may have already begun to experiment with water manipulation during the first few millennia of the Holocene. In a cogent reevaluation of

\(^{10}\) 6,970 +/- 70 \(^{14}\)C yrs BP, Kapel 1967: 17, 31

\(^{11}\) 7,250 +/- 85 \(^{14}\)C yrs BP, Uerpmann 1992: 69
the purpose for tower and wall around Jericho, Bar-Yosef (1986) argues that rather than a
defensive fortification the wall was constructed as early as the PPNA to protect the site
from flooding. Flooding may have been not only a detriment, but water from the spring
of ‘Ain es-Sultan would have offered attractive opportunities for cereal cultivation, which
may have included small-scale water diversion (Miller 1980: 331-332). Although the
precise age of features they identified is of considerable uncertainty, Betts and Helms
(1989) have also argued that small water diversion channels leading into cisterns at the
site of Ibn el-Ghazzia, Jordan may be as early as the PPNB. If early Holocene Levantine
populations were indeed settling in water-rich areas where cultivation was most
productive (see Section 5.3), it is certainly possibly (perhaps likely) that they
experimented with small-scale forms of water management. However, neither
domesticated plants nor animals are evident in Southern Arabia during this interval, and
water manipulation technologies clearly had not developed nor diffused by this time.

A greater array of South Arabian sites from a wider diversity of environments
chronometrically dated to the 9th millennium suggest that foragers increased in number
and ranged more widely. Dates from Shagra, Qatar (8,787 cal yr BP\textsuperscript{12}), from a highland
rockshelter site in Wadi Sana (8,511 cal yr BP\textsuperscript{13}), from Yemen’s Tihama coast (8,235 cal
yr BP\textsuperscript{14}) place 9th millennium foragers in a wide range of desert, highland, and coastal
locales. Like their predecessors, these sites have yielded relatively modest remains
consisting predominately of hearths and scatters of lithics. The Arabian Bifacial
Tradition (ABT), defined by Edens (1982), encompasses numerous regional variants and
facies of stone tool technology including the Rub al-Khali Neolithic (Edens 1988, di
Edens (1988) places the ABT in Southwest Arabia between 8000-4000 \textsuperscript{14}C yrs BP, the
ABT may be more chronologically restricted in Southeast Arabia (Uerpmann 1992). One
of the few excavated deposits that produced ABT materials, the Khuzmum Rockshelter
site in Wadi Sana (SU045-1) yielded hearths, projectile points, and associated retooling
debris indicative of high mobility hunting. The stratification of retooling debris and two
radiocarbon dates separated by hundreds of years suggest the Khuzmum rockshelters
were revisited over a substantial interval (8,511 - 8,237 cal yr BP\textsuperscript{15}). Presumably game
would not have been initially over-exploited, accounting for repeated, brief occupations.

\textsuperscript{12} 7,930 +/- 115 \textsuperscript{14}C yrs BP, Inizan 1988: 103 (on shell?)
\textsuperscript{13} 7,723 +/- 87 \textsuperscript{14}C yrs. BP, McCorriston \textit{et al.} 2002: 68
\textsuperscript{14} After marine reservoir correction of a 7,770 +/- 95 \textsuperscript{14}C yr BP date on shell, Cattani and Bökönyi 2002:34.
\textsuperscript{15} 7,723 +/- 87 to 7,403 +/- 70 \textsuperscript{14}C yrs. BP, McCorriston \textit{et al.} 2002: 68
The second oldest date from Wadi Wutayya falls at the end of the 9th millennium (8,077 cal yr BP\(^{16}\)) and the Saruq Facies that follows at the site during the 7th millennium was interpreted by the site investigators as a regional variant of the ABT (Uerpmann 1992).

7.3 Neolithic: The Origins of Pastoralism and Cultivation

If animal husbandry is considered sufficient to mark the beginnings of the South Arabian Neolithic, conclusively domesticated animals are dated to the late 8th millennium BP. During the mid 8th through 7th millennia the number of sites begins to increase dramatically, including many that have been grouped within the Arabian Bifacial Tradition and associated facies (Potts 1993; Uerpmann 1992). Sites in eastern Saudi Arabia, including Abu Khamis, Dosariyah, and Ain Qannas (7,915 cal yr BP\(^{17}\)), document the southward expansion of foraging, and (along the coast at the former two sites) fishing and shellfish-collecting populations, at least some of whom were herding cattle and ovicaprids (Potts 1993: 177). By the late 8th millennium the inhabitants of present-day United Arab Emirates (UAE) and Oman had developed patterns of subsistence configured to local environments, including ovicaprid husbandry and a focus on littoral resources along the coast. At Suwayh-11 along the coast of Oman relatively few terrestrial fauna were identified and the site appears to be oriented predominately (although not exclusively) towards exploitation of coastal mangrove environments (Charpentier et al. 2000; Lezine et al. 2002). Ovicaprid husbandry is conclusively attested at the inland site of al-Buhais (UAE) during the very late 8th to 7th millennium (Uerpmann et al. 2000). Both domestic cattle and ovicaprids were also identified along the coast at Ras al-Hamra (RH-5 and RH-6) for the late 7th - early 6th millennium (Uerpmann 1989: 164; Cleuziou 2002: 195). Importantly, these sites lay outside the wild range of sheep and goat (Uerpmann 1992: 102). As an offshoot of ovicaprid husbandry first initiated in the Zagros Mountains (Zeder and Hesse 2000) or the Levant (Bar-Yosef 1998), incipient nomadic pastoralism may have developed as early as the 8 or even 9th millennium BP and spread southward (Köhler-Rollefson 1992; Zarins 1990a: 54). As Uerpmann et al. put it,

\(^{16}\) see footnote 11
\(^{17}\) 7,060 +/- 445 14C yrs BP, two additional dates of 6,885 +/- 325 & 6,655 +/- 320 14C yrs BP were also obtained Masry 1974: 113-114 from Cleuziou and Tosi 1998: 123
A population of mobile herders may have moved into the deserts of Arabia during the late 7th and 6th millennia BC, where they lost their economic bonds with sedentary farmers and developed the kind of subsistence pattern starting to become visible due to new excavations at al-Buhais (Uerpmann et al. 2000: 233-234).

Interestingly, the reduced importance of domestic fauna at coastal sites may indicate that the ethnographically known pattern of hunting and herding throughout inland areas in tandem with fishing (and shellfish collecting) along the coast (e.g., Janzen 1986) may have already begun as early as the 8th millennium (Charpentier et al. 2000). Although the extent to which differences between coastal and inland sites represent, either a) individual populations moving seasonally back and forth, or b) ethnically or economically autonomous groups inhabiting separate areas cannot yet be determined, the issue remains an important prospect for future research (Uerpmann et al. 2000).

Numerous sites further document the growth of Southeast Arabian forager-fisherman-pastoralists, including Khor in Qatar, sites throughout the UAE (including in Sharjah, Ras al-Khaimah, and Umm al-Qaiwain Emirates), and Ras al-Hamra, and Ras al-Junayz in Oman (Kapel 1967, Inizan 1988, Potts 1993: 173-177; Cleuziou and Tosi 1998: 123). Although little archaeobotanical evidence is yet available, finds at a handful of sites provide preliminary information. Excavations on the island of Dalma off the coast of UAE yielded evidence for consumption of dates (*Phoenix dactylifera*) during the very late 8th and early 7th millennium (Beech and Shepherd 2001). Although seeds from Ras al-Hamra first interpreted as sorghum have been the subject of considerable debate and have been re-identified as wild *Setaria* sp., flotation of excavated deposits at both Ras al-Hamra 5 and 6 also yielded charred jujube (*Ziziphus* sp.) stones (Beige and Nisbet 1992). The fruit of *ziziphus* (drupes) have been retrieved from later South Arabian sites and are ethnographically eaten raw or ground into flour (Tengberg 2003).

As early as the second half of the 7th millennium BP connections between Mesopotamia and Southeast Arabia are conclusively attested via recovery of ‘Ubaid ceramics at sites along the coast of Saudi Arabia and the United Arab Emirates (e.g., McClure and al-Shaikh 1993; Uerpmann and Uerpmann 1996). Fifteen or more sites in the UAE have yielded ‘Ubaid sherds including Hamriyah (Jasim 1996), Umm Qaiwain (Uerpmann and Uerpmann 1996), Jazirat al-Hamra (Vogt 1994), on Dalma Island (Flavin and Shepherd 1993), and (although they were not decorated) possibly also Ras al-Hamra 5 in Oman (Mery and Schneider 1996: 81). After correction for the marine reservoir
effect, dates of 6,309 and 6,021 cal yr BP\textsuperscript{18}, for instance, mark deposits containing ‘Ubaid sherds at Umm al-Qaiwain, UAE. Dramatic socioeconomic changes in lower Mesopotamia from the 8\textsuperscript{th} millennia onwards undoubtedly contributed to increasingly sustained contacts with Southeast Arabia. The arrival of agricultural populations in lower Mesopotamia during the ‘Ubaid is apparent in the lowermost layers of Ur, Tell el-Ubaid, and Eridu (for instance) and more recently excavated sites such as Tell Oueilli (Huot 1989), and As-Sabiyah, Kuwait (Carter \textit{et al.} 1999). Retrieval of bitumen-covered woven reed fragments and model clay boats at the latter site are indicative of incipient riverine and maritime travel that would subsequently support trade between Sumer, Dilmun (Bahrain), and Magan (Oman) (e.g., Carter 2002; Crawford 1998; Lawler 2002).

Contacts between Mesopotamia and Southeast Arabia during the 7\textsuperscript{th} millennium hold the theoretical (but apparently unexpressed) potential for diffusion of irrigation. Irrigation began in Mesopotamia and Iran at least as early as the late 8\textsuperscript{th} millennium BP (R.M. Adams 1981; Hole \textit{et al.} 1965; Neely and Wright 1994; Oates 1982; Oates and Oates 1976; Sumner 1994; Wilkinson 2003: 73). With the exception of structures identified at Choga Mami (Oates and Oates 1976), assignment of irrigation near this interval is based on indirect evidence, including linear distributions of sites that were most plausibly along canals (Adams 1965: 119; Sumner 1994: 57), a postulated connection between irrigation and larger seed sizes, and cultivation in arid regions that would have required irrigation (Helbaek 1960, 1969, 1972). Although sites such as Umm Dabbaghiya were on the margins of the dry-farming zone (Kirkbride 1972), 8\textsuperscript{th} millennium agricultural settlements in middle and lower Mesopotamia such as Tell es-Sawwan and Tell Oueili would have required irrigation (Huot 1989; Huot 1992). Ceramic similarities between Tell Oueilli and Choga Mami (Huot 1989) are representative of wide cultural contacts (see Henrickson and Thuesen 1989) with at least potential for diffusion (or stimulus diffusion) of irrigation. Small-scale irrigation tentatively dated to as early as the late 7\textsuperscript{th} - early 6\textsuperscript{th} millennium BP along the Rud-I Gushk drainage approximately 40km west of Tepe Yahya, Iran confirm that inhabitants of other locales were utilizing water diversion techniques configured to local conditions (Prickett 1979, 1985). Whether by diffusion or independent invention, irrigation may have appeared nearly as early in parts of Central and South Asia, including Turkmenistan (Lisitsina 1969; Harris \textit{et al.} 1993; Nesbitt and O’Hara 2000), Baluchistan (Scholz 1978; Raikes 1964), Pakistan and India (Francfort 1992); but the origins of systems in each of

\textsuperscript{18} 5,890 +/- 170 \textsuperscript{14}C yrs BP, Uerpmann and Uerpmann 1996: 126; 5,620 +/- 50 \textsuperscript{14}C yrs BP, Uerpmann and Uerpmann 1996: 130, 132.
these regions are still scantly known.

Despite developments in surrounding regions, explorations in both Southwest and Southeast Arabia still have not yet retrieved evidence of crops or irrigation before the 6th millennium. Plant domesticates, such as wheat and barley, could have diffused along with the little known processes that spread ‘Ubaid ceramics (see Potts 1993: 176-177), but (the albeit few) sites with archaeobotanical remains dated before the 6th millennium have not yielded domesticated crops (Tengberg 2003). Substantive adjustments may have been necessary to the habits of temperate adapted cereals before they could be grown in tropical, summer-precipitation-dominated areas (McCorriston in press).

Moreover, such temperate zone domesticates would have not only required irrigation but would have necessitated practices very different from either surface runoff techniques of the Zagros, or perennial flow (alluvial plain) techniques of lower Mesopotamia. Although small-scale structures are often destroyed by subsequent agriculture activity, the present lack of evidence for plant agriculture makes the possibility of 7th millennium irrigation in Southern Arabia seem unlikely. With animal husbandry and rich littoral resources, South Arabian populations may have instead pursued strategies sufficient to provision themselves without irrigation, and local populations may not have reached densities that would have promoted (or necessitated) shifts from foraging to cultivation until later.

In Southwest Arabia, sites along the Yemen’s Tihama coast, western highlands, the intervening Ramlat as-Sab’atayn desert, and throughout Hadramawt, Mahra, and Dhofar are significantly more plentiful during the 7th and 6th millennia BP than they were during the first few millennia of the Holocene. At sites in eastern Oman, including Ramlat Fasad, Bir Khasfa, and Habarut, foragers (who may or may not have practiced animal husbandry) were establishing small, semi-sedentary settlements in an area that would later become a heartland of incense production (Zarins 2002). Zarins (2001) reports numerous sites throughout Dhofar including many in the Wadi Ghadun system and near Shisr but notes a lack of sites on the Salalah coastal plain (possibly because of a marine transgression). Habarut—the type-site for a range of distinctive triangular-cross-section tools, including trihedral rods, and Ramlat Fasad—the type-site for Fasad points made from a blade or flake with a retouched tang—have proven particularly important for understanding Hadramawt-Mahra-Dhofar region (Zarins 2001; Charpentier 1996, 2004). In Wadi Sana, Fasad points are known exclusively as surface finds, while Habarut-type materials (including trihedral points) are known from test excavated deposits. Small, circular house structures such as those identified by Zarins and those
excavated by the Roots of Agriculture in Southern Arabia (RASA) team in Wadi Sana Figure 7.1, 6,406 cal yr BP\(^1\) are providing new evidence of populations whose economic orientation is only vaguely known but is the subject of ongoing research (see Chapter 11; McCorriston \textit{et al.} 2002).

Further west, sites in and along the margins of the Ramlat as-Sab’atayn Desert—including those near Shabwa and around al-Hawa depression (e.g. Inizan \textit{et al.} 1997; Inizan and Ortlieb 1987)—document use of areas that are today extremely arid, but were considerably more hospitable before 5000 BP (Cleuziou \textit{et al.} 1992). At the Ramlat Sab’atayn site of HARii (Wadi Harib), investigators found \textit{Gazella} sp., \textit{Capra} sp. (ibex?), and \textit{Equus} sp. (onagers?) (Fedele in di Mario 1989: 141-145). Although two radiocarbon determinations yielded erroneously recent dates of less than a thousand years, according to the site’s investigators HARii likely dates to 6th to 3rd millennium BP (Fedele 1990: 38). At a western highland site, WTHiii in Wadi al-Thayyilah, deposits excavated in and around small semi-circular house structures can be tentatively dated via associations with early Holocene stratigraphy and paleosol development, most specifically a paleosol date of 6,572 cal yrs BP\(^2\). With the exception of a single bone, cattle remains at WTHiii that may date to as early as the 9th or 10th millennium are of indeterminate wild/domestic status. Animal husbandry is more conclusively attested at the site for early 6th millennium layers where 95% of faunal remains are cattle (Fedele 1985, 1988, 1990: 38). Based on the thin-walls of a single horn-core fragment, cattle from Ash-Shumah along the Tihama coast near Wadi Rima have been reported as domesticated (Cattani and Bökönyi 2002: 44-46). However, 92% of faunal remains retrieved from the site are ass (\textit{Equus asinus}) of uncertain wild/domestic standing (Cattani and Bökönyi 2002: 44-46), and some regard the assertion that cattle were domesticated as inconclusive (Fedele 1992: 74). Although a single radiocarbon date from Ash-Shumah falls in the 9th millennium\(^2\), it seems further work will be required to confirm whether domesticated cattle (or ass) were indeed present along the Tihama (and/or elsewhere in Southwest Arabia) this early. Other sites along the Tihama including SRD-1 (Wadi Surdud) more conclusively show domesticated cattle in the 6th millennium (Tosi 1986; Edens and Wilkinson 1998: 69-70).

While the inhabitants of Southeast Arabia were developing connections along the Persian Gulf, populations in Southwest Arabia were fostering contacts along and across the Red Sea. Evidence of obsidian trade along and across the Red Sea (Francaviglia

\(^{19}\) 5,616 +/- 84 \(^{14}\)C yrs BP, McCorriston \textit{et al.} 2002: 68

\(^{20}\) 5,750 +/- 500 \(^{14}\)C yr BP, Fedele 1990: 33

\(^{21}\) see footnote 14
90), potentially as early as the 8th millennium BP (Zarins 1990b, 1996), is indicative of maritime contacts that would later connect the region (Kitchen 2002). Both plant and animal domesticates, including Levantine domesticates (e.g., wheat, barley, cattle, sheep, and goats) and African domesticates (e.g., sorghum and cattle) could have diffused via this route. When African cattle and sorghum should be officially considered ‘domesticated’ remains controversial (see Blench and MacDonald 2000; Haaland 1995, 1999; Marshall and Hildebrand 2002; Rowley-Conwy et al. 1999). Cattle were likely herded in Egypt as early as the 10th millennium BP (Close and Wendorf 1992; Wendorf and Schild 1998). Sorghum was intensively exploited or cultivated in Egypt by 9th millennium (Wendorf and Schild 1998: 104; Wasylikowa and Dahlberg 1999) and in Sudan by the 6th millennium (Haaland 1995, 1999). Although early dates for domesticated African cattle have recently become somewhat less contentious (Marshall and Hillebrand 2002), based on genetic evidence Rowley-Conwy et al. (1999) maintain that sorghum was not domesticated until as late as 100 AD. Differing views center on whether evidence of human husbandry or high-intensity exploitation, such as presence of cattle in arid areas where they could not have survived on their own, are sufficient to conclude ‘domestication’. Sorghum was undoubtedly cultivated long before 100 AD, but since it outcrosses up to 30% with wild and/or feral varieties it may not have been domesticated in a genetic sense until it was removed from contacts with wild progenitors (Kimber 2000: 11). And cattle could have been herded without distinguishable osteological or genetic changes. Although these issues will likely remain controversial, requiring morphological and genetic changes to define domestication leads research away from a focus on human behavior to a focus on how plants and animals responded. As Zeder and Hesse (2000) argued with reference to goat domestication in the Zagros, morphological changes, if related to the process of domestication at all, are only delayed, and possibly indirect, artifacts of human management. Instead, it is the transformation of strategies...that lies at the heart of the process of animal [and plant] domestication (Zeder and Hesse 2000: 2257).

Domesticated oviscaprids arrive in Egypt during the mid 8th to 7th millennium BP (Marshall and Hillebrand 2002: 110; Wendorf and Schild 1998: 105) and Levantine crops at nearly the same time, or slightly later (Wetterstrom 1993: 201). In addition to previously mentioned potential for diffusion of domesticates along the Persian Gulf, cattle, oviscaprids, wheat, barley, and sorghum were therefore available in the west from
the Levant or Egypt long prior to the earliest finds in Southern Arabia.

The earliest evidence for domesticated crops and first evidence for irrigation in Southwest Arabia coincide during the 6th millennium BP. A critically important archaeobotanical assemblage, consisting of wheat, barley, lentils, chickpeas, peas, and possibly broomcorn millet, was recently recovered from two Bronze Age sites (Hayt al-Suad and Jubabat al-Juruf) in the highlands of western Yemen and dated to the late 6th-early 5th millennium BP (Ekstrom and Edens 2003). Ghaleb’s (1990) work identified agricultural terraces, dated by association with residential occupations, to the late 6th millennium BP. Surveys in Dhamar identified a valley-floor terrace wall near Sedd Adh-Dhra and retrieved a date that calibrates to 5,716 yr BP22. Investigations for this dissertation also retrieved (from sediments above a water diversion channel) two nearly identical dates that calibrate to 5,163 and 5,144 yr BP23. Importantly, substantial-scale irrigation was well underway in the Levant (Kennedy 1995; Kühne 1990; McClellan 1996; Miller 1980; Wilkinson 1998b), Egypt (Butzer 1976), Mesopotamia (Hunt 1988a; Liverani 1996; Postgate and Powell 1988), and Iran (Prickett 1985; Sumner 1994) by this time. Did irrigation diffuse in the west along the Red Sea from the Levant or Egypt, in the east from Mesopotamia, Iran or South Asia, down the middle of the Arabian Peninsula, or some complex combination? Or did it develop independently? While animal domesticates may have been introduced to Southern Arabia with relatively modest difficulties (if necessary food and water could be made available) plant domesticates, including temperate-adapted crops such as wheat and barley, may have required significant modifications to survive and thrive in Southern Arabia (McCorriston in press). It remains unresolved whether tropic-adapted or temperate-adapted crops were the first plant domesticates in Yemen (see de Moulins et al. 2003). As Ekstrom and Edens (2003) noted, impressions of sorghum in ceramics appear in Khawlan (Costantini 1990) at nearly the same time as the Levantine crops, raising the possibility that sorghum was present in some areas of Southwest Arabia but not in others. Moreover, current evidence for irrigation and crops come from independent contexts. And since irrigation structures (including those in Wadi Sana) could have been built to promote the growth of wild plants for gathering, to attract game, or to provision domestic animals (McCorriston et al. 2005a), indisputably placing the earliest irrigation together with domesticated crops remains a unique evidentiary challenge.

23 4,475 +/- 36 & 4,471 +/- 42 14C yrs BP, see Table 8.2.
7.4 The Bronze Age and Beyond

By the late 5th millennium BP, cultivating and herding populations had established small towns and villages throughout Southern Arabia (Cleuziou 2002; de Maigret 2002; Edens 1999; Edens & Wilkinson 1998; Edens et al. 2000; Frifelt 2002; Potts 1993; Wilkinson et al. 2001). Particularly in areas receiving less than 200mm of precipitation per annum, irrigation must have played a significant role. In Southeast Arabia, settlements including Tell Abraq and Hili 8 (U.A.E.), and Bat (Oman), provide evidence of trade contacts with Mesopotamia, Iran, and South Asia (see Cleuziou and Méry 2002). Crops including wheat and barley were identified at all three sites, while sorghum is known only from Hili 8 (Tengberg 2003: 231). At Hili 8, wells were used to tap groundwater, and a moat around the site may have been connected to irrigation channels (Cleuziou 2002: 198-199). Similar undated channels were identified at Bat (Frifelt 2002: 101-104). Techniques used are not specifically known, but likely involved the precursors to aflaj systems that still operate in Southeast Arabia today (see J.C. Wilkinson 1977).

Italian investigations in the Yemen’s western highlands have identified numerous Bronze Age settlements, including Ar-Raqlah 1 (RAQi), Al-Masannah 1 (MASi), and Wadi Yanā’im 1 (WYi) (de Maigret 1990, 2002). Although no macrobotanical remains were retrieved, ceramic impressions indicate that wheat, barley, and sorghum were present during the late 5th millennium (Costantini 1990). Research in Dhamar has documented even larger 5th and 4th millennia settlements including the hilltop site of Hammat al-Qa (Edens et al. 2000; Wilkinson et al. 2001). Terrace agriculture along hillslopes, and dams in valley bottoms, similar to contemporary systems (Eger 1987) supported cultivation in the area (Wilkinson et al. 2001: 255). In Hadramawt, evidence from the 4th millennium BP, including early levels at Shabwa24, nearby at Bi’r Hamad, at Raybun25, and at Sunā and Shi‘b Munayder26 in Wadi Idm (McCorriston 2000; Sedov 1995b, 1996a, 1996b) depict analogous developments in a far distant region.

Building on at least a millennium of previous experience with spring-flow, surface runoff, and terrace agriculture, residents of regions along the margins of the Ramlat as-Sab’atayn Desert developed increasingly sophisticated floodwater irrigation schemes. Although assertions that massive, carefully masoned works near the dam at

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24 The two earliest dates calibrate to 3,897 & 3,882 cal yr BP (3,590 +/- 90 & 3,580 +/- 60 14C BP, Breton 2003: 200)  
25 see Sedov 1996: 79  
26 3,412 cal yr BP (3,190 +/- 30 14C years BP, McCorriston 2000:142)
Ma’rib were built during the 5th millennium BP are difficult to accept (see Francaviglia 2002: 114), radiocarbon dates from irrigation accumulated sediments more convincingly place substantial-scale floodwater irrigation nearly this early (Brunner 1997a, 1997b). In Wadi Marha (ancient ‘Awsan), three radiocarbon assays on charcoal embedded in irrigation-deposited sediments ranged from 3,962 to 1,998 cal yr BP^27 (Brunner 1997a: 196-197). While along Wadi Danah (ancient Saba), Francaviglia (2000: 651) reports dates on wadi sediments ranging from 5,093 to 369 cal yr BP^28. However, rates of silt accumulation on spate fields applied by Francaviglia (2000: 645, 7-8mm/yr) and Brunner (1997a: 196, 10 mm/yr) to extrapolate the beginnings of anthropogenic silt accumulation are considerably lower than measurements made for silt accumulation on modern spate irrigated fields in Eritrea (Tesfai and Sterk 2002: 200, average of 13mm/yr) indicating that (particularly if watershed hydraulics were different in the past or varied over time) sediments could have accumulated more rapidly than estimated making the beginnings of anthropogenic sediment accumulation younger than concluded.

By the late 4th through 3rd millennia BP, several millennia of experience with irrigation contributed to the rise of Southwest Arabian kingdoms, including Ma’īn, Saba, Qatabān, ‘Awsān, and Hadramawt, that each employed large-scale floodwater irrigation. Densely populated centers were renowned for trade in aromatic tree resins via both camel caravans and vessels navigating the Indian Ocean and Red Sea to the Eastern Mediterranean. Sayl waters harnessed by the kingdom of ‘Awsān in Wadi Mahra (for example) were deflected by large deflector barrages and channeled into primary canals tens of meters wide (Brunner 1997b: 80, 82). Waters were momentarily slowed before being divided into secondary and tertiary channels on their way toward banked fields (Brunner 1997b: 82). An area of at least 6,800 hectares was once irrigated (though probably not simultaneously) and canals carried water for as far as 30 km from neighboring Wadi Hammam (Brunner 1997b: 75). Investigations in Wadi Beihan (Bowen 1958; Breton et al. 1998) and at Shabwa (Gentelle 1991) have documented similarly extensive systems of barrages, canals, sluices, and earthen banked fields supporting the kingdoms of Qatabān and Hadramawt. Since early kingdoms were part of an intricate network of trade and political relations, they were most plausibly exposed to, and appear to have exploited, many of the same or very similar irrigation technologies (see also Francaviglia 2002 for descriptions of irrigation around ancient Barāqish).

^27 3,640 +/- 60 & 2,035 +/- 60 14C yrs BP, Brunner 1997a:196-197
^28 4,460 +/- 250 & 255 +/- 406 14C yrs BP, Francaviglia 2000: 651
State leaders and bureaucrats faced considerable political and organization challenges in coordinating specialists with knowledge of hydrological conditions who could design complex systems, and in mobilizing labor for construction, operation, and inevitable maintenance activities. High rates of sediment aggregation on spate-irrigated fields meant that to prevent fields from becoming stranded high-ground, leaders must have often mobilized substantial work crews to raise dams, canals, and remove silt (Bowen 1958; Brunner 1997a; Francaviglia 2000). For large-scale systems these operations (including reconstruction of dams and diversion structures that were periodically breached) were massive undertakings. Given postulated rates of sediment accumulation, Francaviglia (2000: 648) estimated that as many as 10,000 people may have labored for up to 9 months to remove silt behind the Ma’rib dam. A Sabaean inscription from AD 449 records acquisition of, “14,000 camels, 200,000 (?) sheep, 217,000 pounds of flour as well as 630 camel loads of beverages” (Brunner & Haefner 1986: 83) to supply the needs of workers mobilized to renovate the Ma’rib dam. In AD 450 parts of this system were again destroyed, and the king’s order to repair them was apparently ignored (Brunner and Haefner 1986: 83), a clear testament to substantive challenges faced in coordinating such endeavors. Interestingly, none of Southwest Arabia’s most powerful early centers developed in highland areas where rain-fed agriculture was possible, but instead emerged along the edge of the Ramlat as-Sab’atayn Desert29 where irrigation agriculture required far more labor. Harnessing massive *sayl* water flows not only boosted production but irrevocably tied cultivators and food availability to reliance on irrigation waters, and afforded elites the ideological prestige of commanding transformations of hyper-arid landscapes into rich oases.

7.5 Summary

Southwest Arabia holds potential to emerge as a more widely recognized region of transitions to agriculture and a uniquely informative case that helps clarify irrigation’s significance in instigating long-term socioeconomic and political change. Situating findings within a comparative context of inter-regional developments advances understanding of not only of Southwest Arabia itself, but helps delineate the instrumentality of core regions of the Middle East in spawning change in surrounding locales and contributes to more informed narratives about similarities and differences among peoples of a culturally and geographically wider ancient world. Although many

29 It was only much later when the Himyarite capital was established at Zafar that a regional power arose in the highlands (de Maigret 2002: 235-244).
of the plant and animal domesticates that became staples in Southwest Arabia diffused
from surrounding regions (including wheat, barley, ovicaprids, and probably sorghum),
South Arabian populations were in contact with neighboring agriculturalists for at least a
millennium before crops and irrigation appeared during the 6th millennium BP. Given
that Southwest Arabia’s earliest crops came from regions where irrigation had already
become a major productive force, irrigation in Southwest Arabia was likely inspired, to
some degree, by developments elsewhere. Indeed, trade routes are invariably avenues of
information exchange whereby concepts of prosperity afforded by irrigation, rather than
specific technologies, likely disseminated. But irrigation in Southwest Arabia (as further
explored in Chapters 8 and 9) required strategies tailored to unique local environmental
and social landscapes. Rather than a matter of entirely autochthonous development or
wholesale diffusion, ancient Southwest Arabians derived and improvised concepts of
water control, combined them with foreign domesticates, indigenous species, and adapted
them to fit local socioeconomic orientations. By the 5th millennium BP, cultivating and
herding populations had established permanent settlements across the southern Arabian
Peninsula and during the next two millennia experiences with intermediate-scale
irrigation generated floodwater irrigation technologies that stand as a remarkable
testament to advanced, locally-devised, sociopolitically-constituted skills in hydraulic
engineering.
Figure 7.1: House structure (037-3) near the Khuzmum excavated by the RASA Project and dated to the 7th millennium BP (McCorriston et al. 2002, 2005b).
CHAPTER 8

ENVIRONMENTAL PARAMETERS OF IRRIGATION IN SOUTHWEST ARABIA

A wide variety of environmental factors have important influences on the feasibility and effectiveness of disparate irrigation strategies. Structural geology, climatic conditions, geomorphology, and hydrology play crucial roles in delimiting contingencies under which irrigation systems operate. Particularly in the most arid portions of Southwest Arabia (including Hadramawt Governate and Wadi Sana), precipitation occurs only a few days a year. Deeply dissected terrain with sparse ground cover results in low infiltration, leading to sudden and massive water discharges that are difficult to control (cf. Breton 1999: 14). Successful irrigation requires detailed knowledge of natural flow patterns so they can be anticipated well in advance; ancient irrigators may have had only a handful of chances a year to make irrigation work. Unfortunately geoarchaeological analyses that explore hydrological conditions that allowed ancient irrigation systems to function are hampered by the fact that ancient structures are often damaged, destroyed, and may not bear the same relationships to physical landscapes as they did when in use (cf. Wilkinson 2003: 44-70). But detailed analyses of hydrological contexts that reveal operational requirements of ancient irrigation nevertheless offer opportunities to identify connections between environmental conditions and human behavior, and can help evaluate the extent to which strategies developed locally or were the result of inter-regional diffusion. Particularly for large systems that divert substantial quantities of water and suspended sediment, design knowledge must have developed over long periods of time following episodes of trial and most probably, error.

Following Butzer’s (1982: 24) scheme for categorizing scales of climatic variation, environmental factors can be divided according to the temporal scale at which

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30 Although Butzer defined scales of exclusively climatic variation, this study applies his temporal categories to encompass a wider range of environmental variability relevant to irrigation.
they vary. First and second order factors exhibiting seasonal to decadal scale variability, and third or higher order factors exhibiting century to millennial scale variability, play important roles in shaping the viability of irrigation techniques. For irrigation, first and second order factors include short-term meteorological changes, precipitation/evapotranspiration ratios, and the availability of irrigable plants. Third and higher order factors include topographic conditions, drainage patterns, longer-term climate change, the availability of irrigable sediments, and construction materials. Each can vary widely even within restricted locales or watersheds, and can dramatically alter the feasibility and effectiveness of different irrigation strategies.

Southwest Arabian terrain and environments are very different from those of the Middle East generally. Physical conditions including rugged, highland topography and monsoon climates, present unique challenges in comparison with those faced by early irrigators of the Levant, Mesopotamia, or Egypt. While it is possible that ancient inhabitants of Southwest Arabia devised irrigation via exposure to analogous strategies in adjacent regions, foreign techniques could not have diffused without substantive modifications. Irrigation techniques including alluvial fan water diversion and canal irrigation in Iran (e.g., Neely 1974; Oates and Oates 1976; Prickett 1985; Sumner 1994), canalization along the Euphrates (e.g., Postgate and Powell 1988), floodwater cultivation along the Nile (e.g., Butzer 1976), and aflaj systems in Oman (e.g., Costa 1983; J.C. Wilkinson 1977) each occur in unique settings very different from those of Yemen. Although reconstructing irrigation’s origins requires considering whether Southwest Arabians acquired knowledge of foreign techniques and derived strategies suitable to their own surroundings, or developed irrigation independently, conclusively distinguishing these alternatives presents substantive challenges because derived strategies might only vaguely resemble their forerunners in adjacent regions. While the availability of suitable plants is an obvious requirement of irrigation, either foreign domesticates or indigenous grass or tree species could have been the initial targets of irrigation in Wadi Sana (McCorriston in press; McCorriston et al. 2002, 2005a). Beyond the regional availability of domesticates discussed in Chapter 7, what specific plant species were gathered or cultivated in Wadi Sana is a complex topic of ongoing RASA investigations so I leave these complexities to be addressed by others. This study instead reviews structural geology and terminal Pleistocene to mid-Holocene paleoclimatic conditions in Southwest Arabia and focuses on geomorphologic and paleohydrologic conditions relevant to irrigation in Wadi Sana. Since these issues are among those of concern to RASA Project geologists led by E.A. Oches (Dept. of Environmental Science
and Policy, University of South Florida)\(^{31}\), the following discussions draw on their experience, advice, and findings. The overview below also concentrates on better known, larger magnitude paleoclimate oscillations of the terminal Pleistocene-early Holocene transition to help depict the longer-term context of irrigation’s development and characterize lesser-magnitude mid-Holocene changes that are less clearly known, but are nevertheless important to reconstructing the origins of irrigation.

8.1 Structural Geology and Topography

Terrain and topography are crucial in shaping environments, patterns of water flow, and opportunities for irrigation. Because structural geology varies relatively slowly relative to human lifetimes, landscape structure is often overlooked or considered a relatively benign element of humans’ surroundings. Yemen is uniquely known for its picturesque highland terrain that (particularly in western governates) includes lush terraced mountainsides. But terraces require particular combinations of slope, adequate precipitation, sediments, and construction materials that in much of the Hadramawt do not combine in ways that make terrace agriculture a possibility.

Southwest Arabia is situated at the corner of the Arabian plate near the junction of the Red Sea, East African, and Gulf of Aden rifts. Considerable tectonic and volcanic activity in this region has contributed to a diversity of terrain types that can be divided into four general physiographic zones (cf. Brunner 1997a: 191-193; Edens and Wilkinson 1998: 56-61; see Figure 1.1): 1) Coastal Plain, a narrow strip composed of primarily quaternary fluvial deposits including gravel and alluvium found variably along the Red Sea, Gulf of Aden, and Arabian Sea coasts. The Coast Plain along the Rea Sea, for example, is known as the Tihama and reaches approximately 70 kilometers wide. 2) Escarpment, a rugged zone approximately paralleling Yemen’s coastline that rises sharply, forming an abrupt meteorological obstruction. 3) Highlands, heavily dissected mountainous terrain that reaches elevations of nearly 4000 meters in western Yemen and is sharply punctuated by deeply incised wadis. Yemen’s highlands include a variety of geologic units including Tertiary-Cretaceous volcanics in western Yemen, Precambrian basalts northeast of Aden, and Tertiary limestones in eastern Yemen including Hadramawt Governate (Pollastro et al. 1997). And 4) Desert Interior, a vast, hyper-arid expanse of primarily loess and sand known as the Ramlat as-Sab’atayn Desert that forms part of the larger Rub’ Al-Khali (Empty Quarter) region of the Arabian Peninsula.

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\(^{31}\) Wadi Sana paleohydrology is also the subject of ongoing masters thesis research of Dr. Oches’ advisees Joshua Anderson and Kirk Sander.
The region of field studies for this research, Hadramawt Governate, includes a small zone of coastal plain surrounding the port city of Al-Mukalla, but consists primarily of heavily dissected, scree-covered limestone highlands. These highlands are composed of a Paleocene limestone base known as the Umm-er-Radhuma formation that is truncated by the primary drainage feature of the region, Wadi Hadramawt (Beydoun 1964). As one moves north from the port of Al-Mukalla inland toward Seiyun, topography rises sharply to a high cliff-line escarpment—the Southern Hadramawt Arch. Terrain then begins to fall gradually for approximately 100 kilometers over dissected highlands until reaching Wadi Hadramawt, and then rises afterward over the North Hadramawt Arch. The North and South Hadramawt Arches thus form a massive syncline draining east as Wadi Hadramawt becomes Wadi Masila and enters the Arabian Sea near Sayhut (Beydoun 1964). The region north of Wadi Hadramawt-Wadi Masila is sometimes referred to as the Northern Jol and the region to the south as the Southern Jol (Figure 1.1).

One of the tributaries that runs north into Wadi Masila, Wadi Sana is formed by a teardrop shaped watershed approximately 100 km long and up to 60 km wide that covers 3,691 square kilometers (Figures 1.1 and 4.1). In most of the watershed an Umm-er-Radhuma limestone base is overlain by the lower Eocene Jeza’ limestone, creating a deeply incised dendritic drainage network with up to three limestone plateaus. These plateaus and slopes leading to them are either scree covered or bedrock and thus do not allow construction of soil-conserving terraces. South of the town of Ghayl bin Yumain, a large basin (2,084 sq km) converges to form the headwaters of the Wadi Sana main channel. Throughout the western portion of this basin (hereafter referred to as the Ghayl bin Yumain basin) sizable expanses of alluvium, gypsum, and marl deposits form an unusually flat plain that includes remnants of the Lower-Middle Eocene Rus formation (Beydoun 1964). Today villages along the margins of this plain in an area known as Haru, in and near the town of Ghayl bin Yumain, and around the town of Lahaf are the only locations where crops are grown (Figure 4.1). Until recently, springs reportedly extended from Ghayl bin Yumain 13 kilometers downstream (north) to Qalat Habshiya. Although these springs were even more active during the early Holocene (see below), in the last two decades they have successively dried up, potentially exasperated by diesel pumps that rapidly drawdown groundwater.
8.2 Modern and Paleoclimatic Conditions

Climatic conditions exhibit variability on much shorter time scales than structural geology and topography and thus have more proximate impacts on irrigation. Temperature and precipitation have controlling influences on the timing and intensities of water flow, the accumulation and erosion of sedimentary landforms, and evapotranspiration that in turn play crucial roles in delimiting the feasibility of irrigation strategies. The following overview draws on modern climate data and paleoclimatic records including ice cores, sea cores, speleothems, and lacustrine records to assist in understanding irrigation’s origins.

Precipitation in Southwest Arabia is primarily a function of southwest monsoon systems that carry moisture from the Indian Ocean during late spring and summer. These systems are largely controlled by the position of the Intertropical Convergence Zone (ITCZ), a prominent band of clouds where subtropical and equatorial airs converge contributing to relatively higher rainfall. Today the northern hemisphere ITCZ reaches its most southerly position below the equator in January and its most northerly position along the southern edge of the Arabian Peninsula in July. Resultant precipitation varies dramatically according to physiogeography. Moist summer onshore winds precipitate as they rise over Yemen’s coastal escarpment and highlands, casting a rain shadow over areas further inland. Today mean annual rainfall ranges between 300 to 600mm along the Tihama, 200 to over 1000mm across the western escarpment and highlands, to less than 50mm across the desert interior, and between 50 to 150mm across the highlands east of the Ramlat as-Sab’atayn Desert (Eger 1987: appendix 5; Shahin 1996: appendix A). Although continuous, long-term precipitation records are rare, records for Seiyun from 1981-2002\(^\text{32}\) (the closest available to Wadi Sana), show that almost 80% of modern precipitation occurs from March to August with more than 30% falling exclusively within July and August (annual average 78mm).

Modern temperature and humidity vary considerably across Southern Arabia, with higher elevations experiencing relatively cooler temperatures and coastal areas considerably higher humidity. January temperature maxima tend to range in the 20’s Celsius and July temperature maxima in the 30’s. As is commonly the case, coastal areas exhibit considerably less diurnal temperature variability (Shahin 1996: appendix A). The effects of the southwest monsoon across the Gulf of Aden/Arabian Sea coast are also highly variable. Contemporary records for Aden (Yemen) show a considerable drop in

\(^{32}\text{Data provided by Mohammad Aidrus Ali Ahmed (Project Director, Southern Governates Rural Development Project, Seiyun).}\)
relative humidity from June to September in comparison with the other 8 months of the year (65% vs. 72%); while those for Salalah (Oman) show a summer increase in relative humidity over the same intervals (85% vs. 63%) (Shahin 1996: appendix A). In the west Aden receives primarily spring and summer (monsoon) precipitation but to a certain degree is sheltered by the Horn of Africa and is thus affected by hot, dry west-northwesterly *khamsin* winds from Djibouti. To the east Salalah receives warm, moist monsoon winds and associated summer precipitation, but is less affected by the continental African conditions. Although one certainly cannot assume that the same differentials necessarily existed throughout the Holocene, it is nevertheless notable that in addition to dramatic differences between coastal versus inland areas, substantive differences between coastal sites at nearly the same latitude are possible, and even likely.

Modern precipitation throughout Southwest Arabia, particularly for more arid locales such as Hadramawt province, is highly sporadic. Rapid precipitation pulses often occur during a matter of hours; so a single or a handful of short events can account for an entire year’s worth of precipitation. A significant portion of available moisture in some areas occurs in the form of fog and dew rather than rainfall, whereby xeric-adapted species or vegetation near springs become the only dense vegetation naturally sustained. The mountains of Dhofar, for instance, receive 400-500mm of precipitation primarily as a light mist or fog resulting from moist southwest monsoon air trapped under a continental temperature inversion (Fleitmann *et al.* 2003). Areas only a few hundred kilometers east or west (including Wadi Sana) do not presently experience this inversion and instead receive as little as 50mm per annum.

As expected for a landmass that spans such a considerable distance north to south, precipitation source and seasonality patterns also vary dramatically across the Arabian Peninsula. While the southwest corner of the peninsula experiences monsoon-dominated conditions, the central Arabian Peninsula, eastern Oman, and the Arabian (Persian) Gulf experience subtropical conditions with predominantly winter precipitation (Boer 1997). Along the Arabian Gulf coast of Saudi Arabia, for instance, winter precipitation occurs because of northwesterlies from the Mediterranean, depressions west of the Zagros mountains, and occasionally due to moisture from the East Africa/Red Sea region (Barth and Steinkohl 2004). In locales that border summer-dominated versus winter-dominated precipitation zones, such as the coast of Pakistan near Karachi, a more southerly ITCZ and concomitantly reduced southwest monsoon intensity is often compensated for by increased winter precipitation (Luckage *et al.* 2001). This compensatory effect, however, does not appear to have ameliorated periods of decreased southwest monsoon rainfall.
along the southern edge of the Arabian Peninsula. A recent study of Wahiba Sands paleodune development (in eastern Oman) suggests predominantly northbound sediment transport during the last 160,000 years rather than the winter northwesterly winds commonly assumed during periods of high latitude glaciation (Preusser et al. 2002). Although numerous questions still remain, this finding appears to suggest that a more southerly position of the ITCZ may not necessarily enhance northwesterly winds and increase winter precipitation along the southern Arabian Peninsula.

While modern records can help establish approximate frameworks for understanding past climates, they certainly cannot be taken as necessarily representative of climates ancient humans experienced. Pronounced and abrupt changes took place during the late Pleistocene and throughout the Holocene on a variety of time scales. Evidence of the southwest monsoon has advanced dramatically in the last few decades as new regional records including Arabian Sea cores (Clemens and Prell 1990; Leuschner and Sirocko 2000, 2003; Luckage et al. 2001; Sirocko et al. 1993), and speleothem records from Oman and Socotra (Burns et al. 2003; Fleitmann et al. 2003) have been retrieved. When compared to established high-resolution records such as Greenland and Antarctic ice cores, these circum-Arabian Sea records reveal close associations between the southwest monsoon and high-latitude temperature and ice volume fluctuations (Leuschner and Sirocko 2000, 2003; Sirocko et al. 1996). For the late Pleistocene (~100,000 to 10,000 $^{14}$C yr BP) Arabian Sea cores and Socotran speleothems record oscillations first identified and most clearly documented in Greenland and the North Atlantic, including Dansgaard-Oeschger D/O cycles (interstadial warm intervals) and Heinrich events (cold intervals of iceberg discharge) (Burns et al. 2003; Schulz et al. 1998). They also record in detail the two best-known terminal Pleistocene oscillations, the Bølling-Allerød interstadial (warm interval 14.6-12.9 ka cal yr BP) and the Younger Dryas stadial (cool interval 12.9-12.3 ka cal yr BP), further confirming the widespread (global) impact of these events (Schulz et al. 1998; Fleitmann et al. 2003). Collectively these findings demonstrate a pattern of associations between high and low-latitude conditions suggesting that major oscillations connected to global atmospheric changes (e.g., insolation) had substantive impacts on the intensity of the southwest monsoon (Leuschner and Sirocko 2000, 2003). Arabian Sea core paleoproductivity ($\text{CaCO}_3$ and Ba/Al) records, for instance, are demonstrably connected with reconstructed transequatorial insolation differences, indicating that processes which drive seasonal shifts in the position of the ITCZ also force changes in monsoon intensity on annual to orbital time scales (Leuschner and Sirocko 2003). As Fleitmann et al. (2003:1737) noted,
“between 10.3 and 8 ky [\(^{14}\text{C}\)] B.P., decadal to centennial variations in monsoon precipitation are in phase with temperature fluctuations recorded in Greenland ice cores, indicating that early Holocene monsoon intensity is largely controlled by glacial boundary conditions”. In general, warm intervals in the northern hemisphere associate with intervals of increased southwest monsoon intensity (Fleitmann et al. 2003: 1738). Moreover, the onset and termination of events such as D/O oscillations took place suddenly in both high and low latitudes during periods measured in decades or even years (e.g., Dansgaard et al. 1993; Burns et al. 2003), indicating they would have had substantive (although potentially diverse) ramifications for human societies of the time.

Climatic oscillations experienced in Southern Arabia since the last glacial-interglacial transition can be more specifically connected with those of monsoon-impacted subtropical Africa. Highly variable but relatively cold and dry conditions during the late Pleistocene gave way to warmer and moister conditions during the early Holocene. Abrupt Bølling-Allerød warming and Younger Dryas cooling episodes punctuated the final stages of last glaciation, with the final termination of the Pleistocene at approximately 12.3 cal yr BP. From 12.3-8.8 cal yr BP conditions remained generally warm and moist with generally lesser magnitude oscillations than those of the late Pleistocene (Sirocko et al. 1993: Figure 2; Sirocko et al. 1996: Figure 2). From 8,800 years ago onwards precipitation in Southern Arabia began to decline gradually with a more abrupt shift toward aridity near 5,500 to 4,500 cal yr BP. Africa experienced a similarly moist interval during the early Holocene, variably deemed the Holocene climatic optimum (Rossignol-Strick 1999) or African Humid Period (de Menocal et al. 2000). The termination of this phase between 5,700 to 4,200 cal yr BP has been identified as drying of African Lakes (Gasse 2000; Pachur and Hoelzmann 2000; Stager et al. 2003), retreating ice/increased dust in Kilimanjaro ice cores (Thompson et al. 2002), and increased terrestrial dust flux in sea cores off the coast of Mauritania (de Menocal et al. 2000). Interestingly, this shift toward reduced summer monsoon activity and aridity is evident in some circum-Arabian Sea records (e.g., Sirocko et al. 1993; Luckage et al. 2001; Zonneveld et al. 1997) but not others, including comparatively high-resolution speleothems from Oman (Fleitmann et al. 2003). As Fleitmann et al. (2003: 1738) explain, this apparent discrepancy may be the result of nonlinear vegetation-atmosphere feedbacks that induced negative precipitation minus evaporation moisture balance conditions in Africa but not necessarily in some parts of Arabia.

South Arabian terrestrial and coastal paleoenvironmental records depict a sequence of change that parallels chronologies established via aforementioned ice core,
sea core, speleothem and African lacustrine records. An early Holocene humid interval ~12.3 – 5.5 ka cal yr BP is attested to by high stands of Lake Mundafan and other playas and sabkhas of Saudi Arabia (McClure 1976, 1978, 1984, 1996), increased lacustrine activity in the Ramlat as-Sab’atayn desert of Yemen (Lezine et al. 1998), and the paleosol development throughout Yemen’s western highlands (e.g., Wilkinson 1997). Fluctuating sea levels during the Holocene had important impacts on coastal environments (Cartwright 1998; Charpentier et al. 2000). Persian Gulf sea levels rose dramatically from 10.8 to 9.5 ka cal yr BP and reached their Holocene high point near approximately 6,000 cal yr BP (Uchupi et al. 1999). These changes appear to have been closely matched by a mangrove swamp ocean water incursion at Suwayh, Oman near 6,000 BP, followed by lesser incursions at 5,100 and 4,500 cal yr BP (Lezine et al. 2002).

8.3 Geomorphology and Paleohydrology of Wadi Sana

In conjunction with structural geology, topography, and paleoclimate changes, geomorphologic and paleohydrologic conditions and their specific local manifestations play crucial roles in delimiting the feasibility of disparate irrigation techniques. Geomorphological and landcover changes are connected with a complex suite of interrelated variables including insolation, precipitation, vegetation cover, evapotranspiration, and associated runoff. Using a variety of terrestrial records with geographically more constrained signatures, RASA has generated a detailed paleoenvironmental chronology for the Wadi Idm-Wadi Sana area and has identified important precipitation-vegetation-sedimentation associations in middle Wadi Sana that echo the early Holocene moist phase (12.3 – 5.5/5.1 ka cal yr BP) that terminated in an abrupt shift toward aridity (McCorriston et al. 2002).

RASA’s ongoing paleoenvironmental-geomorphological research includes strategic radiocarbon and optically stimulated luminescence (OSL) dating of natural sediment sections to reconstruct periods of sediment deposition and degradation, magnetic susceptibility measurements to identify paleosols (particularly when they are not extensively traceable in section with the naked eye), and dating of tufa deposits created by springs that receded during the Holocene. RASA collaborator K. Cole (US Geological Survey, Colorado Plateau Field Station) has also collected and analyzed hyrax (Procavia sp.) middens (fossilized deposits of plant remains, urine, and other debris) ranging in date from 6,003 to 477 cal yr BP as local paleobotanical indicators.

33 RASA’s dates on hyrax middens range from 5,236 +/- 55 to 415 +/- 40 14C yrs BP, McCorriston et al. 2002: 68, AA31421 & A-11778
The chronology of change identified by RASA mirrors the regional mid-Holocene shift from less arid to more arid conditions identified in aforementioned sea core and lacustrine records. During the early Holocene, relatively high precipitation and correspondingly dense vegetation contributed to comparatively longer-duration, lower energy water flows and sedimentary aggradation along middle Wadi Sana. Of the 39 radiocarbon dates buried in silt and dated by RASA all but two\(^3\) yielded ages older than 5,144 cal yr BP (Table 8.1 and Table 8.2) indicating that widespread silt aggradation largely ceased near this time. A more southerly position of the ITCZ and reduced monsoon intensity led to more arid conditions, less vegetation, and middle Wadi Sana sediment degradation after 5.1 ka cal yr BP. Hyrax middens similarly depict a shift toward arid-adapted species during the mid-Holocene (McCorriston \textit{et al.} 2002; Cole \textit{et al.} 2004).

Paleohydrological conditions in Wadi Sana were critical in delimiting foraging and animal grazing opportunities and played a crucial role in the development of irrigation. Prior to mid-Holocene aridification, lower energy, longer duration flows and spring activity as depicted by tufa deposits along the upper reaches of Wadi Sana would have offered opportunities to divert water along the main channels of Wadi Sana, Wadi Shumlya and other major drainages. Nutrient-rich, slack-water deposits that formed at drainage confluences would have been particularly attractive for cultivation. Once the effects of aridification began, these areas would have successively dried. As vegetation cover dwindled, any sediment that existed in small pockets on slopes and plateaus would have rapidly eroded. As the hydrological regime shifted towards degradation (~5,100 cal yr BP), only sediments at confluences that were outside the reach of main drainage channels (such as those near the Khuizmum) could survive powerful flashflood water erosion. After 4500 BP, erosion of silts would have made opportunities for cultivation increasingly sparse. Torrential short-duration floodwaters characteristic of the area today could not feasibly be harnessed without massive stone diversion structures. Would-be irrigators instead directed their efforts to smaller tributary side channels where lower-energy flows could be diverted from rocky, low-infiltration hillslopes onto remnant silts along the margins of the Wadi Sana. As Yair (2001) outlines (based on long-term runoff

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\(^3\) These two samples yield anomalously young ages of 382 and 648 cal yr BP (293 +/- 39 & 680 +/- 35 \(^{14}\)C yr BP, AA60247 and OS16947). The first date (see Table 8.2) comes from sediments above a check dam (W5-1). The second date (McCorriston \textit{et al.} 2002: 68) comes from a hearth that must have been buried by some means other than widespread alluvial silt deposition.
experiments in the Negev, Israel; see also Shanan 2000) small-scale surface runoff irrigation is effective under arid conditions (< 300mm of precipitation per annum) particularly where bare rocky hillslopes contribute to low infiltration/absorption. However, once annual precipitation falls below 70mm per annum, hillslope runoff irrigation becomes “practically impossible” (Yair 2001: 301). Interestingly, Wadi Sana today receives approximately 70mm of precipitation and Yair’s findings closely correspond to comments of local badu residents of middle Wadi Sana who contend that irrigation in the area is impossible because there is simply not enough water. Clearly irrigation was not always impossible, and it remains to be determined precisely when (after 4000-3000 BP) conditions along the middle Wadi Sana became persistently too arid for hillslope runoff irrigation.

8.4 Summary

A variety of environmental factors, including structural geology, paleoclimatic conditions, geomorphology, and hydrology, played critical roles in delineating the viability and effectiveness of alternative water capture and diversion strategies. Since environmental conditions are constantly variable in the short-term (at seasonal to decadal scales) and the longer-term (at century to millennial scales), human adaptations to environments are dynamic, challenging performances that involve continual changes in the ways humans perceive and choose to respond to a range of shifting alternatives. Irrigation agriculture was well underway in the Levant, Mesopotamia, and Egypt long before Southwest Arabia, but unique local conditions in Southwest Arabia meant that strategies used in other areas could not be transposed unmodified. Southwest Arabia’s arid monsoon climates and deeply dissected, rugged terrain contribute to sudden, massive water discharges that are difficult to control. While paleoclimatic oscillations spawned by global changes and structural geology are broadly similar across Southwest Arabia, geomorphological and hydrological conditions (such as those of Wadi Sana) are most informatively reconstructed at local, watershed-specific levels. Although the details of environmental parameters of irrigation in Wadi Sana, including the influences of 6th millennium BP aridification, are further illustrated by archaeological survey and spatial analysis results described in Chapter 10, physical landscape structure, climatic conditions and their geomorphological and hydrological ramifications played a major role in delimiting opportunities for, and the origins of, irrigation.
<table>
<thead>
<tr>
<th></th>
<th>Sample #</th>
<th>Context</th>
<th>Lab #</th>
<th>(^{14})C yr BP</th>
<th>cal range BP^b</th>
<th>cal yr BP^c</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1998-H13</td>
<td>hearth in silt section NE of Khuzmum</td>
<td>OS16947</td>
<td>680 +/-35</td>
<td>629-683 (0.61)</td>
<td>559-601 (0.39)</td>
</tr>
<tr>
<td>2</td>
<td>2004-WS-4(1)</td>
<td>uppermost wadi silt in paleostage indicator (PSI) infilling</td>
<td>AA61078</td>
<td>4545 +/-45</td>
<td>5046-5320 (0.99)</td>
<td>5423-5435 (0.01)</td>
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<td>3</td>
<td>1998-CS1</td>
<td>Cave Sediment I, ashy layer 0.3-0.4 m from base</td>
<td>OS16958</td>
<td>4610 +/-45</td>
<td>5274-5470 (0.87)</td>
<td>5122-5168 (0.07)</td>
</tr>
<tr>
<td>4</td>
<td>2004-WS-17(1)</td>
<td>PSI wadi silts, 20cm below surface; youngest silt deposition</td>
<td>AA59756</td>
<td>4633 +/-40</td>
<td>5295-5470 (0.99)</td>
<td>5560-5569 (0.01)</td>
</tr>
<tr>
<td>5</td>
<td>2004-WS-17(4)</td>
<td>PSI wadi silts, 90cm below surface; youngest silt deposition</td>
<td>AA59757</td>
<td>4721 +/-56</td>
<td>5437-5585 (0.59)</td>
<td>5321-5421 (0.41)</td>
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<tr>
<td>6</td>
<td>1998-CS2</td>
<td>Cave Sediment II, organic rich layer 0.025m from base</td>
<td>OS18691</td>
<td>4800 +/-60</td>
<td>5447-5650 (0.89)</td>
<td>5327-5384 (0.11)</td>
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<td>7</td>
<td>2004-80-1-H1-1</td>
<td>hearth in silts along margins of small gully</td>
<td>AA60239</td>
<td>5081 +/-70</td>
<td>5656-5941 (0.99)</td>
<td>5973-5984 (0.01)</td>
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<td>8</td>
<td>2004-110-6-1</td>
<td>charcoal in silts</td>
<td>AA60240</td>
<td>5161 +/-43</td>
<td>5875-5996 (0.82)</td>
<td>5753-5826 (0.18)</td>
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<td>9</td>
<td>2004-110-4-A-5-1</td>
<td>charcoal in silts</td>
<td>AA60243</td>
<td>5182 +/-58</td>
<td>5857-6029 (0.75)</td>
<td>5751-5828 (0.13)</td>
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<td>10</td>
<td>2004-WS-7(0.7)</td>
<td>W. Shumlyaa, uppermost burned horizon in 98-WS3 profile; 0.7m below surface</td>
<td>AA59763</td>
<td>5329 +/-42</td>
<td>5993-6213 (0.96)</td>
<td>6243-6269 (0.04)</td>
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<td>11</td>
<td>2004-WS-6</td>
<td>Wadi Sana paleochannel - top edge of channel filling</td>
<td>AA59761</td>
<td>5402 +/-42</td>
<td>6174-6294 (0.82)</td>
<td>6110-6155 (0.11)</td>
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<td>12</td>
<td>2004-80-1-H2-1</td>
<td>geological date on silt section E. across wadi from Khuzmum, 0.25 m below top of silts</td>
<td>AA38380</td>
<td>5485 +/-64</td>
<td>6178-6411 (0.98)</td>
<td>6120-6148 (0.02)</td>
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<td>13</td>
<td>2004-80-1-H2-1</td>
<td>hearth in silts along margins of small gully</td>
<td>AA60241</td>
<td>5545 +/-43</td>
<td>6281-6409 (1.0)</td>
<td>6,344</td>
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^aPublished and unpublished dates in this table are listed with permission of the RASA Project, all dates on charcoal with the exception of #31 which is on shell (Melanoides tuberculata?)

^bRanges calculated with CALIB v5.0.1 using IntCal04 calibration data (see Reimer et al. 2004). Values in brackets indicate relative area under distribution at the 2-sigma (95.4%) confidence interval (for brevity only the two greatest probability ranges are reported).

^cMedian probability for calibration range from CALIB v5.0.1

Continued

Table 8.1: RASA Project radiocarbon dates for silts along middle Wadi Sana and the mouth of Wadi Shumlyaa^a

108
<table>
<thead>
<tr>
<th>No.</th>
<th>Date Code</th>
<th>Description</th>
<th>Method Code</th>
<th>Radiocarbon Date</th>
<th>Age Range</th>
<th>Age Error</th>
<th>Value</th>
<th>Table 8.1 Continued</th>
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<tbody>
<tr>
<td>14</td>
<td>2000-037-3A-006</td>
<td>Abandonment surface inside house built in silt</td>
<td>AA38547</td>
<td>5616 +/- 84</td>
<td>6280-6570 (0.96)</td>
<td>6582-6631 (0.04)</td>
<td>6,406</td>
<td></td>
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<td>15</td>
<td>1999-H10</td>
<td>Hearth in Wadi Shumlya silt section</td>
<td>OS16934</td>
<td>5750 +/- 45</td>
<td>6443-6658 (1.0)</td>
<td>6,550</td>
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<td>16</td>
<td>04-WS-18</td>
<td>W. Sana tributary, middle of wadi silt deposition</td>
<td>AA61077</td>
<td>5765 +/- 45</td>
<td>6452-6665 (1.0)</td>
<td>6,566</td>
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<td>17</td>
<td>2000-037-3A-009</td>
<td>Hearth in silts under and pre house floors containing bifacial notched &quot;desert neolithic&quot; point</td>
<td>AA38544</td>
<td>5806 +/- 64</td>
<td>648-6746 (1.0)</td>
<td>6,606</td>
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<td>18</td>
<td>2004-WS-7(3.6)</td>
<td>W. Shumlya, lower exposed silt in 98-WS3 profile; 3.6m below surface</td>
<td>AA59760</td>
<td>5842 +/- 43</td>
<td>6531-6748 (0.99)</td>
<td>6504-6517 (0.01)</td>
<td>6,658</td>
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<td>19</td>
<td>1999-H2</td>
<td>Bell-shaped pit in Wadi Shumlya silt section</td>
<td>OS16933</td>
<td>5870 +/- 45</td>
<td>6596-6791 (0.95)</td>
<td>6562-6594 (0.05)</td>
<td>6,693</td>
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<td>20</td>
<td>1998-WS2</td>
<td>98 Shumlya (Wadi Section #2, +45cm) hearth in silts along margins of small gully</td>
<td>OS16689</td>
<td>5880 +/- 55</td>
<td>6547-6804 (0.96)</td>
<td>6813-6849 (0.04)</td>
<td>6,702</td>
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<td>21</td>
<td>2004-80-1-H3-1</td>
<td>Wadi Sana paleochannel - basal infilling of channel hearth in silt section NE of Khuzmum</td>
<td>AA60244</td>
<td>5953 +/- 45</td>
<td>6672-6892 (1.0)</td>
<td>6,783</td>
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<td>22</td>
<td>2004-WS-8</td>
<td>Wadi Sana paleochannel - basal hearth in silt section NE of Khuzmum</td>
<td>AA59762</td>
<td>5970 +/- 72</td>
<td>6651-6992 (1.0)</td>
<td>6,810</td>
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<td>23</td>
<td>1998-H14</td>
<td>hearth in silt section NE of Khuzmum</td>
<td>OS16950</td>
<td>6070 +/- 40</td>
<td>6793-7019 (0.96)</td>
<td>7125-7151 (0.04)</td>
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<td>1998-H16</td>
<td>hearth in Wadi Shumlya silt section</td>
<td>OS16935</td>
<td>6080 +/- 55</td>
<td>6794-7031 (0.82)</td>
<td>7094-7156 (0.12)</td>
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<td>25</td>
<td>2004-151-1-H11-1</td>
<td>hearth in silts along margins of small gully near buried ring of cattle skulls</td>
<td>AA59571</td>
<td>6097 +/- 39</td>
<td>6878-7031 (0.78)</td>
<td>7094-7156 (0.14)</td>
<td>6,969</td>
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<td>26</td>
<td>2000-8A</td>
<td>Geological date on silt section E. across wadi from Khuzma as Shumlya, 1.95 m below surface</td>
<td>AA38381</td>
<td>6246 +/- 58</td>
<td>6991-7277 (1.0)</td>
<td>7,171</td>
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<td>27</td>
<td>2000-044-25-1</td>
<td>Hearth 2000-044-25-1 in section ca. 1m below surface E. of 4 rockshelters, Khuzma as Shumlya</td>
<td>AA38546</td>
<td>6352 +/- 57</td>
<td>7171-7341 (0.77)</td>
<td>7348-7417 (0.23)</td>
<td>7,290</td>
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<th>Age Code</th>
<th>Age</th>
<th>2σ Error</th>
<th>1σ Interval</th>
<th>Interval Probability</th>
<th>Radiocarbon Date</th>
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<tr>
<td>28</td>
<td>2004-WS-3(a)</td>
<td>W. Sana - charcoal from base of wadi silts (onset of silt dep.)</td>
<td>AA59764</td>
<td>6387 +/- 61</td>
<td>7242-7426 (0.94)</td>
<td>7,323</td>
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<td>29</td>
<td>2000-044-20-2</td>
<td>Hearth in ashy layer with hearths, 2-3 m below surface in section E. of 4 Khuzmum rockshelters, &quot;desert neolithic&quot; points</td>
<td>AA38545</td>
<td>7432 +/- 60</td>
<td>8160-8383 (0.98)</td>
<td>8,262</td>
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<td>30</td>
<td>2004-WS-10(4b)</td>
<td>lower 1/3 of wadi silts (1.4m above base; 4m below top)</td>
<td>AA59765</td>
<td>9252 +/- 52</td>
<td>10268 (1.0)</td>
<td>10,425</td>
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<td>31</td>
<td>2004-WS-3(b)</td>
<td>shells from base of wadi silts (onset of silt deposition)</td>
<td>AA59768</td>
<td>10254 +/- 55</td>
<td>11759-12185 (0.97)</td>
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<td>Sample #</td>
<td>Sample context</td>
<td>Context</td>
<td>Lab #</td>
<td>Age for</td>
<td>$^{14}$C yr BP</td>
<td>cal range BP&lt;sup&gt;a&lt;/sup&gt;</td>
<td>cal yr BP&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>1</td>
<td>2004-W5-1-T1-6</td>
<td>plant debris check dam</td>
<td>burnt layer</td>
<td>AA60247</td>
<td>terminus ante quem for W5-1</td>
<td>293 +/- 39</td>
<td>286-469 (0.99)</td>
<td>158-164 (0.01)</td>
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<td>2</td>
<td>2004-009-1-T3-7</td>
<td>wood char.</td>
<td>sediment above rock-bordered canal</td>
<td>AA60245</td>
<td>terminus ante quem for 009-1</td>
<td>4471 +/- 42</td>
<td>4969-5297 (1.0)</td>
<td>5,144</td>
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<td>3</td>
<td>2004-009-1-T1-2</td>
<td>wood char.</td>
<td>sediment above rock-bordered canal</td>
<td>AA59569</td>
<td>terminus ante quem for 009-1</td>
<td>4475 +/- 36</td>
<td>5031-5291 (0.91)</td>
<td>4976-5017 (0.09)</td>
</tr>
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<td>4</td>
<td>2004-W23-1-H1-1</td>
<td>wood char.</td>
<td>hearth in silt below water diversion channel</td>
<td>AA60251</td>
<td>terminus post quem for W23</td>
<td>5637 +/- 44</td>
<td>6309-6497 (1.0)</td>
<td>6,418</td>
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<td>5</td>
<td>2004-W13-1-H1-1</td>
<td>wood char.</td>
<td>hearth in silt section near check dam</td>
<td>AA60250</td>
<td>terminus post quem for W13-1</td>
<td>5783 +/- 44</td>
<td>6466-6676 (1.0)</td>
<td>6,584</td>
</tr>
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<td>6</td>
<td>2004-W6-1-H2-1</td>
<td>wood char.</td>
<td>hearth in silt section near check dam</td>
<td>AA60249</td>
<td>terminus post quem for W6-1</td>
<td>5923 +/- 44</td>
<td>6658-6859 (0.99)</td>
<td>6871-6880 (0.01)</td>
</tr>
<tr>
<td>7</td>
<td>2004-W1-4-H1-1</td>
<td>wood char.</td>
<td>hearth on silts near check dam</td>
<td>AA60246</td>
<td>terminus ante quem for W1-1</td>
<td>6168 +/- 51</td>
<td>6935-7178 (0.96)</td>
<td>7197-7242 (0.04)</td>
</tr>
<tr>
<td>8</td>
<td>2004-W5-3A-3</td>
<td>wood char.</td>
<td>hearth in silt section near check dam</td>
<td>AA60248</td>
<td>terminus post quem for W5-3A</td>
<td>6232 +/- 45</td>
<td>7141-7258 (0.55)</td>
<td>7006-7132 (0.45)</td>
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<sup>a</sup>Ranges calculated with CALIB v5.0.1 using IntCal04 calibration data (see Reimer et al. 2004). Values in brackets indicate relative area under probability distribution at the 2-sigma (95.4%) confidence interval.

<sup>b</sup>Median probability for calibration range from CALIB v5.0.1

Table 8.2: Radiocarbon dates for Wadi Sana irrigation structures.
CHAPTER 9

SOCIAL PARAMETERS OF IRRIGATION IN SOUTHWEST ARABIA

In tandem with technical challenges encountered in devising irrigation strategies that are viable and effective amidst inherently variable environments, irrigators face considerable social, political, and cultural obstacles in establishing and maintaining social understandings and relations required for irrigation. Although a long history of research on associations between irrigation and sociopolitical organization has failed to demonstrate simple deterministic associations between forms of irrigation and forms of society, cross-cultural investigations have demonstrated the importance social considerations hold for understanding irrigation practices and their histories. Although it may be tempting to consider irrigation a technical obstacle that simply requires one or a few individuals to devise viable techniques and then teach or join forces with others, such a view ignores inherent social challenges, including that agriculture (particularly irrigation agriculture) often requires substantial cultural reorganizations. Time and energy invested in building irrigation structures, planting, tending, and harvesting crops is expended for delayed returns in ways that may preclude other foraging or pastoral pursuits. New understandings and social relationships, including concepts of land-use, territory, tenure, food and wealth distribution, and power relations are crucial to understanding irrigation as a social force. Socio-organizational requirements thus rival techno-environmental challenges as impediments to successful irrigation strategies.

Examining social circumstances of contemporary small-scale irrigation in Southwest Arabia provides an informative avenue towards understanding social parameters of archaeological systems. Although elements of social relations can be gleaned from the type, layout, and distribution of ancient irrigation, social circumstances related to and responsible for ancient systems are not self-evident archaeologically. Studies of traditional Yemeni agriculture provide opportunities to bridge irrigation
activities of the present with those of the past. Although modern circumstances certainly
cannot be taken a priori as necessarily representative of ancient times, water and arable
land are scarce resources interconnected with sociopolitical relations and ideologies in
ways that make understanding contemporary irrigation practices a critical first step
toward understanding their beginnings.

Water and irrigation agriculture are crucially important parts of life in Southwest
Arabia that are interconnected with social relations, politics, and identity. Although
social relations across the Middle East generally and Southwest Arabia specifically are
the result of complex histories that cannot be considered homogenous, a number of
themes recurrent in Middle Eastern ethnography including the role of tribal identities, the
influences of Islam, and interactions between townsfolk and nomads are concomitantly
important to understanding irrigation. The importance of relations between hadar
(townspeople) and badu (nomads) recognized and first developed as an explanatory
framework by 14th century Arab scholar Ibn Khaldun (1967 [1377]), for example, holds a
significant degree of utility for understanding sociopolitical differences between
irrigating townsfolk and ovicaprid and camel herding nomads of the Hadramawt
(Boxberger 2002: 67-122). Although tribalism is commonly construed in ethnographic
terms as characteristic of nomadic pastoralists, tribal affiliations are no less important in
areas where nomads are rare (or absent) including among sedentary farmers of highland
western Yemen where tribal connections still frame contemporary politics and
agricultural territories (Dresch 1989; Varisco 1982a). The influences of Islam are
similarly crucial for understanding water-use. Islamic (sharī‘a) law describes
circumstances where land and water can be owned or must be shared, and thus defines
contexts within which specific claims must be negotiated. Although historic and modern
influences have induced significant changes in agricultural practices (including
introduction of new technologies such as diesel-pump driven tube-wells), terrace and
small-field agricultural holdings have generally limited mechanization options, and it is
therefore still possible to observe some social aspects of traditional agriculture.

Previous studies of traditional Southwest Arabian agriculture provide a variety of
information on social parameters of small-scale irrigation. Although few English
language publications have focused specifically on irrigation in the Hadramawt
(Rodionov 1999; Salameh 2001; Serjeant 1964), information on irrigation appears as an
associated topic in studies of Hadrami culture, history, and political economy (e.g.,
Boxberger 2002; Bujra 1971; Hartley 1961). For regions of Southwest Arabia beyond
the Hadramawt, including former North Yemen and the ‘Asār region of Saudi Arabia, a
far wider breadth of literature is available. Information on irrigation is available from studies with a variety of research foci including agricultural development (Barnes 1993; Eger 1987; Nugent 2003, Varisco 1990; Vogel 1988), water-rights, water-laws, and sharecropping (Donaldson 2000; Maktari 1971), water allocation (Varisco 1982a, 1983a), medieval agriculture (Serjeant 1974, Varisco 1997), specific crops and cultivation techniques (Bornstein-Johanssen 1975; Varisco 1982b, 1985), as well as general ethnographic studies of agricultural practices (Abdulfattah 1981; Carapico and Tutweiler 1981; Serjeant 1988; Varisco 1983b). A considerable number of investigations examine social aspects of aflaj irrigation systems in Oman (Birks 1984; Costa 1983; Dutton 1989; Mershen 2002; Sutton 1984; J.C. Wilkinson 1977), but aflaj systems common in Southeast Arabia involve socio-organizational circumstances quite different in comparison with the spate, hillslope, and terrace systems common in Yemen.

9.1 Social Relations, Politics, and Identities

A considerable number of studies have documented the importance of tribal relations, leadership, and authority among Southwest Arabian societies (e.g., Adra 1982; Dresch 1982; Gingrich 1989; Shyrock 1990; Stevenson 1985; Swagman 1988; Varisco and Adra 1981). In North Yemen, tribal affiliations were a significant component of political authority as early as the first millennium BC (de Maigret 2002: 200-201, 219). Particular groups such as the Ḥāshid and Bakīl tribal confederacies have existed as a major sociopolitical force in the areas surrounding Sana’a since at least the tenth century AD (Dresch 1984: 33-36). Although the ethnographic term ‘tribe’ is often used interchangeably with the Arabic term qabīla, anthropological (pre)conceptions about tribal societies certainly cannot be uncritically applied. However, certain (albeit controversial) anthropological generalities, including the principle of patrilineal segmentation do hold at least some limited degree of usefulness for understanding relations among Southwest Arabian ‘tribes’. As Dresch notes,

A dispute where honor is dramatically at stake (one involving women, a protected person, a market, or some other marked element) tends to expand to fill the available space: that is, the dispute between A of Ḥāshid and B of Bakīl, for example, is more likely to become a dispute between Ḥāshid and Bakīl (Dresch 1986: 316).

But as Dresch emphasizes, action and outcomes depend on the specifics of disputes at hand, or as he puts it, “the course events take”, so that segmentation can in no way
accurately predict what may or may not happen in any particular instance (Dresch 1986, 1987). Indeed, the notion of segmentation as characteristic of all or even some subset of tribes has been subject to extremely strong criticism (e.g., Bastug 1998; Munson 1993), so these and other classificatory generalizations can offer some useful insights but must be approached with caution.

Although any attempt to describe a system of social identity groups inevitably over-simplifies complex relations, patterns of sociopolitical differentiation do have critical importance for understanding rights and roles in irrigation agriculture. Among townspeople of the Hadramawt, a variety social groups have been distinguished (Bujra 1971: 13-53; Boxberger 2002: 17-37): 1) sāda (sing., sayyid), families of religious standing who claim descent from the Prophet Muhammad, 2) meshā’ikh and qabā’il who identify with particular tribal patrilines and sometimes are also religious authorities, 3) masākin and du’afa’, townsfolk, farmers, and fisherman without official tribal genealogies, and 4) sibīn and ‘abid, soldiers, slaves, household, and agricultural workers. Although published ethnographic information for the Hadramawt is not nearly detailed enough to adequately define the respective roles of each group in irrigation, each bears some resemblance to social groups in other areas of Yemen from which their roles in irrigation can be somewhat more adequately discussed.

Sāda were traditionally recognized as holding the highest degree of ascribed religious prestige and power based on patrilineal descent traced to the Prophet Muhammad. Sāda traditionally held preferential access to education and were considered learned and pious, although in practice this could vary significantly from the ideal, and sāda were not necessarily wealthy (Varisco 1982a: 156-163). In the Hadramawt, sāda often kept written genealogical records, were distinguish by dress, deference in titles of address, and sāda women did not marry men who were not sāda (Boxberger 2002: 19-24). As Bujra (1971: 68) calculated for the town of Hureidha, sāda held proportionally more land per household than other groups and controlled the vast majority of waqf (religiously endowed) land. Individuals of the sāda family holding the hereditary position of mansib in Hureidha would lead religious ceremonies and in some cases organized annual feasts (Bujra 1971: 21 & 44). Sāda conducted duties of local administration, avoided market craftwork, and rented a considerable portion of their land to sharecroppers. In both al-Ahjur, North Yemen (Varisco 1982a: 162) and in Hureidha sāda farmed their own land as well (Bujra 1971: 68), although as Serjeant (1964: 48) describes this may not have been the traditional norm.
Mashāʾikh and qabāʾil are two groups who were both formally considered tribespeople and linked here for the sake of brevity. Both held ascribed status based on tribal patriline. The former were religious authorities before the arrival of the sāda in the tenth century AD, and to a certain degree competed with sāda for scholarly, religious renown. The latter were (at least stereotypically) known for bravery, honor, military prowess, ability to carry arms, and generally were pastoralists or farmers rather than shopkeepers or craftsmen. Indeed, tribesmen (more generally known as badu) were both settled farmers who lived in villages surrounding larger towns, and nomadic herdsmen, depending on familial background. While in North Yemen the term shaykh refers to individual tribal leaders (see Dresch 1984; Shyrock 1990; Swagman 1988), in Hadramawt the term shaykh seems to have historically lost this exclusive meaning, and only the plural form of shaykh (mashāʾikh) was used to refer to tribesmen (cf. Boxberger 2002: 24). Two additional positions of tribal leadership, mugaddam (village headmen), and hākim (local magistrate) were also important. Although marked by significant regional differences, both operated in ways analogous to position of shaykh in North Yemen—positions were generally associated with particular patrilines but standing still had to be achieved based on skill, most commonly in dispute arbitration (Hartley 1961). In the case of both Hureidah and al-Ahjur, settled tribesmen owned most of the land they farmed, and sometimes held a small amount sharecropped by others (Bujra 1971: 68; Varisco 1982a: 173). As Dresch (1989: 280) reports for a village in North Yemen, the minimum amount of land generally required per qabāʾil household was approximately 150 libna (~1 hectare) with an average of 285. Although physio-geographic conditions are very different in the Hadramawt, this roughly corresponds with landholding in Hureidha where qabāʾil households held an average of approximately 1 hectare (Bujra 1971: 68).

Masākīn and duʿafaʾ encompass a wide variety of townsfolk, craftsmen, merchants, farmers, and fishermen. Although neither held official genealogical status as tribesmen and were therefore prohibited from carrying arms, the term hadar or ‘civilized’ was sometimes used as a broad descriptor for both (Boxberger 2002: 31). Farming was considered a prestigious occupation. Prior to the Quaʿity state, masākīn and duʿafaʾ were prohibited from owning land (Bujra 1971: 63) and therefore may be tentatively compared with banī khums in North Yemen who similarly prohibited from owning land or rights to water, and instead practiced a variety of market professions (Varisco 1982a: 174; Stevenson 1985). In more recent times, however, masākīn in Hureidha owned almost as much land per household as other groups and like qabāʾil also sharecropped land owned
by sāda and mashāʾikh (Bujra 1971: 68). Masākin and ḍuʿaʃaʾ were variably known for work as vendors, merchants who practiced a variety of hereditary crafts, as well as household servants, and farmhands. Farmwork including a variety of laborious tasks including digging, raising, and carrying water from wells, constructing irrigation channels, and plowing fields.

Sibān and ʿabīd formed a final category of relatively low status servants, guards, and workers. Both were traditionally beholden to particular client households for employment and protection, although in recent times they also worked on an opportunistic basis for pay. They often moved with patron households, who were obligated to provide for them, even (or particularly) in times of hardship or drought. In both North Yemen and the Hadramawt pay was sometimes provided in the form of sorghum stalks (gasab) which could be used for or sold as fodder (Dresch 1989: 296).

The aforementioned identity groups describe relations among Hadrami townsfolk. Relations in rural areas including those far distant from Hadrami towns are substantially different and far less information is available. Although details published in English are sparse, Janzen’s (1986, 2000) work among populations of Dhofar provides one of the geographically closest detailed studies that depicts socioeconomic orientations comparable to those across the prehistoric-early historic Southern Jol. Indeed, the significance of Dhofari and Mahri populations has not been lost to archaeologists including Zarins (1992b) and el-Mahi (2001) who review them as a means of understanding ancient cultural ecology of the region. Janzen (1986: 53-163) describes three populations of Dhofar, goat and cattle herding “Beduin” of northern deserts, goat and cattle breeding “Jebali” of the escarpment and highlands, and the “Hadr” townsfolk of the coast. The latter two groups cultivate sorghum. Ḥadhar townsfolk lived permanently along the Indian Ocean, while jabalis periodically returned to sorghum fields during the course of vertical transhumance from the coast to the highlands during which they sought fodder for their cattle. Although jabalis’ highland fields were traditionally surrounded by walls to protect crops from grazing, it is not clear from Janzen’s descriptions whether or not they traditionally irrigated them. Like Janzen, neither Zarins (1992) nor el-Mahi (2001) mention water diversion. Given that these areas received nearly 500mm of precipitation per annum (often in the form of fog or dew caused by a temperature inversion, see Section 8.2) irrigation may not have been practiced, but further work is required to more conclusively determine irrigation’s presence or absence.

117
Regionally and locally diverse ideologies of water and water-use, including Islamic traditions of jurisprudence on land and water rights, are centrally important as sociocultural parameters of irrigation. While contemporary traditions are obviously not synonymous with those of prehistory, long-standing customs highlight the importance of ideologies of water that operate in tandem with local environmental contingencies. Communal ritual visits to tombs of venerated ancestors, including famous annual pilgrimages to the tomb of the Prophet Hud in Wadi Masila, are of well-known significance in Hadrami culture (Boxberger 2002: 155-159; Knysh 2001). Rodionov (1997) describes pilgrimage to the tomb of Mawlā Mater (Patron of Rain) in Wadi al-Kisrah, Hadramawt demonstrating the intricate ideologically-imbued importance of sacred places connected with water in Hadrami landscapes. Although Islamic law acknowledges local traditions of water-rights and ownership, there often remain tensions between tribal custom (‘urf) and Islamic (sharī’a) law (see Boxberger 2002: 25; Maktari 1971: 3-8). However, one of the most basic, honored principles of Islamic law pertaining to water is the distinction made between water bestowed by God that must be accessible to all, versus water harnessed by people that can be privately controlled (e.g., Lancaster and Lancaster 1999: 129; Maktari 1971: 13-20). Given that irrigators who invest substantial energies in capturing water often need to protect their investments from encroachments of wandering pastoralists and their herds, exclusive ideologically-reinforced rights to captured water most plausibly extend (in some form) as early as the beginnings of water control.

9.2 Socio-Logistics of Irrigation Work and Management

Even given a significant body of literature on traditional Yemeni agriculture, beyond basic identity-group roles, surprisingly few specifics are known about irrigation operation and management. To understand the socio-logistics of irrigation work and management, one not only needs detailed understanding of technologies but knowledge of what specific tasks were required for construction, operation, and maintenance, who (ideally and actually) held the knowledge about these tasks, how land, water, and food products were controlled and distributed, and how water-rights and disputes were expressed. Although understanding task issues requires long periods of concentrated fieldwork, some basic aspects can be gleaned for the Hadramawt from available literature including Serjeant (1964) and Rodionov (1994; 1999) and a number of recent publications in Arabic (Al-Khanbashi and Badr n.d.; Ba-Qhaizil et al. 1996).
Traditional irrigation practices in the Hadramawt include a variety of spring-water (‘ayn and ghayl), well-water (bi’r and sināwa), and floodwater (sayl) strategies. Each requires a range of labor-coordinating activities, with sayl systems tending to be the most complex because they are the largest in areal scale, involve the greatest number of participants, and require rapid coordination in response to short rainfall episodes. Indeed, recent studies of sayl water systems in western Hadramawt help illustrate this traditional technical and social complexity (e.g., Ba-Qhaizil et al. 1996; Al-Khanbashi and Badr n.d.).

Ba-Qhaizil et al.’s (1996) study of sayl systems in Wadi Daw‘an provides an informative general description of intermediate-scale floodwater management practices. Landholders (usually no less than forty) share the cost of installing systems that irrigate areas generally larger than ten hectares. A committee of five to seven people is formed. A ra‘id al-sāqiyya supervises operation and maintenance of primary sāqiyya canals, while a ra‘id al-nakhīl supervises systems that lead from the primary canals to individual fields of date palms and understory cereals (cf. Serjeant 1964: 47). The committee head, known as khiyyl, oversees the system. Most importantly khiyyls are responsible for supervising allocation, assessing damage caused by floodwaters, collecting funds from landholders or generated by land set aside for maintenance and repairs, and mobilizing labor. As Rodionov (1999:120) describes, khiyyl managers were often sāda or mashā‘ikh, but the position was elected rather than hereditary (Redkin 1995: 200-201). Khiyyls were charged with the job of ensuring practices conformed to local traditions but conventionally held no official or monocratic political authority.

Disputes arising from differing conceptions of water-rights, responsibilities, and expectations about how irrigation should operate reflect the cultural intricacies of irrigated landscapes. Ethnographic investigations show that mitigating and resolving disputes is one the most central aspects of Yemeni tribal and Islamic authority, and conflicts about water were (and are) a primary source of dispute (Hartley 1961: 187; Lichtenthaler 2000). In the Hadramawt, disputes were frequently referred to a hākim (local magistrate) considered expert in tribal customs. Hartley (1961), who examined the role of hākim as one of the primary foci of his dissertation, describes how resolving controversies about irrigation was an important skill, and some hākins were specifically known for capabilities on the topic (Hartley 1961: 95, 143-144). For long-standing or particularly contentious disputes, sāda of local religious standing or an Imam were consulted for judgments about water-rights and law. Salameh (2001) describes a 16th century manuscript outlining the opinions of two Islamic scholars solicited for judgment
about rights to control and modify canals and banked-field systems. The complex issues of water ownership Salameh describes, particularly relationships among upstream/downstream users, illustrate how water-rights and responsibilities were envisioned and mediated according differing local landscapes, conventions, and interpretations of general Islamic water law.

Although only preliminary observations can be gleaned about traditional Southwest Arabian irrigation management positions, persons holding the position of ʿaqīl (pl., ʿuqqāl; literally meaning ‘wise’) and wakīl in North Yemen sometimes conduct duties similar to khiyyls. Varisco (1982a: 340-344), for instance, describes the position of wakīl in al-Ahjur who oversees ghayl water allocation and helps mobilize labor for maintenance (cf. Serjeant 1988: 146). In a number of other publications ʿaqīls are briefly noted as lower-level shaykhs or village leaders but their precise roles and duties (including those related to irrigation) are not outlined (Adra 1982: 52, 55; Dresch 1984: 36; Stevenson 1985: 94). I had a brief opportunity to visit a village in Khawlan, western Yemen (Hajarat Shokan) and speak with an ʿaqīl who described his role in overseeing water allocation for terrace agriculture. His associate, who held the position of amīn, reportedly used a short stick to measure out field areas in the aforementioned libna units (~ 64 sq. meters, Dresch 1989: 313) for determining allocation of water. Interestingly, this practice is very similar to that in the Hadramawt where a unit known as a maṭira (~16 to 24 sq. meters) is used to measure field areas by individuals holding the similarly hereditary position of maṭāʿ ir35 (cf. Bujra 1971: 56; Serjeant 1964: 42). Although khiyyl managers are not found in al-Qatn, Hadramawt where crops are watered from wells (Rodionov 1999: 121), or in towns of the Wadi Sana watershed, khiyyl and other management positions provide useful insights for understanding ancient management options and offer promising opportunities for continued ethnoarchaeological research (see Section 10.5 and Chapter 11).

9.3 Summary

Ancient irrigation in Southwest Arabia, in conjunction with environmental parameters, was subject to a variety of sociocultural and political contingencies. Although contemporary social relations certainly cannot be considered synonymous with those of the prehistoric past, operational requirements of different irrigation techniques are challenging to conceptualize based on archaeological records alone.

Ethnoarchaeology provides means of identifying socio-logistical aspects of irrigation work and management and their social ramifications. Throughout ancient and recent histories of Southwest Arabia nomadic herders are (and were) in continual search for water and forager for their herds. As illustrated by the importance of water in Islam, ideologically-imbued conceptions of land and water-rights are of critical social importance in establishing and legitimizing claims to irrigable areas. While design, operation, and maintenance tasks for small (less than 10 hectare) runoff systems can be accomplished at the domestic group level, as the size of areas irrigated and the number of people involved increases (such as among larger sayl systems of Wadi Daw’an), irrigators encounter new managerial challenges. In the Hadramawt, both khiyyl irrigation managers and the water user committees they led helped ensure sayl irrigation practices conformed to local norms of equity, but elected khiyyl managers’ authority was held in check and subject to consent. Particularly among intermediate and large-scale systems, control of land and water contribute to sociopolitical differentiation as illustrated, for instance, by the complex range historic social identity groups in the Hadramawt and their corresponding rights and responsibilities as landholders, dispute arbitrators, sharecroppers, and laborers. While social contingencies and ramifications of irrigation are diverse, ethnoarchaeological understandings of traditional Southwest Arabia practices are of considerable utility for interpreting social parameters of emerging ancient systems.
CHAPTER 10

FIELDWORK AND ANALYTICAL RESULTS: EVALUATING THE RELATIVE IMPACTS OF ENVIRONMENT AND SOCIAL CONTINGENCIES

While previous studies of contemporary irrigation in Southwest Arabia provide an informative baseline for considering ancient practices, archaeological survey, geomatics, and ethnoarchaeological investigations in Wadi Sana provide new evidence that clarifies how the lives and choices of Yemen’s earliest irrigators were tied to both environmental and social circumstances. One-hundred-seventy-four ancient irrigation structures were documented during archaeological survey, showing irrigation played a substantial role even in locales that today are too arid for cultivation. Although ancient techniques differed somewhat through time in concert with changing climate, the collective sample exhibits a generally consistent pattern of small-scale runoff (shrūj) irrigation. Statistical analyses demonstrate how the distribution of these structures is associated with hydrological variables, most predominantly landform type and water flow accumulation, and therefore, that structure locations were strategically chosen based on ancient knowledge of environmental conditions. Preliminary ethnoarchaeological investigations (conducted predominantly in the Wadi Sana watershed) help illustrate how modern populations in towns and rural areas utilize water resources. Surface runoff irrigation is no longer as common as it was in the prehistoric past. But contemporary Hadrami land-use, water-use, and irrigation techniques nevertheless provide a variety of insights on socio-logistics useful for reconstructing the origins of irrigation.

10.1 Archaeological Survey

The sample generated for this dissertation consists of 174 irrigation structures along the main channel and tributaries of Wadi Sana discovered during surveys in 1998, 2000, and 2004 (Table 10.1; Figure 10.1). Survey encountered a number of small natural
springs seeping from the limestone bedrock along Wadi Sana, but no ancient wells, cisterns, or other water collection features were identified. Although such structures may have existed and could have been destroyed, natural springs appear to have provided the primary ancient and historic source of water for domestic consumption and animals (see Section 10.5). Structures known to be modern because they exhibited evidence of mechanical construction (e.g., bulldozer scars) or were reported to have been in recent use were excluded from the archaeological sample. With a small number of exceptions, all archaeological water management remains encountered are irrigation structures of a type referred to by local Hamum badu as \( \text{shrūj} \).\textsuperscript{36} 

\( \text{shrūj} \) systems in the area consists of two basic types of structures, 1) diversion channels that direct runoff from rocky hillslopes, and 2) check dams that slow runoff (often from the aforementioned diversion channels), distributing moisture and nutrients on arable sediments (Figures 10.2 and 10.3). As described below, some test excavation of irrigation structures and sampling for Optically Stimulated Luminescence (OSL) dating of was conducted in 1998. Beyond surface recording, no structures were excavated or sampled during RASA fieldwork in 2000. In 2004, survey targeting irrigation was conducted specifically for this study (see also Section 4.1). Test excavations were dug in five locales (009, 013, W1, W5, and W19, see Figure 10.1), and 42 samples for Optically Stimulated Luminescence (OSL) and radiocarbon dating were collected from or near nine structures. OSL dating results are not yet complete, but radiocarbon assays run for 8 samples clarify dating results from 1998 and facilitate a basic chronological reconstruction of irrigation’s appearance and development from about 5000 years ago (Table 8.2).

Particularly in middle Wadi Sana, limited natural and human-induced landscape impacts contribute to exceptional preservation so that remains including hearths, habitation, and irrigation structures dating before 5000 years ago are preserved on wadi silt surfaces. With areas of good preservation and high visibility, how to spend limited recording time in the most effective ways possible is one of the greatest challenges of survey. Structures identified during RASA Project fieldwork in 1998, 2000, and 2004 were given a designation consisting of the year, survey unit number, and site number (e.g., 2000-009-1). In descriptions below the year is omitted (e.g., 009-1). In 2004, each locale where irrigation structures were identified during targeted survey for irrigation was designated a “WATER” survey unit (23 in total with one later excluded because it was

\textsuperscript{36}Although the term \( \text{shrūj} \) has a variety of local meanings, it is used in the Hadramawt to describe a variety of small-scale irrigation techniques and is adopted as the most appropriate term for the type of surface runoff irrigation found in ancient Wadi Sana (see Section 10.5).
found to be modern). This different notation was used to signify slightly different recording methods applied in the two cases. That is, WATER survey unit areas were not delineated by GPS and systematically surveyed at 10-meter spacing (see Section 4.1). However, in both cases a water management form was completed for each structure or clustered group of structures (Appendix A) and each structure was delineated as a line vector using a Trimble GPS backpack. Under optimal conditions this receiver configuration can provide sub-meter accuracy. In practice our absolute accuracies were considerably less (approximately 3 meters) but are more than sufficient for GIS analyses and still provide relative accuracies (among adjacent features) of less than one meter. Diagnostic artifacts were seldom found in association with irrigation features in ways that could facilitate dating, but associations with landforms, and circular tower tombs and triliths found in the vicinity of some irrigation structures help interpret their ages.

10.1.1 Test Excavated and Sampled Structures: The earliest conclusively dated irrigation structure, a 74-meter long rock-bordered canal designated 009-1 is the single most important structure for understanding the origins of irrigation in Wadi Sana. This small canal, located along the Wadi Shumly a main channel 1.4 kilometers east of the Khuzmum (see Figures 10.1 to 10.11), was first identified during RASA survey in 1998 and subsequently published in a short report (McCorriston and Oches 2001). Although it was originally interpreted as a check dam, subsequent investigations revealed that it is better interpreted as a water diversion channel or ‘rock-bordered canal’. Two lines of small boulders are visible on the surface for 41 meters, after which the stones enter a silt bank (natural section) cut by a small wash that dissected the structure (removing sediments but leaving the stones it dislodged stranded in a shallow gully). In 1998 the RASA team cleaned and examined the natural section, and excavated a 3 by 0.5 meter test unit approximately 5.5 meters northwest of the section that confirmed it continued as a buried feature. The team retrieved a sample for Optically Stimulated Luminescence (OSL) dating from the section approximately a half meter below the structure. This OSL assay yielded an age of 7,300 +/- 1,500 years ago. Given the age of sediments determined by radiocarbon assays on hearths embedded in sediments nearby (see below)

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37While differential correction provided by Omnistar Inc. uses Virtual Base Station (VBS) technology that aims to interpolate between base stations, sub-optimal accuracy is likely due to the fact that the two nearest Omnistar base stations are located in Abu Dhabi and Bahrain, approximately 1100 kilometers away from our study region.

38Dated by Ashok Singhvi at the Sheffield Centre for International Drylands Research, Lab Code 98222-2
it was suspected that the actual age probably fell at the younger end of the error range.

In 2004 more rigorous attempts were made to better establish the age and original extent of 009-1. The test trench excavated in 1998 was expanded to 1 by 3 meters and two test trenches were excavated down the length of the structure to determine if it continued further than had been identified in 1998 (Figures 10.9, 10.10, and 10.11). These efforts revealed the full preserved length of the structure (74 meters). The structure runs at a bearing of approximately 332 degrees. From the southeast, remains of the structure are visible on the surface for 41 meters and then enter the aforementioned naturally-cut section and continue under the present surface for 33 meters where the canal terminates at an approximately 5 meter drop carved by the deeply cut modern Wadi Shumlya main channel. Although the stones are scattered somewhat in the gully area, two distinct lines of stones embedded or buried in silt are evident in 6 locations (Figure 10.5). Two radiocarbon samples from sediments immediately above stones of the structure 26 meters apart (one from test trench 1 and one from test trench 3) yielded ages of 5,163 cal. and 5,144 cal yr BP respectively39.

Numerous lines of evidence indicate 009-1 was a rock-bordered canal constructed prior to 5000 cal yr BP. Examinations of the naturally cut section show that prior to construction the area was part of an active fluvial channel (the Wadi Shumlya main channel or a meander) where successive layers of silt and gravel were laid during periods of alternating flow intensity. The structure was constructed of two earthen banks approximately one meter apart, each supported on the outside edge by a line of small boulders40. Sometime near 5,144 BP the 009-1 structure was destroyed by floodwaters and the earthen banks were washed away. The cobbles shifted slightly and were buried approximately 0.50 m deep by undifferentiated silt. The two dated wood charcoal fragments probably originated from burning of vegetation in the area just upstream from the structure. Burned surfaces are common in silts along Wadi Sana and many contain similar charcoal fragments. Although there is a possibility these fragments may have come from trees or vegetation which died prior to construction of the structure and were subsequently washed in during burial of the structure long after 5,144 BP (i.e., that the

39 4,475 +/- 36 and 4,471 +/- 42 14C yrs BP, AA59569 and AA60245 (see Table 8.2).
40 One other structure with the same construction as 009-1 was discovered in Wadi Sana (2004-117-1) but no opportunities were available to date it. An analogous water diversion channel (in current use) was observed by the author during fieldwork in Eastern Tigray, Ethiopia. The structure was composed of an earthen bank backed with small boulders that diverted water from an intermittently flowing spring. A picture of apparently similar “rock-bordered canal” in the Safford Valley, Arizona was published by Neely (2001a: Figure 4).
structure is actually much younger than the dates), RASA Project reconstructions make this possibility highly unlikely. Of the 39 radiocarbon samples buried in silt and dated by RASA since 1998 all but two yielded ages older than those obtained on charcoal above 009-1 (see Table 8.1 and 8.2). RASA geomorphological reconstructions show that middle Wadi Sana silt deposition took place during the terminal Pleistocene-early Holocene and ceased near 5000 cal yr BP when more arid conditions resulted in a shift to an erosive rather than accumulative hydrological regime (see Section 8.3). RASA has not found silts beds in the middle Wadi Sana deposited after 5,144 BP, providing good reason to conclude that the dates obtained for 009-1 provide an accurate terminus ante quem for the structure. That is, it was constructed, destroyed and buried before 5000 BP. Indeed, two dates collected in 1998 from natural silt sections along the path cut by Wadi Shumlya just north of 009-1, yielded ages of 6,693 and 6,702 cal yr BP. The former comes from a bell-shaped pit 24 meters away and 3.54 meters below 009-1. Given the position or 009-1 relative to the pit, this equals an average of 2.3 millimeters per year of sediment accumulation over 1549 years, an estimate generally consistent with measurements on spate irrigated fields (cf. Section 7.4). Although the precise location of the latter date from a nearby hearth could not be determined relative to 009-1 in 2004 or 2005 because of subsequent erosion since 1998 along the 5 meter drop cut by Wadi Shumlya, it also supports the accuracy of assays taken above 009-1.

To further substantiate the interpretation that 009-1 was indeed a canal-like water diversion channel, elevations along the length of 009-1 were measured in 2005 (using a Wild theodolite). The wide areal pattern of silt deposition indicates that Wadi Shumlya previously meandered throughout a span of up to 400 meters between limestone bluffs (Figure 10.4). In contrast with the location of the modern Wadi Shumlya main channel north of 009-1 (Figure 10.5), local patterns of silt deposition and the orientation of 009-1 suggest that the Wadi Shumlya main channel was previously south of 009-1, and that water traveled along 009-1 from southeast to northwest. To evaluate this interpretation, elevation readings were taken in all six locations where embedded or buried boulders were found along the 74 meter length of the structure. Too steep a downward slope would have eroded the channel’s earthen banks; too steep an upward slope would prevent water flow along the structure. Elevations show a consistent decrease from southeast to northwest. In total elevation drops 0.53 meters in 74 meters giving a slope of 0.7%. This is grade is consistent with gradients for small earthen canals that generally vary between

415,870 +/- 45 14C yr BP (H2, Wadi Section 1, 24m away from 009-1) & 5,880 +/- 55 14C yr BP (Wadi Section 2, ~10m away from 009-1), McCorriston et al. 2000: 68.
1 and 3% (Charles 1988: 34). Collectively, findings strongly support the conclusion that 009-1 was a rock bordered canal constructed before 5,000 BP, making it one of the oldest dated irrigation features in Southwest Arabia.

Although silt beds east of the Khuzmum, of where 009-1 is located, are incised with small washes and are cut by a modern road, two other nearby irrigation structures were discovered and test excavated. The first was discovered in 1998 in an area known as the Gravel Bar Site (000-1) 195 meters south of 009-1 (Figure 10.4). The surface of the site is covered by a dense scatter of Arabian Bifacial Tradition (ABT) lithics published in a short report (D. Walter et al. 2000). Three test trenches were excavated in 1998 to determine if sub-surface lithics were present and investigate a series of limestone slabs protruding from the surface. Although lithics did not extend any significant depth below surface, their very high density and the fact that they did not exhibit evidence of water-transport damage suggest that they remain in situ. The limestone slabs, the remains of an ancient check dam, were discussed in the aforementioned report by McCorriston and Oches (2001). Since 1998 no further work has been conducted at this location. As discussed by McCorriston and Oches (2001: 675), these slabs have no in situ natural source. They too large to have been water-transported and therefore must have been carried 50 meters from a nearby bedrock outcrop by ancient irrigators who aligned them on end like dominos as a check dam (Figure 10.12). Both an OSL date of 10,400 +/- 4,500 years ago42 from below the slabs and the ~8000-5000 year old ABT lithics capping the structure suggest it was constructed at least 4 or 5 thousand years ago, near in time to 009-1. Although the precise water flow patterns when the structure was constructed are difficult to determine because of subsequent erosion and road construction, the structure lies below a small catchment draining an approximately 0.27 square kilometers area, which likely would have supplied the waters slowed by the dam.

The second test excavated structure near 009-1, is a water diversion channel (013-1) with a preserved length of 14 meters first discovered in 1998 (Figure 10.13). It is located on a raised area of stranded wadi silts along the main channel of Wadi Shumlya approximately 340 meters downstream from 009-1 (see Figure 10.4). The structure is only preserved at the highest point of a small (approximately 20 square meter) raised area of silt. Although 013-1 likely extended further than 14 meters, most of it was destroyed as sediments surrounding this raised area eroded. In 2004, a 1 meter by 0.5 meter trench was excavated to determine the depth of the structure, and search for datable materials.

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42 Dated by Ashok Singhvi at the Sheffield Centre for International Drylands Research, Lab Code 98SB1-0.60
The structure was shallowly buried, extending only 10 centimeters below the surface. Below it a loose sandy deposit containing shells (*Melanoides tuberculata*?) suggest that the area was part of a moist, fluvially active or slack water area. No wood charcoal was obtained for dating and given problems inherent in dating shell these samples have not been analyzed. Shell samples do provide opportunity for dating if shell carbon uptake could be addressed.

The next test excavated structure, W1-1, is located within an area designated WATER 1 that was first identified in 1998, then further recorded and excavated in 2004. This area is located near the mouth of a small tributary of Wadi Sana approximately 3 kilometers upstream from the Khuzmum (see Figure 10.1). Seven structures are located in the immediate vicinity. All are located in a gully/depression eroded from surrounding silt beds approximately 50 meters across (Figure 10.14). The largest structure, W1-1, is a curvilinear dam (Figure 10.15). Two test units 50 by 50 centimeters across were excavated to determine how deep below surface the structure extended. Although the structure appears very large, excavations revealed that this is an illusion caused by erosion. The structure was originally a curved wall approximately 50 centimeters high. As sediments around it eroded the small boulders and cobbles of which it was constructed slid downslope to cover and protect sediments trapped under what had been a free-standing wall. Today it appears much larger than it was originally. Two samples were collected just below the basal stones of the structure for OSL dating, but laboratory analyses are not yet complete. Fourteen hearths on a silt knoll 16 to 39 meters south of the structure offered promising sampling opportunities (Figure 10.16). It was hypothesized that since they are upstream and at approximately at the same height as the original base of the structure these hearths must post-date its use since they would have been washed away if placed there during times of fluvial activity in the gully. Two hearths were sampled, the single sample submitted for dating yielded an age of 7,071 cal yr BP. Although we originally hypothesized that this would be a *terminus ante quem* for the structure, an age this early for the dam is difficult to accept. The assay on the hearth is most probably accurate. There has been very little silt accumulation during the past 5000 years in the middle Wadi Sana (see Section 8.3) and charcoal samples from shallowly buried hearths and burned surfaces have yielded similarly early dates. But

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43 6,168 +/- 51 14C yr BP, see Table 8.2
44 For example, a date 0.25 m below a natural silt surface yielded an age of 5,485 +/- 14C yr BP (AA38380, McCorriston et al. 2002: 68), and another 0.40 m below surface yielded an age of 5,637 +/- 14C yr BP (AA60251, see Table 8.1).
the dam is likely not this old. Precise elevation measurements were made in 2005 with a Wild theodolite. The dated hearth lies 0.5 centimeters above the level of the basal stones of the dam in one test unit, and 19.5 centimeters below the basal stones of the other test unit, so it is indeed at approximately the same height. Although it is difficult to explain how the hearths could be upstream and at approximately the same height as the check dam without being destroyed by water flow when the dam was used, these contextual relationships are tentative and it is equally difficult to accept an age this early for the dam (approximately 2000 years older than any other evidence for irrigation or agriculture in Southwest Arabia). Even after many hours of inspections in the area with RASA Project geologists water flow patterns in the area are very difficult to interpret with certainty because of complex local patterns of erosion. Possibly the hearths were very shallowly buried when the dam was in use, or we have misinterpreted ancient water flow in the area. Since we expect that OSL assays will not be precise enough to conclusively resolve this confusion, the question of W1-1’s age may remain unresolved.

Another group of structures designated WATER 5, approximately 2.7 kilometers upstream from the Khuzmum, consists of three check dams and a 75 meter long water diversion wall. The check dams are distributed for 200 meters down the length of a small tributary of Wadi Sana that drains a small 0.28 square kilometer catchment (Figure 10.17). They would have slowed sediment-laden waters in the gully and provided an approximately half hectare irrigated area. The wall, still in an excellent state of preservation, blocked waters from an adjacent hillslope to prevent erosion of silts along the margins of the gully. Based on its preservation, and the general lack of desert varnish on its stones, the wall was thought to have been no more than approximately 1000 years old, but we speculated that some of the other check dams may have been older. The final check dam (W5-1, constructed of mounded sediment backed by a wall of small boulders, see Figure 10.18) was breached on its northern end allowing examination of it in section. Once cut back by shovel and trowel, this section revealed four major strata, including the sediments used to construct the dam, and a layer of charred plant detritus that washed over the dam (Figure 10.19). One radiocarbon and two OSL samples were collected from the section. The radiocarbon sample from the charred layer yielded an age of 382 cal yr BP\textsuperscript{45}, indicating that the layer of charred plant detritus that washed over the dam was deposited relatively recently. An additional radiocarbon sample retrieved from a hearth embedded in silts before down cutting of the WATER 5 gully yielded a \textit{terminus post}

\textsuperscript{45} 293 +/- 39 \textsuperscript{14}C yr BP, see Table 8.2
quem age for the gully of 7,159 cal yr BP (see Table 8.2) that does little to clarify the age of WATER 5. Although the former date does not necessarily prove that the final check dam (W5-1) was constructed or used as recently as 382 BP, it is possible that this structure was built near in time to the 75 meter long wall and that at least some efforts to irrigate in Wadi Sana continued well into the Islamic era.

Another group of structures designated WATER 19 is located 8.8 kilometers upstream from the Khuzmum just south of RASA’s fieldcamp in 2000, 2004, and 2005. WATER 19 consists of a water diversion channel and a check dam at the mouth of a small tributary that drains an area of 0.18 square kilometers. Four water diversion channels that directed water toward five additional check dams were found 230 meters north. Like W5-1, the check dam in the main tributary was constructed of earth with a stone wall backing and was breached near the middle (Figure 10.20). Two samples were collected for OSL dating from the section created by the breach, but results are not yet available.

Radiocarbon samples from three other areas WATER 6, WATER 13, and WATER 23 provide terminus post quem dates of 6,747, 6,584 and 6,418 cal yr BP (see Table 8.2) further confirming that irrigation originated after the 7th millennium.

10.1.2 The Collective Sample: While a review of all 174 irrigation structures (see Table 10.1) would be needlessly time consuming, some general observations about the collective sample are useful and indeed necessary to address the geomatics analyses that follow. Collectively the sample of 174 irrigation structures exhibits a consistent pattern of small-scale surface runoff diversion along side drainages with relatively low-energy water flow. Only two structures, 009-1, and 013-1 were found along the primary channel of major wadis. These structures are likely among the earliest of the sample and were operable under conditions of greater precipitation when more vegetation contributed to conditions of longer-duration, lower-energy discharge along primary wadi channels.

While the precise ages of most structures in the sample of 174 are of some uncertainty (indeed irrigation structures are extremely challenging to date), some general characteristics provide clues about their ages. The following interpretations utilize observations about the context, construction, and remains associated with irrigation structures (similar to methods advocated by Doolittle et al. 1993) to help interpret their ages.

There are good reasons to suspect that many structures in the sample of 174 are younger than 009-1 and 000-1, the only two structures conclusively dated before 5000
BP, but most are likely not younger than the 3rd millennium BP. Since RASA geomorphological reconstructions show that middle Wadi Sana silt aggradation largely ceased after 5000 BP, surveys aimed to find structures buried in silt that would therefore provide a tentative *terminus ante quem* and might offer opportunities for sampling. Although some structures may be so deeply covered that they would require subsurface detection methods to identify them, no structures other than 009-1 and 000-1 were found buried (or partially buried) in more than a few centimeters of silt. In a number of locales (W6, 7, 8, 9, 10, 19) diversion channels were used to direct water from plateaus into gullies between wadi silt beds and bedrock slopes along the margins of Wadi Sana (Figures 10.21, 10.22, and 10.23). These gullies provide convenient capture points, but would have only started to form after middle Wadi Sana silt bed degradation had begun. Check dams in these gullies frequently abut silt beds, but they are not deeply buried in them. One structure (134-5) was constructed using the stones of a trilith stone emplacement, and if one accepts a date for the pre-existing trilith near the cusp of the Common Era this provides an approximate *terminus post quem*. The well-preserved state of some structures, including the 75 meter wall found at WATER 5, suggest that attempts to manage water flow may have continued into the Islamic era. However, there is only sparse evidence for human activity in Wadi Sana from the 3rd millennium BP onwards. In three field seasons of survey and one year of excavation RASA has found graffiti and triliths, but less than fifty ceramic sherds, no hearths, encampments, nor domestic structures that can be convincingly placed after the 3rd millennium (McCorriston et al. 2002: 81-83). If the most intense period of human activity in Wadi Sana from the 7th through 4th millennium BP (that includes small circular houses) is applied as a guide (McCorriston et al. 2002), most *shrūj* diversion channels and check dams likely fall near the end of this interval during the 5th and 4th millennia BP. Indeed, many *shrūj* structures (e.g., 078, 134, WATER 1, 6, 7, 8, 9, 14, 15, 19) are found near circular tower tombs (Figure 10.24) dated elsewhere in Southwest Arabia to the late 6th and 5th millennia BP (Steimer-Herbert 2004; Steimer-Herbert et al. in press). Although proximity does not prove that irrigation structures and circular tower tombs are the same age, it suggests that they may be. RASA has initiated investigations that specifically concentrate on cairn tombs that will help clarify their relations with irrigation structures.

46Zarins (2001: 134) places triliths in his Iron Age IAB period (325 BC to 650 AD). al-Shahri (1991: 193) reports two dates from trilith hearth charcoal of 2,050 +/- 100 and 2,100 +/- 120 ^14^C yr BP (2,027 and 2,085 cal yr BP), and de Cardi et al. (1977: 28) reports a date of 1,899 ^14^C yr BP (1,840 cal yr BP) from Sharqiyah, Oman.
Although the age of most irrigation structures is not known for certain, since they arguably fall predominantly during the 5th and 4th millennia, cannot be accurately placed into more definitive age categories, and collectively exhibit an analogous pattern of shrūj surface runoff irrigation, they are analyzed as a combined sample that testifies to ancient irrigation practices in Wadi Sana.

10.2 Satellite Remote Sensing and GIS Hydrological Modeling

Satellite remote sensing analyses conducted for this research model terrain and landforms to help evaluate associations between the distribution of irrigation structures and landscape characteristics. Four types of satellite imagery, MODIS, LANDSAT, Quickbird, and ASTER provide modifiable, multi-scalar perspectives at scales from 250-meter to 60-centimeter resolution (Table 4.1). Each type was used for visualization and image map production, while the fourth was also used for two quantitative procedures, Digital Elevation Model (DEM) generation and landform classification. A DEM consists of grid cells with associated elevation values, while a landform classification image consists of grid cells with associated landform category values. The ASTER DEM and landform classification image serve as the principal inputs for GIS-based hydrological modeling and spatial modeling of irrigation structure locations.

10.2.1 DEM Generation: A 15-meter resolution DEM for a 60 by 120 kilometer area covering the entire Wadi Sana watershed was produced from two ASTER satellite images (Figure 10.25). This DEM not only provides a highly informative means of visualizing terrain in the study region but is also the basis for GIS modeling of flow direction, accumulation, and watershed boundaries. The process of investigating possible methods for DEM generation began in 2000. Methods considered for DEM production included topographic map digitization, use of NASA’s SRTM (Shuttle Radar Topography Mission) DEMs, and extraction from SPOT or RADARSAT imagery. The only topographic maps available were Soviet 1:100,000 scale, not of sufficient detail for analyses of small watersheds. SRTM data was not released in time to complete GIS analyses, and as of June 2005 only 90-meter resolution SRTM DEMs were available for regions outside the United States. Although extraction via SPOT or RADARSAT imagery was an option, less time-consuming, semi-automated methods are available for use with ASTER (see Hijazi n.d.; Selby n.d.)
Satellite imagery DEM extraction requires highly accurate spatial control to link and properly orient stereo images. Ground Control Points (GCPs) assign Cartesian coordinates for locations visually identifiable on images, while Tie Points (TPs) connect the ground location on one image to the same location on another. ASTER imagery consists of 15 bands from 15 to 90-meter resolution (Abrams et al. 2002). Two spectrally identical 15-meter resolution bands (3n and 3b) are slightly offset from one another (off-nadir) to facilitate DEM extraction (Hirano et al. 2003).

The ASTER DEM for used for this study was extracted using the Orthoengine module of PCI Geomatica 9.0 software. Two contiguous, cloud-free ASTER level L1B images taken on February 23, 2002 were acquired from NASA’s EOS Data Gateway\(^{47}\). Together they offer coverage of the entire Wadi Sana watershed and ensured that clouds did not hamper the extraction process. Preliminary analyses completed in 2002 and 2003 (using GCPs available from fieldwork in 2000) showed that ASTER DEM extraction is an effective technique for Wadi Sana. Although imagery-based DEM extraction can yield poor results in flat terrain, Wadi Sana’s rugged topography make it particularly good candidate for producing imagery-derived DEMs. Although preliminary analyses yielded promising results, they were only successful for small areas where sufficient GCPs were available. More GCPs covering the full extent of both ASTER images were collected during fieldwork in 2004. With these GCPs, the extraction and editing process took approximately two full months of daily laboratory work to complete. Sixty-four Ground Control Points and forty-three Tie Points linked four separate image bands (bands 3n and 3b from both ASTER scenes). All GCPs were collected using the same Trimble GPS backpack used for archaeological survey. Tie points were selected by visual inspection of the imagery and automated collection using PCI Orthoengine. These GCPs and TPs were carefully adjusted so the images were geometrically aligned with accuracies of just over two pixels (30 meters)\(^{48}\). Two epipolar stereo pairs (images reprojected to a common orientation so they are aligned on a common x-axis) were produced from the four image bands. The DEM was then extracted and geocoded to Universal Transverse Mercator (UTM) projection Zone 39P (ellipsoid WGS 84) at a 15m pixel sampling interval using a minimum (cutoff) elevation of 300 meters and a maximum elevation of 2100 meters.

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\(^{47}\) EOS Data Gateway: http://edcimswww.cr.usgs.gov/pub.imswelcome

\(^{48}\) Ground Control Point x-axis Root Mean Square (RMS) error of 32.24 meters and y-axis Root Mean Square (RMS) error of 35.53 meters. Tie Point x-axis RMS error 4.82 meters and y-axis RMS error 4.46 meters.
Once the DEM was extracted it was edited and filtered with PCI Focus to remove inaccuracies and holes composed of failed values. A repeated series of noise removal, Gaussian and mean filters were applied to smooth out areas with anomalous values. Areas of clearly erroneous values (based on visual inspection) were outlined and interpolated based on the values of surrounding pixels. The edited DEM was exported to ArcInfo ASCII Grid format using PCI Orthoengine, and imported to ESRI ArcMap 8.2 using the ArcToolbox Import to Raster – ASCII to Grid function. The geometric model created for DEM extraction was also used to orthorectify two images composed of ASTER VNIR (very near infrared) bands 1-3, and ASTER SWIR (shortwave infrared) bands 4-9, respectively. These images would later be used as GIS basemaps, and for landform classification.

10.2.2 Landform Classification: Multispectral landform classification for the RASA Project began prior to fieldwork in 2000. A scheme consisting of 7 landform types based on sediment and clast types, slope, and vegetation cover was devised in consultation with RASA geologists. Unsupervised classification methods applied using LANDSAT 5 imagery produced classified image maps focused on the Wadi Sana drainage north of Ghayl Bin Yumain (Harrower et al. 2002). For this dissertation the area of analysis expanded to encompass the entire Wadi Sana watershed, and efforts were made to improve classification accuracy (particularly since it would form a critical input for GIS spatial modeling). An eighth landform type—Playa/Sabkha—was added to encompass areas of the Rus formation in the western portion of the Ghayl Bin Yumain basin (Table 10.2). Since the first three ASTER bands are higher resolution than LANDSAT, and ASTER includes a greater range of electromagnetic spectra (see Table 4.1), ASTER replaced LANDSAT for use in classification.

Landform classification involved a sequence of procedures applied to a 10-band image comprised of ASTER bands 1 through 9, and DEM-derived slope (Figure 10.26). Using the supervised classification functionality of ERDAS Imagine 8.6 software, 52 polygons (delineated as survey units during RASA Project fieldwork in 2000 and 2004) served as training samples to define spectral signatures for each of the eight landform types. An extensive sequence of trial and error using alternative decision rules showed that a combination of the non-parametric, parallelepiped and the parametric, maximum likelihood rules produced the most accurate results (see ERDAS 1997: 243-253). The fuzzy convolution function adjusted each pixel value according to surrounding values in a 7x7 pixel window reducing the speckled appearance typical of multispectral
classifications. Accuracy assessment results show modest improvements over classifications produced in 2000 (Tables 10.3 and 10.4). Inherent limitations in the ability of LANDSAT and ASTER to distinguish landform classes in the area appear to be a primary accuracy limiting factor.

10.2.3 GIS Hydrological Modeling: Hydrological modeling applied the ArcHydro module for ArcGIS (Maidment 2002). Water flow is commonly modeled in GIS by defining for each DEM grid cell the immediately adjacent cell with the lowest elevation value. Since each DEM grid cell has 8 immediately adjacent neighbors this method is referred to as the 8-direction pour point model (Olivera *et al.* 2002: 68-72). DEMs commonly contain inaccuracies and anomalous depressions known as ‘sinks’, so modifications to correct DEM values are generally necessary before flow patterns can be determined. First, a vector (line) layer depicting stream or channel networks (commonly obtained from pre-existing topographic maps) is used as input for a function that reduces DEM values along channel paths and produces an Agree DEM. Then a fill sinks function is run to fill-in anomalous depressions. Once these steps are completed, flow direction can be defined using the 8-direction pour point model, and a flow accumulation grid is produced by adding together the number of cells that flow into any given cell. This flow accumulation grid is then used to define stream networks, and locations where streams intersect can be used to define flow catchments (Figure 10.27).

Although ArcHydro provides a general framework for terrain processing, no large-scale map of channel networks was available for Wadi Sana, so a slightly more extensive sequence of procedures was necessary (Table 10.5). First the fill sinks function was run on the raw DEM. Then flow direction and flow accumulation grids were calculated. Flow accumulation was used to produce a stream definition layer that produced a line wherever water from more than 5000 cells accumulated. This stream definition layer was then edited (smoothed and corrected) for the entire Wadi Sana watershed via comparison with ASTER imagery. Although no map of stream networks was initially available, this sequence of procedures produced one. After editing and correction, this stream definition layer was then used to begin the sequence of terrain processing procedures again, this time starting by ‘burning’ an Agree DEM from the original, raw DEM. Since resultant hydrological data layers would be used for statistical modeling, the improved accuracy offered by this process was advantageous. Stream

49 For further information on the ArcHydro version of this function see: http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html

135
networks and catchments were produced using a variety of stream definition thresholds, including 500, 1000, and 5000 cells. Particularly when absolute measurements of flow are available, ArcHydro (and other software such as HEC-RAS\textsuperscript{50}) include functionality for processing watersheds, stream networks, channel cross-sections and their attributes. Since no flow data was available and spatial modeling proved time-consuming, none of these functions were employed.

10.3 Spatial Modeling I: Data Generation Methods and Initial Results

A spatial modeling approach based on archaeological predictive modeling provides means of evaluating associations between irrigation structure locations and environmental variables to help explain why Wadi Sana’s ancient irrigators selected some areas for irrigation but not others. This involved two steps: GIS data generation, followed by univariate testing and multivariate modeling. Methods are based on those of archaeological predictive modeling with some important differences. Rather than producing models that aim to predict the location of undiscovered irrigation structure locations (sites), analyses emphasize identification and quantification of variables that best account for locations of irrigation structures already discovered by survey. The logistic regression approach applied is predictive in the sense that it uses input (independent) variables to produce logit functions that distinguish (or ‘predict’) presence or absence of irrigation; but this is not archaeological predictive modeling (in a strict or usual sense of the term) because it does not aim to predict locations of undiscovered sites. Although logistic regression results could be used to find new irrigation structures, the focus of this study lies in reconstructing ancient human behavior rather than mitigating damage to archaeological resources. Moreover, a predictive model focused solely on irrigation structure locations would not serve as an appropriate Cultural Resource Management (CRM) tool because it would not account for, or predict, the location of other types of sites. Predictive models have produced highly informative results, but complexities encountered in producing models often consume researchers’ attention. Predictive models frequently establish associations between sites and environmental variables, but they often do not explain or explore causation. Discussions of results often neglect to adequately address, 1) why variables used in particular models are associated with site locations, and 2) if and how they were responsible for ancient human choices. For instance, in a recent publication on predictive modeling for CRM in Pennsylvania

\textsuperscript{50} For information of HEC-RAS see http://www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html
and West Virginia, Duncan and Beckman (2000) describe results of predictive modeling where they examined 70 independent variables and selected 26 of them (e.g., elevation, slope, distance to water source) to produce predictive models, but they do not discuss in detail why ancient peoples selected areas at particular elevations or with particular slopes. While this may be appropriate in a Cultural Resource Management context, environmental variables are granted a priori significance and archaeologists are hardly any closer to understanding why ancient peoples of Pennsylvania and West Virginia preferentially utilized some areas over others. Accordingly, this study not only aims to produce results that distinguish irrigation-present from irrigation-absent locations, but additionally aims to more explicitly understand what it was that led ancient irrigators to choose some areas for irrigation but not others. Although the spatial modeling approach used is based on predictive modeling methods, the general term ‘spatial modeling’ is used to emphasize understanding of factors responsible for prehistoric irrigation structure location choices rather than exclusively prediction of irrigation presence/absence.

The following spatial modeling compares data for two types of samples, the sample of 174 irrigation structures mapped during archaeological survey, versus two separate irrigation-absent samples. Kolmogorov-Smirnov (K-S) and logistic regression statistics compared irrigation-present versus irrigation-absent samples for three variables, slope, water flow accumulation, and landform. Each of these variables exhibited statistically significant associations with the irrigation structure locations (see below). Although other variables including elevation, watershed size, distance to channel networks, and runoff/run-on ratio\(^{51}\) were considered, for reasons discussed below the accuracy (and/or appropriateness) of data for these variables was found to be highly problematic so they were excluded from quantitative analyses. Flow accumulation and slope data were generated from the aforementioned ASTER DEM, while landform data was generated from the ASTER image classification.

Selection of variables for univariate testing and multivariate modeling involved careful considerations of relevance, and how data could and should be produced. First, hydrological data and the landform classification image were visually compared with the distribution of irrigation structures. Although most irrigation structures are located along middle Wadi Sana, surprisingly, they do not necessarily appear to lie in areas of highest flow accumulation (see Figure 10.1). As recognized during fieldwork, irrigation structures do appear to be associated with landform types. Check dam structures are

\[^{51}\text{Runoff/run-on ratio is the size area irrigation structures capture water from versus the size area they distribute water to, also sometimes described as catchment to cultivated area (e.g., Shanan 2000: 86).}\]
frequently located on or near wadi silts along the bottom edge of slopes leading to plateaus, while water diversion channels are often found on top of plateaus. Since both flow accumulation and landform type appeared to be relevant but could not be adequately evaluated based on visual inspection alone, each of them was selected for quantitative analyses.

Although elevation, watershed size, distance to channel networks, and run-off/run-on ratio were considered as potential candidates for quantitative analyses, they each involved a variety of problems and were therefore excluded. Even if these variables exhibited statistical associations with the distribution of irrigation structures, these associations would not necessarily provide valid means to help understand why ancient peoples selected some areas for irrigation but not others. Elevation varies substantively throughout the Wadi Sana watershed. But since the Southern Jol drops in elevation from south to north, the lowest plateau in the middle Wadi Sana is at the same elevation as the highest plateau at the north end of Wadi Sana, so landscape conditions at a particular elevation in one area are not appropriately comparable with landscape conditions at the same elevation elsewhere.

Watershed size and distance to stream (channel) networks encounter Modifiable Areal Unit Problem (MAUP) issues. Both are based on the number of cells selected to define stream networks. That is, if the stream definition threshold is set to 500 (see Section 4.2), catchments will be produced for areas where two streams consisting of 500 or more accumulated cells intersect, and all catchments will be nearly the same size. If the stream definition threshold is increased or decreased, the pattern of networks and catchments will correspondingly change. Patterns produced are thus a function of arbitrary choices made by the user rather than externally meaningful criteria. Since flow accumulation (for this research) is the source data used to produce stream network and catchment maps (see Section 10.2.3), but is less subject to arbitrary threshold choices, it was used to evaluate associations with water flow instead.

Runoff/run-on ratio was also considered as a potential variable for quantitative analyses, but run-on (irrigated) areas could not be accurately defined for the vast majority of structures. Even if runoff/run-on ratios could be calculated for some areas of irrigation, this variable has no meaning for irrigation-absent areas and therefore could not be used to compare irrigation-present with irrigation-absent samples. Moreover, flow accumulation provides a better measure of runoff (catchment) areas above irrigation structures; flow accumulation is subject to the accuracy and resolution of the DEM used, but is less subject to users’ discretion (than would be the case if one manually delineated
catchment areas).

The following spatial models utilize slope, flow accumulation, and landform-type data generated from ArcMap GIS software to compare irrigation-present with irrigation-absent samples. Standard GIS functionality produced circular (for initial models 50-meter) buffers around the mid-point of each of the 174 structures in the Irrigation-Present sample. The Hawth’s Analysis Tools extension for ArcMap\textsuperscript{52} then generated data for each buffer area. Hawth’s \textit{Zonal Statistics} function produced (maximum, minimum, mean, and sum) values for slope and flow accumulation raster grid cells throughout each buffer area. Hawth’s \textit{Thematic Raster Summary} tool determined the buffer area proportion of each landform type. The first irrigation-absent sample (Sample 1) consists of 174 points randomly selected throughout the Wadi Sana watershed. The second irrigation-absent sample (Sample 2) consists of 174 random points throughout RASA Project survey units that contained no evidence of irrigation, and were more than 50m away from any survey unit that did contain evidence of irrigation\textsuperscript{53}. Slope, flow accumulation, and landform-type data were generated for both irrigation-absent samples using the same buffer and Hawth’s Analysis Tools methods employed for the irrigation-present sample.

Statistics run on SPSS (v.13) software compared data for the irrigation-present versus irrigation-absent samples to determine what was different about locations with irrigation versus locations without irrigation and thus help identify why ancient irrigators chose some locations but not others. The Kolmogorov-Smirnov (K-S) test was used for univariate testing of slope, flow accumulation, and seven landform types\textsuperscript{54}. The K-S test is based on the maximum absolute difference between cumulative distribution functions. When this difference is sufficiently large (depending on the 95% confidence interval used for this study) the null hypothesis (that irrigation structures are distributed at random with respect to the variable being tested) is rejected and the two samples are considered statistically distinct. The K-S test is a common method for evaluating the significance of variables independently before incorporating them in multivariate archaeological predictive models (e.g., Ebert 2004: 51; Kvamme 1985: 217-224). It is particularly

\textsuperscript{52} Hawth’s Analysis Tools for ArcMap is a free software add-on that supplements the capabilities of ArcMap software, for further information see http://www.spatialecology.com.

\textsuperscript{53} These two irrigation-absent samples produce results at different spatial scales. Reasons why they were used are further discussed in Section 10.4

\textsuperscript{54} Since the playa/sabkha landform type is only found in one very restricted part of the watershed where no ancient irrigation structures were found, all playa/sabkha grid cells were recoded as scree slope so playa/sabkha would not become a spurious predictor of irrigation structure absence.
appropriate for this purpose because it is non-parametric (i.e., it does not require that variables are normally distributed) and is responsive to dissimilarities in means, variances, skewness, or kurtosis (Kvamme 1985: 220).

Univariate K-S tests show that slope, flow accumulation, and landform type are each associated with the distribution of irrigation structures (see data code abbreviations in Table 10.6). For Irrigation-Absent Sample 1, FAC_MAX and SLP_AVG yield the highest K-S test z-values, and therefore best differentiate the irrigation-present from irrigation-absent sample (Table 10.7). For Irrigation-Absent Sample 2, FAC_SUM and SLP_MIN yield the highest K-S test z-values; but the two variables yielding the highest z-values during previous Sample 1 tests (FAC_MAX and SLP_AVG) are a close second (Table 10.8). For both samples, differences between proportions of wadi channel, wadi silts, plateau, bedrock terrace, and bedrock slope landform types are all statistically significant at the 95% confidence level. For all variables and variable formats wadi silts (WS) yield by far the highest z-score values and therefore best distinguish the irrigation-present from irrigation-absent samples (Tables 10.7 and 10.8).

Logistic regression predicts a binary dependent variable such as presence/absence based on multiple independent variables that can be discrete, continuous, or both. Like the K-S test it is commonly used for archaeological predictive modeling (Kvamme 1990a: 275; Wheatley and Gillings 2002: 171-176) Logistic regression is particularly useful for this purpose because independent variables do not have to be normally distributed, or linearly related to the dependent variable (Rice 1994). SPSS uses an iterative maximum likelihood method to generate predictions of a binary dependent variable, in this case presence/absence of irrigation within a buffer area radius.

Logistic regression modeling results for the Irrigation-Present versus Irrigation-Absent Samples 1 and 2 demonstrate a powerful ability to predict presence/absence of irrigation based on landform type (Tables 10.9 and 10.10). Although K-S tests indicated that many variables and variable formats (i.e. max, min, mean, and sum) were statistically significant, those with the highest K-S test z-score values were not necessarily the best predictors of irrigation presence/absence when using logistic regression. Manual stepwise procedures were therefore used to determine which variables and variable formats were the best logistic regression predictors of presence/absence. These procedures involved manually running logistic regression forward (each iteration adds variables) and backward (each iteration subtracts variables) until highest accuracies were achieved. For both irrigation-absent samples only variables that were statistically significant at 95% confidence level according to the Wald chi-square test were included.
as predictors in final models. For initial models, overall predictive accuracies of 86.2% and 76.7% respectively show a reduced predictive ability when using Irrigation-Absent Sample 2 (Table 10.9 vs. Table 10.10). At the watershed scale (Irrigation-Absent Sample 1), wadi channel, wadi silts, plateau, and bedrock terrace landform classes are statistically significant predictors of irrigation structure locations. At a reduced scale restricted to the Wadi Sana main channel (Irrigation-Absent Sample 2), only one of these—wadi silts—remains a statistically significant predictor, and two new variables (bedrock slope and minimum slope) appear as statistically significant predictors of irrigation structure locations. As discussed below, variation in results as scale is altered is a function of Modifiable Areal Unit Problem (MAUP) issues.

10.4 Spatial Modeling II: Sampling and Modifiable Areal Unit Problem (MAUP) Issues

To properly understand what K-S tests and logistic regression analyses reveal about the distribution of irrigation structures, sampling and Modifiable Areal Unit Problem (MAUP) issues must be addressed. Once basic methodologies were chosen and preliminary results completed, these issues could be more clearly identified. MAUP describes a type or category of capricious analytical results that occur because of discretionary (or arbitrary) data aggregation, categorization, and scale choices (see Section 4.2). The influences of MAUP on analytical and statistical outcomes have been described in most detail with reference to scale and data aggregation problems encountered when using modern census data (e.g., Openshaw 1983; Fotheringham and Wong 1991). The significance of MAUP for archaeological spatial analyses has been mentioned (Kvamme 1990a: 269; Lock and Harris 2000: xx-xxi; McCorriston and Harrower 2005) but never described in detail, nor considered as an encumbrance of particular spatial analyses.

For analyses of irrigation in Wadi Sana, MAUP (and related sampling and data generation) issues can be divided into four types: 1) sample universe, 2) data categorization, 3) site-type, and 4) buffering/data generation. Although attempts were made to eliminate or alleviate the influences of these issues whenever possible, in many cases they are difficult (or impossible) to avoid, and in some cases they offer important insights about ancient irrigation. The first two were addressed (but not explicitly discussed) by methods described in the previous section. In this section, the first two problems are more explicitly discussed and results of additional K-S testing and logistic regression modeling aimed to address the latter two problems are described. Two additional sets of K-S test and logistic regression analyses were completed. For both of
these additional sets the Irrigation-Present sample was split according to the two basic
types of structures (check dams and water diversion channels) and compared to
Irrigation-Absent Samples 1 and 2 using both 50m and 15m buffer areas (Tables 10.11 to
10.18).

10.4.1 Sample Universe Issues: Sample universe issues arise because of discretion
involved in choosing the size and shape of areas used for analyses. Although the Wadi
Sana watershed was the primary study area for this research, sampling was not random
throughout the entire watershed. The vast majority of archaeological remains are situated
along main path of Wadi Sana and major tributaries. The watershed is large (3,691 sq.
km); plateau areas are extremely rugged and difficult to access. Random sampling of the
entire watershed would have meant surveyors would spend most of their time searching
areas with very few sites. Instead, the RASA project conducted stratified random
sampling in strips along the main path of Wadi Sana, so that each strip included part of
the plateau on either side. Areas distant from main channel paths were visited but were
not randomly sampled. Although this was a more productive use of limited time and
resources it also created a significant problem—although research interests to some
extent focus on the watershed as a whole, stratified random sampling did not. Use of two
separate irrigation-absent samples helps address this issue. Irrigation-Absent Sample 1
compares irrigation structure distributions with the entire watershed, while Irrigation-
Absent Sample 2 helps determine whether the same factors are operable if the sample
universe is restricted to areas along the main path of Wadi Sana that were systematically
sampled. Data for Irrigation-Absent Sample 1 were generated from 174 locations
randomly selected throughout the watershed. Since these locations were not actually
visited, Sample 1 is not strictly an irrigation-absent sample but is referred to as such to
simplify descriptions of analytical procedures. The watershed-wide frequency of
irrigation structures is likely very low. The overall density of irrigation structures in
stratified random samples along Wadi Sana is 0.06 structures per hectare. At this density
(equivalent to one structure every 19.23 hectares) only 7 irrigation structures would be
located within the area encompassed by the random watershed-wide sample of 174
locations using 50 meter buffers, and only 1 structure using 15 meter buffers. Moreover,
results of judgmental survey indicate that the actual watershed-wide density of irrigation
structures is much lower. Even if some of these 174 locations do contain irrigation
structures, Irrigation-Absent Sample 1 is effectively a watershed-scale sample not strictly
of irrigation absence, but of watershed-wide conditions that are still appropriate and
informative to compare with areas where irrigation is present (cf. Kvaamme 1990b). Although one could randomly sample the entire watershed, areas distant from main channel are not road accessible; some would take days to reach on foot, and given the low densities involved, it is not clear this would be an appropriate expenditure of time and resources.

Sample universe issues are not only important to consider as a potential analytical encumbrance, but also prompt one to consider how results vary as sample universe boundaries expand or contract. When check dams and water diversion channels are grouped into a single irrigation-present sample, wadi silts was the only consistent (statistically significant) logistic regression predictor at both the Wadi Sana watershed and Wadi Sana main channel scales (Tables 10.9 and 10.10). When check dams and water diversion channels are separated, wadi silts and plateau landform types are the only consistent predictors of check dam locations at both the watershed and main channel scales (Tables 10.12 and 10.16). That is, check dams are located on or near wadi silts, and away from plateaus. Findings for water diversion channels are more ambiguous. At the watershed scale diversion channels are positively associated with the wadi channel landform type, while at the Wadi Sana main channel scale this association is reversed (Tables 10.14 and 10.18). Although these findings indicate that landform types are primary determinants of irrigation structure location choices, they also illustrate how statistical associations can change as the sample universe scale is modified. Spatial associations that change with scale are not necessarily fallacious. But associations that are stable at multiple scales (e.g., associations between check dams and wadi silts) offer more rigorous evidence and, for archaeology, provide for more conclusive arguments that spatial associations reflect underlying human choices.

10.4.2 Data Categorization Issues: GIS analyses are particularly subject to data categorization problems because discretionary choices are frequently required, and their influences are not always immediately apparent. When categorized, grid layers (such as those produced from a DEM) are subject to MAUP. Slope, for instance, can be arbitrarily classified into a few or many categories (see Section 4.2; McCorriston and Harrower 2005), and different types of GIS software offer a variety of different categorization methods. Stream networks defined on the basis of number of cells accumulated, and watersheds subsequently defined on the basis of defined streams are similarly subject to users’ discretion. These types of discretionary choices can have critical influences on analytical and statistic results (Dungan et al. 2002; Fotheringham
and Wong 1991; Openshaw 1983).

For analyses of irrigation in Wadi Sana, one method used to alleviate these problems was to use continuous (unclassified) variable formats whenever possible. Slope and flow accumulation data were not categorized; they were output as continuous data. Analysis with stream networks and flow catchments based on discretionary stream definition thresholds were avoided. Although analyses with GIS-derived stream networks and watersheds are possible, it would then be important to determine if and how results change as stream definition thresholds are modified, requiring a considerable number of additional analytical trials.

For inherently categorical data layers, such as landform type, use of continuous formats is impossible. Analytical results are not only subject to the accuracy of classifications, but are also a function of the categorization system used. Comparisons of satellite imagery-based classifications with indigenous views of landcover have shown that technical classifications based on ecological and/or geological criteria are only one mode of categorization (Jiang 2003; Robbins 2001, 2003). Nature produces continuous, infinitely variable landscapes: humans produce classifications. Landform types are spatially heterogeneous, grade from one to another, and are arguably as much a reflection of the interests of the categorizer as they are immutable characteristics of landscapes (Robbins 2001, 2003). Even when attempts are made to apply precise, scientifically derived classificatory criteria, subjective decisions are required at numerous stages of analysis. Landcover classifications are to some extent subjective, and are a particular instance of MAUP (Hay et al. 2003). Factors such as number of classes, size of sample universe, and methods used to define spectral signatures for distinguishing classes all have important impacts on analytical outcomes. Archaeologists frequently use pre-existing landcover or soils maps for predictive modeling, but often neither accuracy nor the methods used to define categories are discussed. The categories used for this research were defined according to explicit geomorphological criteria (see Table 10.2; Harrower et al. 2002). Buffer areas were used to consider the proportion of each type within specified areas around irrigation structures to ameliorate the influences of classification error. Preliminary efforts were made to compare categories with local, indigenous views of drainage patterns and landcover (see Section 10.5). Although comparisons of imagery-derived versus indigenous views of landscapes are new to archaeology, they offer highly informative prospects for future research.

Notwithstanding the complexities of devising an appropriate landform categorization system, check dams exhibit clear positive associations with wadi silts. K-
S test results for wadi silts show the highest z-score values that consistently fall beyond the 0.999 confidence interval (6.84, 4.51, 5.86, and 3.83, see Tables 10.11 and 10.15). For logistic regression predictions of check dam presence/absence, wadi silts similarly yield the highest Wald chi-square values (37.480, 20.839, 47.989, 35.553, see Tables 10.12 and 10.16). Collectively these results show strong positive associations between wadi silts and check dams, suggesting that the location of wadi silts was a primary factor influencing the check dam location choices of ancient irrigators in Wadi Sana.

10.4.3 Site-Type Issues: Defining what a site is and including different types of ‘sites’ within a single sample can conflate factors responsible for their locations. For this study individual irrigation structures were effectively defined as ‘sites’, and for initial analyses check dams and water diversion channels were grouped into a single ‘Irrigation-Present’ sample. But since factors influencing the locations of check dams and diversion channels are likely very different, subsequent modeling considered these two types of structures independently.

Results for check dams and diversion channels analyzed independently show that different variables are important in the two cases. For Irrigation-Absent Sample 1, logistic regression modeling was much better able to account for the locations of check dams than diversion channels (92.0% vs. 79.4%, see Tables 10.12 and 10.14). For Irrigation-Absent Sample 2, logistic regression achieved nearly the same overall accuracies for check dams and diversion channels (79.3 vs. 80.3, see Tables 10.18 and 10.17). For both Sample 1 and Sample 2, accuracy for predicting observed diversion channel absence was much higher than for predicting observed diversion channel presence (91.4% vs. 36.7%, see Table 10.14; 93.7% vs. 32.7 %, see Table 10.18). More simply put, these trials account for check dam locations with high levels of accuracy (92.0% and 79.3%, see Tables 10.12 and 10.16), and they account for where diversion channels are not located, but cannot predict as well for where diversion channels are located (Tables 10.14 and 10.18). Observations made during archaeological survey offer a potential explanation. Diversion channels frequently divert water toward check dams. While locations of check dams are influenced by landform type (most primarily wadi silts), diversion channels may be controlled by the location of check dams they divert water towards. In other words, while some locations are completely inappropriate for diversion channels accounting for accurate predictions of where channels are not located, where channels are located may be determined more by the location of check dams rather than environmental factors included in logistic regression models. However, analyses
that further explore associations between check dams and diversion channels would be required to conclusively confirm or refute this potential explanation.

Since one might expect that flow accumulation would be an important predictor of irrigation structure locations, findings for flow accumulation call for closer attention. Flow accumulation only appears as a statistically significant variable for logistic regression in one case (see Table 10.14). But K-S test results show that flow accumulation is indeed associated with both check dam and diversion channel locations. K-S tests are based on the maximum difference between cumulative distribution functions. In every case where flow accumulation was evaluated by K-S tests, the maximum difference is statistically significant and the difference is positive for check dams and negative for diversion channels (Tables 10.11, 10.13, 10.15, 10.17). Cumulative percent graphs of flow accumulation illustrate these relationships (Figures 10.28 and 10.29). In both cases the function for diversion channels rises sharply above the irrigation-absent sample in the left side of the graphs showing that diversion channels are preferentially located in low-flow areas. The function for check dams falls below the irrigation-absent sample and is most steep on the right side showing that check dams are preferentially located in higher flow areas (Figures 10.28 and 10.29). Although implications of these results are discussed more extensively in Chapter 11, they show that ancient irrigators preferentially selected areas of low-flow for diversion channels and relatively higher (moderate) flow for check dams.

**10.4.4 Buffering/Data Generation Issues:** The size and shapes of areas used to generate data for irrigation-present and irrigation-absent samples also have important influences on modeling results. Because of inaccuracies in the slope, flow accumulation, and landform data layers, considering each irrigation structure location exclusively as a single-pixel point would increase potential for erroneous representation of sample locations. Instead, producing a buffer area around each structure and averaging data generated for that area more accurately depicts actual landscape conditions. Indeed, irrigation structure locations were probably selected not only on the basis of conditions immediately where they lay, but also in the areas immediately surrounding them. However, discretion involved in choosing the size and shape of these buffer areas introduces a number of problems. Each irrigation structure was recorded during archaeological survey as a linear feature. Although GIS software includes functionality for generating buffers around irregularly shaped linear features, data for irrigation-absent samples could not be produced for precisely the same size and shape areas. Using two
different methods could introduce potentially spurious differences between irrigation-present and irrigation-absent samples. The aforementioned method of drawing circular buffers around irrigation structure mid-points was therefore selected to generate data (see p. 139). Because the size of these buffer areas is arbitrary, analyses with both 50-meter and 15-meter radius buffer areas were conducted. Results show minor differences between 50-meter and 15-meter buffer methods, with 15-meter buffer areas consistently exhibiting a reduced ability to distinguish between irrigation-present and irrigation-absent samples. These results suggest that irrigation structure locations may have been selected according to a 50-meter or larger area around them. To further address these issues future analyses might draw irregularly shaped buffers around irrigation structures and then devise a method to randomly select precisely the same size and shape areas for irrigation-absent data generation.

10.5 Ethnoarchaeology

Results of preliminary ethnoarchaeological investigations in Wadi Sana provide information on water-use, land-use, and social parameters of contemporary small-scale irrigation that enhance understanding of ancient practices. Ethnoarchaeological research was conducted in conjunction with archaeological survey and excavation, most exclusively over 5 weeks in 2004 and 2005. Although these investigations cannot serve as a replacement for a more complete ethnoarchaeological study that would require much longer duration fieldwork, they provide an informative basis for beginning to consider social factors relevant to small-scale irrigation in the region. Research efforts focused on clarifying the meaning of the term *shrūj*, finding contemporary *shrūj* and other small-scale systems, and identifying some of their socio-logistical requirements. In addition to research conducted in Wadi Sana, explorations of other areas of the Hadramawt and Yemen allowed comparison with irrigation techniques in other contexts. Irrigation systems investigated during ethnoarchaeological fieldwork were not mapped in detail, but do offer informative opportunities to compare the basic function and scale of modern systems with ancient systems documented by archaeological survey.

While the system of identity groups for towns along Wadi Hadramawt described in Section 9.1 was considered in light of what was learned in Wadi Sana, published descriptions have basic similarities to but do not appropriately describe social relations or identity groups encountered during fieldwork. There are no *sāda* in Wadi Sana, populations in towns and villages are much smaller and are characterized by an arguably more diverse range of tribal affiliations. Since time was not available for investigations
comprehensive enough to adequately understand and define local identity group roles in
detail, a simple, basic distinction between townsfolk and rural pastoralists is used instead.
Accordingly, the following descriptions outline water-use practices among peoples with
two primary socioeconomic orientations: 1) nomadic pastoralists who herd sheep, goats,
and camels throughout Wadi Sana’s rugged, heavily-dissected highlands, and 2)
sedentary farmers who tend date palms and grow cereals in a number of small towns and
villages including Ghayl bin Yumain, Lahaf, and Haru (Figure 4.1). While there is a
substantial overlap between the livelihoods and familial backgrounds of these groups,
they use land and water in very different ways. Water for irrigation agriculture in towns
is traditionally obtained from three sources: 1) ghayl springs that emerge from bedrock in
Ghayl bin Yumain, 2) floodwater (sayl) flows in wadi channels, and 3) hang-dug sināwa
wells located in high water-table areas. Traditional rural sources used for non-cultivation
purposes in the hinterlands include springs that trickle from limestone bedrock along the
lower reaches of the Wadi Sana main channel, and karīf reservoirs used to capture runoff
to provision animals.

Wadi Sana’s heavily dissected highlands are home to nomadic Hamum badu, who
herd sheep, goats, and camels, but during at least the last 50 to 100 years there has been
very little crop agriculture outside of towns and villages where water resources are
concentrated. Although contemporary badu recognize ancient diversion channels and
check dams as “very old” shrūj irrigation, contemporary hillslope water flow is not
sufficient, and is not used for cultivation. Fewer than 10 locales where machinery-
constructed earthen barriers were built along main wadi channels near the Khuzmum
testify to relatively recent efforts to capture water for agriculture. According to local
residents these efforts were organized by local tribesmen during the last 30-50 years but
proved unsuccessful and never generated viable crops. In each case earthen constructions
were breached and destroyed by powerful flash floodwaters. Contemporary populations
obtain water for human and animal consumption from springs (‘ayn, ghalt), runoff
reservoirs (karīf), or purchase it from trucks that deliver water on a periodic basis.
Although a diesel-pump-driven well was drilled near the Khuzmum in 1999, the pump on
the well failed and as of April 2005 had not been repaired. Although precise estimates
are challenging because encampments move regularly, approximately 100 men, women,
and children inhabit Wadi Sana north of Ghayl bin Yumain. Nuclear or extended family
encampments are exclusively along the main wadi channels, where water and fodder can
be found. Local badu distinguish a variety of landform types including wadi channels
(rahāba or misya), wadi sediments (fīn), wadi bottom areas (surum), lower plateaus
(ruqba), and upper plateaus (magid). They also use a number of terms to distinguish drainages of different sizes. Small catchments that drain areas smaller than 2 square kilometers are known as sīgha, medium size drainages are known as sh‘ab, and larger catchments and their channels are known by the general Arabic term wādīn (sing. wādī). Badu of middle Wadi Sana know the intricate dendritic pattern of drainages and named wadis over a stretch of at least 45 kilometers north of Ghayl bin Yumain throughout which they travel and relocate encampments regularly based predominantly on the availability of browse suitable for goats.

Today irrigation agriculture is practiced in the vicinity of Ghayl bin Yumain, Haru and Lahaf, and to a lesser degree near the mouth of Wadi Sana just south of the village of Sana. Investigations focused on irrigation in and around Ghayl bin Yumain and areas immediately to the west near the town of Haru. Population figures are not known but the largest settlement, Ghayl bin Yumain, is likely home to a thousand or more people. As discussed in Chapter 6, the term ghayl is used throughout Southwest Arabia to describe spring or perennial water flows of considerable quantity as opposed to ‘ayn a term used for springs with modest flow. Waters referred to as ghayl are also found in the town of Ghayl Omar in Wadi Sah south of Seiyun, and near the town of Ghayl Ba Wasir along the Indian Ocean coast east of Al-Mukalla. Waters in Ghayl Oman emerge from the wadi bed in an area of constricted topography similar to Ghayl bin Yumain, while waters of Ghayl ba Wasir are found in sink-holes and are used via qanāt-like tunnels that deliver for agricultural and non-agricultural uses (Hehmeyer et al. 2002). Although springs in Ghayl bin Yumain were historically located near the center of town, at the time of fieldwork in 2005 there had been no substantial rain in 3 years, no sayl in 5 years, and springs had been dry for at least 2 years. Near the end of RASA’s 2005 field season there were two short rainfall episodes that produced floods along the middle Wadi Sana but since travel was nearly impossible at the time their ramifications for agriculture in Ghayl bin Yumain are not known. Tufa outcrops on the northern and western edges of Ghayl bin Yumain’s date palm groves indicate that ghayl springs originally covered a much larger area. While springs have likely receded due to climate change, diesel pumps in use today can rapidly draw-down groundwater so detailed hydrological ground-water studies would be required to determine why springs have dried.

A combination of spring (ghayl), well (sināwa), and flashflood (sayl) waters traditionally support date palm and cereal farming in Ghayl bin Yumain. As in the

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55 Information on local perceptions and definitions of landforms was collected by RASA co-director, Dr. Abdalaziz bin ‘Aqil (General Organization for Antiquities Museums and Manuscripts, Al-Mukalla).
Hadramawt generally, the two traditionally most important crops in Ghayl bin Yumain are date palms (nakhl) and sorghum (dhura). Farmers also grow wheat (qamḥ), barely (sha‘īr), millet (misablī), and alfalfa (barsīm); the latter two are used exclusively as fodder. Sorghum is traditionally planted in the spring/summer and wheat in the fall. Sayl floodwaters enter town from four directions, Wadi Haru, Wadi Milayn, Wadi Jareb, and Wadi Naheb. Spring and sayl waters are captured from wadis using either a barrier known as a mahraf which leads to a canal (zamīr), or start directly from a zamīr itself when a barrier is not needed. After entering canals water is then diverted to individual fields (jaraba) using a stone sluice (minkī), earthen access point (sagī), or a stone lined tunnel cut through the base of the canal (khudara). These terms are similar to those reported by Serjeant (1964: 38, 43) for Hureidha where a canal is known as a sāqiyya, while zamīr refers to a barrage, and minkī a sluice (cf. Ba-Qhaizil et al. 1996). Wells named sināwa (after the method used to extract water) are located in sediments along wadi beds in high water-table areas. They are usually a few meters in diameter with a ramp leading to the bottom. A cow, camel, or person descends the slope with a rope and raises a bucket attached to a wooden structure above the well so that water can be delivered to palms by hand or via small channels (cf. Boxberger 2002: 87-88). For Hureidha, Bujra (1971: 59) reports use of sināwa wells to water date palms. In Ghayl bin Yumain sināwa were reportedly used primarily to water date palms, but were also observed in use for watering cereal crops, and are undoubtedly crucial when sayl or ghayl waters are unavailable. Although diesel pumps have in many cases replaced traditional means of drawing water from wells, methods of water delivery remain similar and most frequently involve small earthen channels that lead to individual fields subdivided into small plots a few meters across.

Meanings of the term shrarū (sing., shāraj) in Southwest Arabia exemplify considerable regional variation in agricultural practices and terminology. In the Hadramawt the term shrarū generally refers to land that is irrigated by hillslope runoff rather than wadi (sayl) floodwaters. In Wadi Dawʿ an the term describes irrigation of fields surrounded by low stone walls with access points that let water in from small diversion channels (Ba-Qhaizil et al. 1996: 85; Al-Khanbashi and Badr n.d.: 91). In the region of Lahj near Aden, “shrāj (sing. ashruj)” refers to secondary or sub-channels that divert sayl floodwaters from main channels towards fields (Maktari 1971: 58). In Wadi Sana the term shrarū variably refers to small extended-family farms, or small surface runoff diversion channels. In western Wadi Hadramawt farms are sometimes named after wells that water them for example, “Bir Bin Mahdi, Bir al-Shams, and Bir BaWaʾil”
(Boxberger 2002: 87), while in Ghayl bin Yumain, extended family farms are named as individual šārāj that contain up to 200 individual fields (jaraba). Maktari (1971: 63) briefly describes the unpaid position of “shaikh al-shārīj” who is appointed by landholders to supervise sub-channels leading to fields in Lahj. Serjeant (1988: 143) similarly describes “shaykh al-sharīj” and similar titles use to denote supervisors of small channels, and Hartley (1961: 106) mentions the individuals known as hākim al-shrūj who specialize in adjudication of matters involving small-scale irrigation.

Management of irrigation in Ghayl bin Yumain is considerably less complex than management systems used for larger systems in other parts of the Hadramawt. Labor for irrigation in Ghayl bin Yumain is generally mobilized at the household level. Landowners arrange tenure agreements in which sharecroppers take 1/3 to 3/4 of the harvest depending on the quality of the land and associated water availability. These arrangements are similar to those reported in North Yemen by Donaldson (2000), who identified proportions retained by sharecroppers as high as 9/10 to as low as 1/5, with most systems involving “halves, thirds, or quarters” (2000: 143). For plowing, Ghayl bin Yumain farmers sometimes hire an ox, team of oxen, or a camel if required, and farmers sometimes hire laborers compensated with sorghum stalks (qasab) to be used as animal feed. Farmers plant sorghum using a board known as a suraba, which hits the ground while seed is distributed. No khiyyyl or other irrigation managers reportedly exist in Ghayl bin Yumain, and the matira is apparently not used as a unit of measure (cf. p. 120). Most farms are small enough to be operated by an extended family, and sayl waters enter directly from wadis so that there is no need for lengthy canals that divide water among complex landholdings. Because irrigation systems were considerably smaller and less complex than those of Wadi Daw‘an, for instance, they appear not to have required intricate means of measurement, supervision, and dispute mitigation56, but further research would undoubtedly help further clarify the more acephalous types of arrangements Ghayl bin Yumain farmers employ instead.

10.6 Summary

Results of fieldwork and analyses in Wadi Sana shed considerable new light on the influences of environmental and social parameters of incipient irrigation. Archaeological survey identified 174 irrigation structures distributed predominately along the middle Wadi Sana. Irrigation began during the mid to late 6th millennium (calibrated)

While the strength of associations between irrigation structure locations and hydrological conditions are difficult to immutably quantify because of malleability introduced by Modifiable Areal Unit Problem (MAUP) and related sampling and data generation issues, spatial modeling results show that irrigation structure locations were chosen based on intricate knowledge of monsoon runoff and the availability of wadi silts sediments. The small size of irrigated areas (generally less than one hectare) indicate that early systems were likely managed at the household level without need for irrigation managers or water users associations and did not generate surplus sufficient for substantial control and redistribution by persons of elevated social status. Ultimately understanding irrigation’s origins requires situating developments within context of long-term societal trajectories. The following chapter pursues a historical narrative explanation of developments in Wadi Sana as a means to exemplify factors structuring irrigation’s origins in Southwest Arabia.
Figure 10.1: Ancient irrigation structures along middle Wadi Sana.
Figure 10.2: A typical shrūj water diversion channel (W16-1B).

Figure 10.3: A typical shrūj check dam (W6-1).
Figure 10.4: The Khuzmum area at the mouth of Wadi Shumlya showing rock-bordered canal 009-1 and vicinity.
Figure 10.5: Plan map of rock-bordered canal 009-1 (box on the left aligns with box on the right to extend a total distance of 74 meters).
Figure 10.6: Southeast end of rock-bordered canal 009-1 showing two lines of embedded small boulders in foreground and stranded boulders in background.

Figure 10.7: Rock-bordered canal 009-1 showing two lines of embedded small boulders.
Figure 10.8: Rock-bordered canal 009-1 showing two lines of embedded small boulders in naturally-cut section (from the top looking down).

Figure 10.9: Test pit 1 of rock-bordered canal 009-1 showing two lines of buried small boulders.
Figure 10.10: Test pit 2 of rock-bordered canal 009-1 showing two lines of buried small boulders.

Figure 10.11: Test pit 3 of rock-bordered canal 009-1 showing two lines of buried small boulders.
Figure 10.12: Check dam 000-1 showing imbricated slabs.

Figure 10.13: Plan map of water diversion structure 013-1.
Figure 10.14: The vicinity of WATER 1.

Figure 10.15: Check dam W1-1.
Figure 10.16: Hearth W1-4-1 near check dam W1-1 (hearth is immediately above the black and white meter-stick shown in center foreground of photograph).

Figure 10.17: The vicinity of WATER 5.
Figure 10.18: Check dam W5-1.

Figure 10.19: Check dam W5-1 section drawing.

A - sand with rounded pebbles (present before dam)
B - poorly sorted silty sand with pebbles (construction material for earthen dam with cobble backing)
C - burnt lens with shell and tubular charcoal (root?) fragments (from burning upstream of dam)
D - sand with occasional pebbles (accumulated as water flowed up to and over dam)
Figure 10.20: Check dam W19-1.

Figure 10.21: The vicinity of WATER 6 through 9.
Figure 10.22: WATER 7 diversion channels. Water naturally flows to the gully shown on the left side of photograph, small walls extending from the bottom center of photograph divert water toward gully shown in the center background.

Figure 10.23: WATER 8 gully between bedrock slope and silts. Check dams slow waters flowing between silt embankment on the left and bedrock slope on the right.
Figure 10.24: Circular tower tomb near WATER7.
Figure 10.25: Wadi Sana Digital Elevation Model (DEM) extracted from ASTER imagery (top left - Khuzmum area close-up, top right - Khuzmum area overview, bottom left - Ghavl bin Yumain, bottom right - mouth of Wadi Sana).
Figure 10.26: Wadi Sana watershed landform classification.
Figure 10.27: Wadi Sana drainage network (catchments are shown in the inset only).
Figure 10.28: Flow accumulation for check dam and diversion channel locations versus Irrigation-Absent Sample 1 locations (lines represent cumulative percent of flow accumulation sum within 15 meter buffers around points).

Figure 10.29: Flow accumulation for check dam and diversion channel locations versus Irrigation-Absent Sample 2 locations (lines represent cumulative percent of flow accumulation sum within 15 meter buffers around points).
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| 88 | 2004-W23-6  | check dam  | 1747260 | 337746 | 677 | 4  |
| 89 | 2004-W23-7  | check dam  | 1747353 | 337769 | 679 | 12 |
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<td>Greater than 15° slope or cliff (sometimes covered in talus and/or scree) that separates upland plateaus from all other classes.</td>
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<td>Angular clasts often of a low (&lt; 20°) gradient between bedrock slopes, terraces, and wadi sediments.</td>
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<td>Plateau</td>
<td>Upland bedrock surfaces above bedrock slopes and cliffs, covered in primarily angular carbonate small cobble size clasts.</td>
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<td>Sub-rounded to rounded clasts often capping wadi silts and adjacent to wadi channels.</td>
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<td>The youngest low angle (&lt; 5°) or horizontal bedrock surface adjacent to wadi sediments and/or scree slopes, covered in primarily small cobble size carbonate clasts.</td>
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<td>Pinkish tan colored areas of very fine sand and silt above wadi channels, that often contain isolated lenses and scattered cover of gravel and/or scree.</td>
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<td>Playa/Sabkha</td>
<td>Alluvial plain with gypsum and marl deposits found in the eastern Ghayl bin Yumain basin.</td>
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<td>Wadi Channel</td>
<td>The lowest and most fluvially active area often demarcated by whitish gray rounded cobbles, boulders, and more prevalent vegetation.</td>
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Table 10.2: Landform class definitions
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<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Plateau</td>
<td>3</td>
<td>0</td>
<td>60</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gravel Terrace</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>26</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Bedrock Terrace</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Wadi Silt</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>6</td>
<td>4</td>
<td>97</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Playa/Sabkha</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Wadi Channel</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>36</td>
<td>0</td>
<td>51</td>
</tr>
</tbody>
</table>

Values represent pixels designated to particular landform classes in stratified random reference data and supervised classification imagery, respectively.

Table 10.3: Landform classification accuracy assessment error matrix

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Percentage of Landscape</th>
<th>Reference Totals</th>
<th>Classified Totals</th>
<th>Number Correct</th>
<th>Producers Accuracy</th>
<th>Users Accuracy</th>
<th>Kappa Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock Slope</td>
<td>27.1</td>
<td>40</td>
<td>46</td>
<td>25</td>
<td>62.5%</td>
<td>54.4%</td>
<td>0.502</td>
</tr>
<tr>
<td>Scree Slope</td>
<td>12.4</td>
<td>41</td>
<td>58</td>
<td>28</td>
<td>68.3%</td>
<td>48.3%</td>
<td>0.435</td>
</tr>
<tr>
<td>Plateau</td>
<td>47.8</td>
<td>80</td>
<td>68</td>
<td>60</td>
<td>75.0%</td>
<td>88.2%</td>
<td>0.859</td>
</tr>
<tr>
<td>Gravel Terrace</td>
<td>0.9</td>
<td>36</td>
<td>34</td>
<td>26</td>
<td>72.2%</td>
<td>76.5%</td>
<td>0.746</td>
</tr>
<tr>
<td>Bedrock Terrace</td>
<td>1.5</td>
<td>38</td>
<td>40</td>
<td>29</td>
<td>76.3%</td>
<td>72.5%</td>
<td>0.702</td>
</tr>
<tr>
<td>Wadi Silt</td>
<td>5.1</td>
<td>153</td>
<td>130</td>
<td>97</td>
<td>63.4%</td>
<td>74.6%</td>
<td>0.629</td>
</tr>
<tr>
<td>Playa/Sabkha</td>
<td>2.6</td>
<td>14</td>
<td>10</td>
<td>9</td>
<td>64.3%</td>
<td>90.0%</td>
<td>0.897</td>
</tr>
<tr>
<td>Wadi Channel</td>
<td>2.6</td>
<td>82</td>
<td>98</td>
<td>51</td>
<td>62.2%</td>
<td>52.0%</td>
<td>0.423</td>
</tr>
</tbody>
</table>

**Totals**

|                     | 100           | 484           | 484               | 325           |

Overall Proportion of Area Correctly Classified = 67.2%

Overall Kappa Statistic = 0.603

Table 10.4: Landform classification accuracy assessment statistics
1) Fill Sinks
2) Flow Direction
3) Flow Accumulation
4) Stream Definition (for editing and correction)
5) Agree DEM (using original raw DEM)
6) Fill Sinks
7) Flow Direction
8) Flow Accumulation
9) Stream Definition (using various thresholds)
10) Stream Segmentation
11) Catchment (Grid)
12) Catchment (Polygon)

Table 10.5: List of GIS hydrological modeling procedures

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAC</td>
<td>flow accumulation</td>
</tr>
<tr>
<td>SLP</td>
<td>slope</td>
</tr>
<tr>
<td>MIN</td>
<td>minimum</td>
</tr>
<tr>
<td>MAX</td>
<td>maximum</td>
</tr>
<tr>
<td>SUM</td>
<td>sum</td>
</tr>
<tr>
<td>AVG</td>
<td>average (mean)</td>
</tr>
<tr>
<td>LN</td>
<td>natural log</td>
</tr>
<tr>
<td>SS</td>
<td>scree slope</td>
</tr>
<tr>
<td>WC</td>
<td>wadi channel</td>
</tr>
<tr>
<td>WS</td>
<td>wadi silts</td>
</tr>
<tr>
<td>PL</td>
<td>plateau</td>
</tr>
<tr>
<td>BT</td>
<td>bedrock terrace</td>
</tr>
<tr>
<td>GT</td>
<td>gravel terrace</td>
</tr>
<tr>
<td>BS</td>
<td>bedrock slope</td>
</tr>
</tbody>
</table>

Table 10.6: Spatial modeling data code abbreviations
Table 10.7: Kolmogorov-Smirnov results for Irrigation-Present versus Irrigation-Absent Sample 1

<table>
<thead>
<tr>
<th>FAC-MAX</th>
<th>FAC-SUM</th>
<th>SLP-AVG</th>
<th>SLP-MIN</th>
<th>SS%</th>
<th>WC%</th>
<th>WS%</th>
<th>PL%</th>
<th>BT%</th>
<th>GT%</th>
<th>BS%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference</td>
<td>0.21</td>
<td>0.20</td>
<td>-0.33</td>
<td>-0.29</td>
<td>0.09</td>
<td>0.30</td>
<td>0.62</td>
<td>0.48</td>
<td>0.20</td>
<td>0.12</td>
</tr>
<tr>
<td>Z-value</td>
<td>1.93</td>
<td>1.88</td>
<td>3.06</td>
<td>2.68</td>
<td>0.80</td>
<td>2.79</td>
<td>5.74</td>
<td>4.50</td>
<td>1.88</td>
<td>1.13</td>
</tr>
<tr>
<td>Sig. (2-tail)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.54</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 10.8: Kolmogorov-Smirnov results for Irrigation-Present versus Irrigation-Absent Sample 2

<table>
<thead>
<tr>
<th>FAC-MAX</th>
<th>FAC-SUM</th>
<th>SLP-AVG</th>
<th>SLP-MIN</th>
<th>SS%</th>
<th>WC%</th>
<th>WS%</th>
<th>PL%</th>
<th>BT%</th>
<th>GT%</th>
<th>BS%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference</td>
<td>0.23</td>
<td>0.24</td>
<td>0.13</td>
<td>0.15</td>
<td>0.08</td>
<td>0.23</td>
<td>0.50</td>
<td>0.16</td>
<td>0.50</td>
<td>0.16</td>
</tr>
<tr>
<td>Z-value</td>
<td>2.14</td>
<td>2.20</td>
<td>1.23</td>
<td>1.39</td>
<td>0.75</td>
<td>2.14</td>
<td>4.66</td>
<td>1.45</td>
<td>1.39</td>
<td>0.43</td>
</tr>
<tr>
<td>Sig. (2-tail)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.096</td>
<td>0.04</td>
<td>0.63</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.99</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 10.9: Logistic regression results for Irrigation-Present versus Irrigation-Absent Sample 1

<table>
<thead>
<tr>
<th>Predicted Absent</th>
<th>Predicted Present</th>
<th>Total</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Absent</td>
<td>156</td>
<td>18</td>
<td>174</td>
</tr>
<tr>
<td>Observed Present</td>
<td>30</td>
<td>144</td>
<td>174</td>
</tr>
<tr>
<td>Total</td>
<td>186</td>
<td>162</td>
<td>348</td>
</tr>
</tbody>
</table>

cut value = 0.40

Variables in the Equation

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>Wald</th>
<th>Chi-Square</th>
<th>Wald Significance</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC%</td>
<td>2.48</td>
<td>12.41</td>
<td></td>
<td>0.00</td>
<td>11.91</td>
</tr>
<tr>
<td>WS%</td>
<td>6.51</td>
<td>31.30</td>
<td></td>
<td>0.00</td>
<td>671.36</td>
</tr>
<tr>
<td>PL%</td>
<td>-1.27</td>
<td>10.22</td>
<td></td>
<td>0.00</td>
<td>0.28</td>
</tr>
<tr>
<td>BT%</td>
<td>3.72</td>
<td>6.82</td>
<td></td>
<td>0.01</td>
<td>41.19</td>
</tr>
<tr>
<td>Constant</td>
<td>-0.66</td>
<td>7.51</td>
<td></td>
<td>0.01</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Table 10.9: Logistic regression results for Irrigation-Present versus Irrigation-Absent Sample 1
<table>
<thead>
<tr>
<th>Predicted Absent</th>
<th>Predicted Present</th>
<th>Total</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Absent</td>
<td>134</td>
<td>40</td>
<td>174</td>
</tr>
<tr>
<td>Observed Present</td>
<td>41</td>
<td>133</td>
<td>174</td>
</tr>
<tr>
<td>Total</td>
<td>175</td>
<td>173</td>
<td>348</td>
</tr>
</tbody>
</table>

cut value = 0.40

Variables in the Equation

<table>
<thead>
<tr>
<th>Variables</th>
<th>B</th>
<th>Wald</th>
<th>Chi-Square</th>
<th>Wald Significance</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS%</td>
<td>3.01</td>
<td>42.01</td>
<td>0.00</td>
<td>20.26</td>
<td></td>
</tr>
<tr>
<td>BS%</td>
<td>2.65</td>
<td>21.24</td>
<td>0.00</td>
<td>14.21</td>
<td></td>
</tr>
<tr>
<td>SLP-MIN</td>
<td>-0.06</td>
<td>5.90</td>
<td>0.02</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-0.69</td>
<td>15.12</td>
<td>0.00</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

Table 10.10: Logistic regression results for Irrigation-Present versus Irrigation-Absent Sample 2

<table>
<thead>
<tr>
<th>Variables</th>
<th>Difference</th>
<th>Z-value</th>
<th>Sig. (2-tail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAC-MAX</td>
<td>0.29 (0.21)</td>
<td>2.50 (1.79)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>FAC-SUM</td>
<td>0.28 (0.22)</td>
<td>2.37 (1.87)</td>
<td>0.00 (0.02)</td>
</tr>
<tr>
<td>SLP-AVG</td>
<td>-0.39 (-0.38)</td>
<td>3.34 (3.20)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>SLP-MIN</td>
<td>-0.33 (-0.36)</td>
<td>2.80 (3.11)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>SS%</td>
<td>0.13 (0.06)</td>
<td>1.08 (0.49)</td>
<td>0.19 (0.97)</td>
</tr>
<tr>
<td>WC%</td>
<td>0.38 (0.23)</td>
<td>3.19 (1.96)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>WS%</td>
<td>0.80 (0.53)</td>
<td>6.84 (4.51)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>PL%</td>
<td>-0.64 (-0.55)</td>
<td>5.42 (4.73)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>BT%</td>
<td>0.17 (0.06)</td>
<td>1.47 (0.52)</td>
<td>0.03 (0.95)</td>
</tr>
<tr>
<td>GT%</td>
<td>0.13 (0.03)</td>
<td>1.10 (0.29)</td>
<td>0.18 (1.00)</td>
</tr>
<tr>
<td>BS%</td>
<td>-0.19 (-0.16)</td>
<td>1.61 (1.33)</td>
<td>0.01 (0.06)</td>
</tr>
</tbody>
</table>

*values outside brackets are for 50m buffer areas, values in brackets are for 15m buffer areas

Table 10.11: Kolmogorov-Smirnov results for Check Dams vs. Irrigation-Absent Sample 1 (50m & 15m buffers)*
Predicted Absent | Predicted Present | Total | % Correct* \\
---|---|---|---
Observed Absent | 162 (159) | 12 (15) | 174 (174) | 93.1 (91.4)
Observed Present | 12 (27) | 113 (98) | 125 (125) | 90.4 (78.4)
Total | 174 (186) | 125 (113) | 299 (299) | 92.0 (86.0)
cut value = 0.5

Variables in the Equations

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>Wald Chi-Square</th>
<th>Wald Significance</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS%</td>
<td>9.129 (3.821)</td>
<td>37.48 (20.839)</td>
<td>0.000 (0.000)</td>
<td>9221.341 (45.646)</td>
</tr>
<tr>
<td>PL%</td>
<td>(-)5.828 (-4.074)</td>
<td>9.864 (22.578)</td>
<td>0.002 (0.000)</td>
<td>0.003 (0.017)</td>
</tr>
<tr>
<td>WC%</td>
<td>2.561 (2.210)</td>
<td>12.715 (12.989)</td>
<td>0.000 (0.000)</td>
<td>12.948 (9.116)</td>
</tr>
<tr>
<td>GT%</td>
<td>4.615 (n/a)</td>
<td>5.61 (n/a)</td>
<td>0.018 (n/a)</td>
<td>100.947 (n/a)</td>
</tr>
<tr>
<td>SLP_MIN</td>
<td>n/a (-0.077)</td>
<td>n/a (13.867)</td>
<td>n/a (0.000)</td>
<td>n/a (0.926)</td>
</tr>
<tr>
<td>Constant</td>
<td>(-)1.288 (0.451)</td>
<td>17.417 (1.894)</td>
<td>(0.00) 0.169</td>
<td>0.276 (1.570)</td>
</tr>
</tbody>
</table>

*values outside brackets are for 50m buffer areas, values in brackets are for 15m buffer areas
*values labeled "n/a" were not significant and were not included in the model

Table 10.12: Logistic regression results for Check Dams vs. Irrigation-Absent Sample 1 (50m & 15m buffers)*

<table>
<thead>
<tr>
<th></th>
<th>Difference</th>
<th>Z-value</th>
<th>Sig. (2-tail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAC-MAX</td>
<td>(-)0.24 (-0.42)</td>
<td>1.45 (1.33)</td>
<td>0.03 (0.06)</td>
</tr>
<tr>
<td>FAC-SUM</td>
<td>(-)0.22 (-0.27)</td>
<td>1.38 (1.69)</td>
<td>0.05 (0.01)</td>
</tr>
<tr>
<td>SLP-AVG</td>
<td>(-)0.21 (-0.20)</td>
<td>1.31 (1.22)</td>
<td>0.07 (0.10)</td>
</tr>
<tr>
<td>SLP-SUM</td>
<td>(-)0.18 (-0.23)</td>
<td>1.10 (1.42)</td>
<td>0.18 (0.04)</td>
</tr>
<tr>
<td>SS%</td>
<td>(-)0.06 (-0.02)</td>
<td>0.39 (0.15)</td>
<td>1.00 (1.00)</td>
</tr>
<tr>
<td>WC%</td>
<td>0.11 (0.03)</td>
<td>0.69 (0.20)</td>
<td>0.73 (1.00)</td>
</tr>
<tr>
<td>WS%</td>
<td>0.14 (0.01)</td>
<td>0.85 (0.06)</td>
<td>0.46 (1.00)</td>
</tr>
<tr>
<td>PL%</td>
<td>(-)0.27 (-0.17)</td>
<td>1.64 (1.07)</td>
<td>0.01 (0.20)</td>
</tr>
<tr>
<td>BT%</td>
<td>0.28 (0.13)</td>
<td>1.67 (0.78)</td>
<td>0.01 (0.58)</td>
</tr>
<tr>
<td>GT%</td>
<td>0.10 (0.06)</td>
<td>0.62 (0.34)</td>
<td>0.84 (1.00)</td>
</tr>
<tr>
<td>BS%</td>
<td>0.23 (-0.93)</td>
<td>1.39 (0.57)</td>
<td>0.04 (0.90)</td>
</tr>
</tbody>
</table>

*values outside brackets are for 50m buffer areas, values in brackets are for 15m buffer areas
^K-S test for FAC_MAX_LN yields the same results

Table 10.13: Kolmogorov-Smirnov Statistics for Diversion Channels vs. Irrigation-Absent Sample 1 (50m & 15m buffers)*
### Predicted Absent vs. Predicted Present:

<table>
<thead>
<tr>
<th></th>
<th>Observed Absent</th>
<th>Observed Present</th>
<th>Total</th>
<th>% Correct*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Predicted Absent</strong></td>
<td>159 (169)</td>
<td>15 (5)</td>
<td>174 (174)</td>
<td>91.4 (97.1)</td>
</tr>
<tr>
<td><strong>Predicted Present</strong></td>
<td>31 (39)</td>
<td>18 (10)</td>
<td>49 (49)</td>
<td>36.7 (20.4)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>190 (208)</td>
<td>33 (15)</td>
<td>223 (223)</td>
<td>79.4 (80.3)</td>
</tr>
<tr>
<td><strong>Cut value = 0.25</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Variables in the Equations:

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>Wald Chi-Square</th>
<th>Wald Significance</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BT%</td>
<td>5.311 (3.165)</td>
<td>11.212 (8.379)</td>
<td>0.001 (0.004)</td>
<td>202.643 (23.686)</td>
</tr>
<tr>
<td>GT%</td>
<td>3.583 (2.504)</td>
<td>4.546 (4.268)</td>
<td>0.033 (0.039)</td>
<td>35.969 (12.236)</td>
</tr>
<tr>
<td>WC%</td>
<td>1.982 (n/a)</td>
<td>3.915 (n/a)</td>
<td>0.048 (n/a)</td>
<td>7.259 (n/a)</td>
</tr>
<tr>
<td>FAC_MAX_LN</td>
<td>(-0.277 (n/a)</td>
<td>5.356 (n/a)</td>
<td>0.021 (n/a)</td>
<td>0.797 (n/a)</td>
</tr>
<tr>
<td>Constant</td>
<td>(-0.742 (-1.455)</td>
<td>3.862 (68.554)</td>
<td>0.049 (0.000)</td>
<td>0.476 (0.233)</td>
</tr>
</tbody>
</table>

*values outside brackets are for 50m buffer areas, values in brackets are for 15m buffer areas

### Table 10.14: Logistic regression results for Diversion Channels vs. Irrigation-Absent Sample 1 (50m & 15m buffers)*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Difference</th>
<th>Z-value</th>
<th>Sig. (2-tail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAC_SUM</td>
<td>0.31 (0.22)</td>
<td>2.61 (1.91)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>FAC_AVG</td>
<td>0.31 (-0.23)</td>
<td>2.61 (1.39)</td>
<td>0.00 (0.04)</td>
</tr>
<tr>
<td>SLP_SUM</td>
<td>0.19 (0.12)</td>
<td>1.62 (0.72)</td>
<td>0.01 (0.69)</td>
</tr>
<tr>
<td>SLP_MIN</td>
<td>(-0.20 (-0.22)</td>
<td>1.70 (1.89)</td>
<td>0.01 (0.00)</td>
</tr>
<tr>
<td>SS%</td>
<td>(-0.08 (-0.05)</td>
<td>0.70 (0.39)</td>
<td>0.71 (1.00)</td>
</tr>
<tr>
<td>WC%</td>
<td>(-0.23 (-0.13)</td>
<td>1.95 (1.14)</td>
<td>0.00 (0.15)</td>
</tr>
<tr>
<td>WS%</td>
<td>0.69 (0.45)</td>
<td>5.86 (3.83)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>PL%</td>
<td>(-0.28 (-0.24)</td>
<td>2.35 (2.01)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>BT%</td>
<td>0.12 (0.20)</td>
<td>1.03 (0.17)</td>
<td>0.24 (1.00)</td>
</tr>
<tr>
<td>GT%</td>
<td>(-0.05 (-0.04)</td>
<td>0.49 (0.35)</td>
<td>0.97 (1.00)</td>
</tr>
<tr>
<td>BS%</td>
<td>0.17 (0.09)</td>
<td>1.48 (0.80)</td>
<td>0.03 (0.54)</td>
</tr>
</tbody>
</table>

*values outside brackets are for 50m buffer areas, values in brackets are for 15m buffer areas

### Table 10.15: Kolmogorov-Smirnov results for Check Dams vs. Irrigation-Absent Sample 2 (50m & 15m buffers)*
<table>
<thead>
<tr>
<th>Predicted Absent</th>
<th>Predicted Present</th>
<th>Total</th>
<th>% Correct*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Absent</td>
<td>144 (146)</td>
<td>30 (28)</td>
<td>174 (174)</td>
</tr>
<tr>
<td>Observed Present</td>
<td>32 (45)</td>
<td>93 (80)</td>
<td>125 (125)</td>
</tr>
<tr>
<td>Total</td>
<td>176 (191)</td>
<td>123 (108)</td>
<td>299 (299)</td>
</tr>
</tbody>
</table>

Cut value = 0.4

Variables in the Equations

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>Wald Chi-Square</th>
<th>Wald Significance</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS%</td>
<td>3.577 (2.259)</td>
<td>47.989 (35.553)</td>
<td>0.000 (0.000)</td>
<td>35.754 (9.573)</td>
</tr>
<tr>
<td>PL%</td>
<td>-3.511 (-2.690)</td>
<td>10.091 (11.026)</td>
<td>0.001 (0.001)</td>
<td>0.03 (0.068)</td>
</tr>
<tr>
<td>BS%</td>
<td>1.586 (1.227)</td>
<td>7.202 (7.471)</td>
<td>0.007 (0.006)</td>
<td>4.883 (3.411)</td>
</tr>
<tr>
<td>Constant</td>
<td>-1.073 (-0.747)</td>
<td>27.185 (17.728)</td>
<td>0.000 (0.000)</td>
<td>0.342 (0.474)</td>
</tr>
</tbody>
</table>

*values outside brackets are for 50m buffer areas, values in brackets are for 15m buffer areas

Table 10.16: Logistic regression results for Check Dams vs. Irrigation-Absent Sample 2 (50m & 15m buffers)*

<table>
<thead>
<tr>
<th>Difference</th>
<th>Z-value</th>
<th>Sig. (2-tail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAC_MAX</td>
<td>(-0.28, -0.22)</td>
<td>1.74 (1.36)</td>
</tr>
<tr>
<td>FAC_SUM</td>
<td>(-0.25, -0.26)</td>
<td>1.52 (1.62)</td>
</tr>
<tr>
<td>SLP_MIN</td>
<td>0.12 (-0.09)</td>
<td>0.74 (0.55)</td>
</tr>
<tr>
<td>SLP_MAX</td>
<td>0.24 (0.12)</td>
<td>1.47 (0.76)</td>
</tr>
<tr>
<td>SS%</td>
<td>(-0.11, -0.07)</td>
<td>0.68 (0.40)</td>
</tr>
<tr>
<td>WC%</td>
<td>(-0.32, -0.28)</td>
<td>1.96 (1.72)</td>
</tr>
<tr>
<td>WS%</td>
<td>(-0.09, -0.08)</td>
<td>0.53 (0.52)</td>
</tr>
<tr>
<td>PL%</td>
<td>0.31 (0.23)</td>
<td>1.94 (1.43)</td>
</tr>
<tr>
<td>BT%</td>
<td>0.22 (0.09)</td>
<td>1.38 (0.53)</td>
</tr>
<tr>
<td>GT%</td>
<td>(-0.04, -0.02)</td>
<td>0.25 (0.10)</td>
</tr>
<tr>
<td>BS%</td>
<td>0.46 (0.23)</td>
<td>2.81 (1.40)</td>
</tr>
</tbody>
</table>

*values outside brackets are for 50m buffer areas, values in brackets are for 15m buffer areas

Table 10.17: Kolmogorov-Smirnov results for Diversion Channels vs. Irrigation-Absent Sample 2 (50m & 15m buffers)*
<table>
<thead>
<tr>
<th></th>
<th>Predicted Absent</th>
<th>Predicted Present</th>
<th>Total</th>
<th>% Correct*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Absent</td>
<td>163 (166)</td>
<td>11 (8)</td>
<td>174 (174)</td>
<td>93.7 (95.4)</td>
</tr>
<tr>
<td>Observed Present</td>
<td>33 (38)</td>
<td>16 (11)</td>
<td>49 (49)</td>
<td>32.7 (22.4)</td>
</tr>
<tr>
<td>Total</td>
<td>196 (204)</td>
<td>27 (19)</td>
<td>223 (223)</td>
<td>80.3 (79.4)</td>
</tr>
</tbody>
</table>

cut value = 0.4

**Variables in the Equations**

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>Wald Chi-Square</th>
<th>Wald Significance</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS%</td>
<td>3.04 (1.571)</td>
<td>16.675 (7.632)</td>
<td>0.000 (0.006)</td>
<td>20.903 (4.813)</td>
</tr>
<tr>
<td>WC%</td>
<td>(-)2.596 (-2.245)</td>
<td>10.443 (10.642)</td>
<td>0.001 (0.001)</td>
<td>0.075 (0.106)</td>
</tr>
<tr>
<td>SLP_MIN</td>
<td>(-)0.133 (-0.045)</td>
<td>8.396 (4.809)</td>
<td>0.004 (0.028)</td>
<td>0.876 (0.956)</td>
</tr>
<tr>
<td>Constant</td>
<td>(-)0.792 (-0.649)</td>
<td>9.55 (5.604)</td>
<td>0.002 (0.018)</td>
<td>0.453 (0.523)</td>
</tr>
</tbody>
</table>

*values outside brackets are for 50m buffer areas, values in brackets are for 15m buffer areas

Table 10.18: Logistic regression results for Diversion Channels vs. Irrigation-Absent Sample 2 (50m & 15m buffers)*
CHAPTER 11

DISCUSSION: WADI SANA AND THE ORIGINS OF IRRIGATION IN ANCIENT SOUTHWEST ARABIA

From the Paleolithic through the Iron Age, Wadi Sana includes evidence from a long span of prehistory and ancient history that provides an informative case for understanding the origins of irrigation in Southwest Arabia. Archaeological remains include lithic scatters, hearths, tombs, encampments, and small habitation structures that form a complex landscape palimpsest. Like others across Southwest Arabia, Wadi Sana’s inhabitants turned to irrigation during the course of long-term environmental and social changes, and it is therefore informative to set irrigation’s origins, and results of this dissertation, within a chronological context of developments in Wadi Sana before and after the 6th millennium BP.

Foragers first arrived in Wadi Sana sometime during the late Pleistocene, most probably after 500,000 years ago. Lithic scatters found across plateaus above wadis mark travel routes that offered attractive vantage points for tracking game. It is still unknown whether foragers were present continuously during the late Pleistocene or only during periods of relatively increased precipitation. But ice-age forager-hunters left behind huge scatters of lithics. On the plateau southwest of the Khuzmum, for instance, a dense ‘carpet’ of raw material and lithics covers at least 14 hectares. While this area was probably also used as a raw material source during the Holocene, this and other scatters include Levallois flakes and cores (Crassard 2004).

By the early Holocene less arid and probably less variable climatic conditions made Wadi Sana an increasingly attractive foraging territory. Ninth millennium BP foragers returned to Khuzmum rockshelters and open-air sites along wadis to camp and re-tool. Trihedral points with esthetic transverse flaking (including those retrieved from Khuzmum rockshelter excavations) are part of a wider industry found throughout
Hadramawt-Mahra-Dhofar (Charpentier 2004). At the upper Wadi Sana site of Manayzeh (155-2), a 2.5 meter deep stratigraphic sequence (that includes a range of distinctive Arabian Bifacial Tradition tool types) shows that 8th millennium BP\textsuperscript{57} foragers camped near springs that are only small seeps today, but flowed more vigorously during the early Holocene.

As early Holocene human populations increased, game would have become correspondingly less plentiful. Sometime during the late 8th or 7th millennium, cattle husbandry elicited dramatic social and economic changes. As depicted by a ring of 42 cattle skulls recently excavated (but not yet directly dated) near the Khuzmum in middle Wadi Sana, early cattle husbandry was intricately connected to ritual (McCorriston \textit{et al.} 2005b). The phylogenetic affiliations of these cattle and whether or not cattle rituals were instigated by the cosmological role of cattle elsewhere (e.g., Cauvin 2000) will be critical to understanding their origins. No longer as tied to oscillating game availability, 7th millennium cattle herders built widely-spaced small circular houses (see Figure 7.1) around the Khuzmum where intersecting waters of Wadi Sana and Wadi Shumlya afforded vegetation-rich, slack-water areas where their cattle could graze.

It is within this context after many millennia of foraging, and a shorter but still extensive history of animal husbandry, that irrigation originated in Wadi Sana during the mid to late 6th millennium BP. Although we presently have no archaeobotanical evidence of ancient crop cultivation in Wadi Sana, if crops did arrive before 5500 BP they likely would have been grown in naturally water-rich microenvironments that were most productive and least risky, including around the Khuzmum or near springs along the lower reaches of Wadi Sana and near Ghayl bin Yumain. The earliest irrigation in Wadi Sana (dated before 5,144 cal yr BP) rivals the earliest evidence for agriculture or irrigation elsewhere in Southwest Arabia suggesting that irrigation appeared in remote, inland areas nearly as early as it did in any other highland or coastal locale.

While it remains impossible to definitively exclude the possibility that Wadi Sana’s first irrigation structures were built by forager-pastoralists who watered wild plants for game and/or their herds, cross-cultural and local ethnographic evidence indicate that early irrigators were probably not exclusively foragers or pastoralists, but more likely pursued a transhumant combination of hunting, gathering, herding, and small-scale crop cultivation. Levantine crops (and possibly sorghum) had arrived in

\textsuperscript{57} Thus far only a single date of 7,732 cal yr BP, (6,902 14\textsuperscript{C} yr BP, AA59570) is available for Munayzah but the site likely spans a much long interval from the early Holocene onwards, and the nearby spring is still used today.
Southwest Arabia by the 6th millennium BP (Ekstrom and Edens 2003; Costantini 1990). Cross-culturally irrigation appears to have been rare among foragers; and pastoralists generally do not feed irrigation’s products to animals without cultivating and consuming crop products themselves.

Ethnographic analogs drawn from the Hadramawt-Mahra-Dhofar region suggest that 6th millennium BP residents of Wadi Sana were nomadic cattle herders who irrigated crops with summer monsoon rains and moved toward the coast to find pasture during winter. Wadi Sana today receives approximately 70 mm of precipitation per annum and is too arid for cattle or irrigation. Like nomadic goat and camel herding *badu* in arid northern deserts of Dhofar (Janzen 1986: 133), contemporary *Hamum badu* along middle Wadi Sana do not irrigate or build dwelling structures. But Wadi Sana was far more humid before 5000 BP and likely resembled modern climates along the escarpment/highlands of Dhofar that today receive 400 to 500 mm of precipitation predominantly as monsoonal fog. *Jabali* cattle herders along this escarpment move seasonally in complex patterns, primarily from the coast in winter to the highlands in summer, build houses, and cultivate sorghum (el-Mahi 2001; Janzen 1986, 2000; Zarins 1992b, 2001: 131-134). And *Jabali* houses (4 to 5 meters in diameter with 80-centimeter high stone walls, capped by branches supported by a central post, Janzen 1986: 125-126) bear striking resemblance to circular 7th millennium houses excavated by RASA near the Khuzmum (see Figure 7.1). While these similarities do not prove 6th millennium BP irrigators in Wadi Sana cultivated crops, in lieu of direct archaeobotanical confirmation, they suggest the ethnographically most important crop, sorghum, or Levantine crops, may have arrived with irrigation.

Mid-Holocene recession of the southwest monsoon and an associated shift toward more arid conditions around 5,100 cal yr BP dramatically altered precipitation-vegetation-sedimentation patterns and transformed hydrological regimes. Since dates for irrigation and aridification can still only be placed sometime during the mid to late 6th millennium, it is not entirely clear if incipient irrigation first occurred just prior to, or concurrent with, aridification. However, the earliest preserved irrigation structures were found near the main channel of Wadi Shumlya suggesting that initial constructions were built prior to full onset of contemporary arid-zone flashflood runoff regimes because such modest diversion channels likely could not have harnessed powerful floodwaters. As the full terrestrial effects of aridification materialized (over a span of at least a few hundred years), vegetation cover fell dramatically, and runoff patterns shifted from lower-energy aggradating flows to sudden, massive, eroding discharges characteristic of the area today.
Flows from springs would have fallen significantly and only major ghayl springs near Ghayl bin Yumain would have provided flows sufficient for cultivation. In the face of these more arid conditions, and the concomitantly elevated impacts of grazing, irrigation shifted from the 5th millennium BP onwards toward smaller tributary drainages where low-energy runoff could be more easily managed. Although ancient irrigators may not have been directly cognizant of environmental changes that may have occurred relatively gradually over centuries or millennia, they undoubtedly experienced their ramifications and developed detailed knowledge of runoff that allowed strategic selection of areas for water diversion. It was within these challenging environmental parameters that shrūj irrigation originated.

The results of GIS spatial modeling lead to informative, but unexpected conclusions. One might anticipate that in the face of increasingly arid conditions irrigation structures would be built in areas with the greatest flow potential; but ancient irrigation structures in Wadi Sana are not located in areas of highest flow accumulation. Like many other hyper-arid areas of the Middle East, conditions in Wadi Sana involve runoff from rocky terrain often devoid of sediment with relatively little vegetation. When rain occurs there is very little infiltration/absorption. Most water runs-off and accumulates rapidly in channels generating short-duration, powerful flows. The greatest challenge, therefore, was not identifying areas of highest flow accumulation, but instead selecting areas with relatively moderate-energy flow where runoff could be encouraged with small diversion structures to run slowly onto sediments contributing to accumulation rather than erosion. Spatial modeling further shows that check dam locations were determined by the location of wadi silt sediments that in turn affected the location of diversion channels that directed water towards them.

In conjunction with the technical and environmental challenges of incipient irrigation, dramatic transformations in the ways ancient peoples perceived social landscapes were crucial to irrigation’s origins. Understandings of landforms and flow patterns took on dramatically new importance as incipient irrigators became interested not only in foraging and grazing but in areas with potential for water diversion. As ancient irrigators manipulated water flow they became less dependent on periodicities of wild resources, while simultaneously reliant on new ideologies of landuse, water control, and territory. Water was no longer an open resource, but a domain of anthropogenic control. Investments in irrigation structures were not only landesque capital improvements (Blaikie and Brookfield 1987) promising future economic payoffs, but borrowing a term Sheridan (2002) used to describe the importance of small-scale
irrigation intakes in North Pare, Tanzania, irrigation structures served more broadly as *symbolic landesque capital* that communicated claims to water and land. New ideologies of hydraulically altered landscapes, including who held knowledge of irrigation techniques and was authorized to employ that knowledge in particular areas, shaped social relations at the cusp of irrigation’s origins.

Establishing claims to water and irrigable land, while maintaining transhumant mobility, was one of irrigation’s most significant social stumbling blocks. Circular tower tombs scattered across the plateaus above Wadi Sana (Figure 10.24), that are dated to the late 6th and 5th millennium (cal yr BP) elsewhere in both Southwest and Southeast Arabia (Braemer *et al.* 2001; Cleuziou 2002: 196-197; de Maigret 2002; Steimer-Herbert 2004; Steimer-Herbert *et al.* in press), confirm that Wadi Sana’s residents had long-distance contacts with peoples across the southern Arabian Peninsula. In at least some areas with similar (beehive or turret-style) cairn tombs, local peoples developed irrigation strategies tailored to their own local conditions (Cleuziou 2002: 198-199; Frifelt 2002: 101-104).

As J.C. Wilkinson (1983b) describes, territory rights among nomads of Oman often involved rights to particularly practices such as grazing in specified areas, rather than ownership of land itself. Ancient claims to land for irrigation in Wadi Sana would have involved dramatic shifts in the purposes for which lands were claimed, and circular tower tombs likely played an important role in establishing claims to hydrologically altered landscapes. Unlike similar scale modern field systems in Dhofar (Janzen 1986: 105), fields in ancient Wadi Sana were not surrounded by walls to protect crops from animals. Particularly since irrigation in Wadi Sana was concentrated along a travel corridor, fields may have required protection from unauthorized grazing, and tombs provided means to affirm territory rights.

As evident via comparison with local ethnographic systems, irrigation in ancient Wadi Sana likely operated on a communal basis without supra-household coordination or associated social stratification. Design, construction, operation, maintenance tasks required for incipient *shrūj* systems could have easily been accomplished at the domestic group or extended family levels. Of these tasks, design was the most challenging. Diversion channels are located in low-flow, low-slope areas where the direction and potential velocities of water flow are not conspicuously apparent. To choose appropriate locations, would-be irrigators would have to anticipate potential water flows along plateaus and the sides of wadis well in advance of monsoon rains. Although they are difficult to measure precisely enough for quantitative analyses, irrigated areas in ancient middle Wadi Sana were not larger than a few hectares. Based on the approximately 1
hectare areas supporting individual qabā‘il households in North Yemen and Hurediah (see Section 9.1), these areas likely supported nuclear or possibly extended families but probably did not produce substantive redistributable surplus.

Irrigation’s origins were a function of both inter-regional influences and unique local ingenuities. Even though 7th millennium Southeast Arabian populations were in some form of contact with Mesopotamian groups who practiced irrigation (as evident by ‘Ubaid ceramics found at sites in the UAE and Oman), they do not appear to have adopted irrigation until significantly later, possibly as late as the 6th or even 5th millennium BP. Cultivars and irrigation therefore did not spread as soon as they were encountered, but required devising new practices suitable for Southern Arabia’s unique environmental and social contexts (including Wadi Sana’s deeply dissected rocky terrain inhabited by nomadic forager-herders). Rather than specific irrigation technologies, it was concepts of prosperity irrigation that had potential to afford that likely diffused. While shrūj surface runoff irrigation in Hadramawt exemplifies one type of early Southwest Arabian irrigation, analogous hillslope runoff, spring flow, and terrace systems were simultaneously developing in western Yemen. In each case irrigation diffused more by stimulus than unadulterated transplantation of preexisting irrigation techniques.

As 5th millennium peoples of Wadi Sana continued developing shrūj systems, agriculturists in western Yemen were devising cultivation and irrigation techniques capable of supporting permanent fortified settlements (Wilkinson and Edens 1999; Wilkinson et al. 2001). As larger-scale systems produced crop surpluses, control of inter-household food distribution would have offered staple financing avenues of power and social differentiation (cf. Earle 1997). Larger-scale systems required more labor and involved concomitantly new organizational/managerial challenges. Decision-making, communication, water and land allocation, and dispute mitigation issues would have induced unique social challenges that required socioculturally and ideologically negotiated solutions. Larger Bronze Age systems most plausibly involved appointed or elected irrigation managers and/or water users associations that may have proactively aimed to restrict individuals or social groups from gaining autocratic authority.

Leadership came with both positive and negative consequences that particularly for prehistoric systems are difficult to define archaeologically. Contemporary intermediate-scale systems (including those of Wadi Daw’an/Wadi Amd) offer opportunities for further ethnoarchaeological investigations to help better understand ancient irrigation management alternatives.
From the 4th through 2nd millennia BP, middle Wadi Sana was apparently far more sparsely populated. Ceramics, a primary type of evidence about agricultural societies elsewhere, are extremely rare along the middle reaches of Wadi Sana and its tributaries. In four 8-week RASA Project field seasons (1998, 2000, 2004, and 2005) fewer than 50 ceramic sherds (all from the Pre-Islamic period) were discovered, testifying to the high mobility of Wadi Sana’s hunting, foraging, herding, irrigating, and trading populations. Although substantial Bronze and Iron Age settlements including Shabwa, Husn al-‘Ab, Raybun, Husn al-‘Urr, and Makaynun are found along Wadi Hadramawt, only one major settlement has been identified in the Wadi Sana watershed thus far. This fortified Himyarite period hillfort known as Qalat Habshiya stands prominently on bluffs at the entrance of Wadi Sana proper, approximately 10 kilometers north of Ghayl Bin Yumain. Although critically important, this site has not been the subject of detailed archaeological investigations. Itinerant tradespeople plying aromatics that supported ancient kingdoms were undoubtedly making their way through Wadi Sana by the 3rd millennium. They carved graffiti at campsites in Wadi Sana, and may have constructed the trilith cairns that illustrate cultural contacts across the Southern Arabian Peninsula (see de Cardi 1977; al-Shari 1991). Although we do not yet know if Qalat Habshiya was constructed to control incense trade, inscriptions from Qalat Habshiya indicate that the hillfort exerted authority as a regional gateway to Wadi Sana and beyond (Beeston 1962: 41-42).

11.1 Summary

From the Paleolithic through the Iron Age, the chronology of changing lifeways in Wadi Sana provides an informative local example of factors structuring irrigation’s development. While Pleistocene foragers left behind Levallois flakes and cores, the timing and duration of their activities is at present extremely difficult to define. During the 9th millennium BP forgers camped at rockshelters and open-air sites leaving Arabian Bifacial Tradition tools and re-tooling debris exhibiting geographically wide affiliations with contemporaries across the Hadramawt-Mahra-Dhofar region. By the 7th millennium Wadi Sana’s residents were herding cattle and building small circular houses near the Khuzmum at the confluence of Wadi Sana and Wadi Shumlya. Irrigation began in Wadi Sana during the mid to late 6th millennium BP providing a crucial new supplement to foraging and herding that ameliorated periodicities of plant resource availability. New understandings of landscapes as hydrologically malleable domains of anthropogenic control were crucial to establishing claims to land and water. Analogous surface runoff
and terrace agriculture strategies simultaneously emerged in western Yemen forming the foundations of large-scale floodwater irrigation technologies that sustained regionally powerful Iron Age kingdoms.
CHAPTER 12

CONCLUSIONS: THE RELATIVE INFLUENCE OF ENVIRONMENTAL VERSUS SOCIAL PARAMETERS

The origins of irrigation in ancient Southwest Arabia involved a variety of environmental and social parameters that combined to shape early trajectories of ancient food producing societies in the region. While evaluating the relative influences of environmental and social factors is a matter of substantive epistemological complexities, this study indicates that both are critically important and that methods that aim for a compromise between processual and postprocessualism, and therefore more balanced appraisals of both environmental and social factors, provide the most informative means of understanding irrigation’s origins in Southwest Arabia. The previous chapter focused on Wadi Sana as a case study to clarify how irrigation originated. This chapter focuses on epistemological issues involved in explaining transitions to agriculture and identifies avenues for investigations with potential to further clarify the subsequent co-elaboration of irrigation and societies in ancient Yemen.

Archaeologists face substantial challenges identifying and evaluating factors responsible for transitions from foraging to food production. Climate change, population pressure, human-plant coevolution, and changing social relations have each held long-standing utility as general explanations and factors traceable within regions. The long history of competition between these explanatory variables (in which no single factor has prevailed) indicates that multivariate analyses that comparatively evaluate more than one factor are required. Historical narrative explanations help situate events in chronological frameworks, but if archaeologists are to continue seeking general explanations analysts need to evaluate the relative importance of different factors and themes of competing explanations with attention to epistemological divides that structure research outcomes. This study traced one important theme, the relative influence of environmental versus...
social parameters, focusing on Southwest Arabia as a less archaeologically known region with potential to generate new insights about societal transitions from foraging to food production.

Conflicts between processual and postprocessual perspectives in explanations for transitions to agriculture reflect latent ontological/epistemological differences that needlessly divide and isolate approaches that are powerfully complementary. Proponents of archaeology as science frequently advocate hypothesis testing with quantitative data as the most constructive means of investigating prehistory. Scientific methods frequently lend themselves to, and are most appropriate for, materialist analyses of environmental and economic factors and thus are of primary concern to an extremely wide swath of processualist research. Although advocates of science frequently postulate, for instance, associations between the distribution of sites and environmental circumstances, social and ideological factors are frequently marginalized as means of facilitating adaptations to environments or controlling access to resources rather than driving forces in-and-of themselves. In contrast, advocates of interpretive methods in archaeology emphasize sociocultural particularities that (via human agency) led ancient peoples to unique choices based on motivations that allegedly supersede environmental/economic considerations. But postprocessual approaches grant sociocultural factors primacy irrespective of technological, environmental, and economic factors that are often not apparent, nor are adequately appraised, with exclusively interpretive methods.

A landscape-oriented, critical realist combination of processual-materialist and postprocessual-idealist perspectives provides a far more accurate illustration of irrigation’s origins in Wadi Sana (and Southwest Arabia more generally) than either perspective alone. This study evaluated the hypothesis that, in terms of type and location, the remains of ancient irrigation structures are strongly associated with hydrological variables reflecting close behavioral ties to ancient environmental conditions. While this hypothesis testing experiment proved usefully informative, it highlights reasons why exclusively science-oriented GIS methods are prone to neglect social factors that are more difficult to quantify as maps and, via consideration of Modifiable Areal Unit Problem (MAUP) issues, demonstrates how quantitative GIS results are malleable in ways rarely acknowledged or addressed. From a scientific-materialist perspective, one could argue that associations between hydrological conditions and irrigation structure locations demonstrated by spatial (predictive) modeling in this study show that environmental circumstances appreciably shaped ancient human choices and behavior. In one of the primary cases, spatial modeling predicts the presence/absence of check
dams with 92% accuracy (Table 10.12), indicating that environmental criteria had major influences on ancient choices of locations for irrigation structures. But parameters delineated by environments cannot be considered the totality of archaeological nor human significance. From a humanistic-idealist perspective, one could argue that in hyper-arid conditions where little water and few areas of arable land were available, associations between irrigation structures and hydrological conditions are virtually a given, and what is instead more challenging and crucial to explain is how people generated, held, and disseminated understandings of landscapes required for irrigation, including new ideologies of landuse, water manipulation, and territory.

The relative significance of these distinct but complimentary materialist/idealist perspectives that respectively emphasize environmental or social factors as primarily determinants of human behavior and choices is challenging to resolve. While one could pursue solely materialist or idealist lines of inquiry, with arguably more comprehensive results, this would only serve to reiterate preexisting epistemological problems that haunt contemporary archaeological explanations. Geomatics technologies offer attractive means for quantitative analyses that allow archaeologists to measure associations between physical (landscape) environments and material remains. However, these advantages are accompanied by significant drawbacks: 1) few geomatics tools are specifically designed for archaeology, and adapting methods devised in other disciplines can involve time-consuming technical obstacles, and 2) a myriad of complex analytical and statistical techniques can introduce analytical biases that lead analysts to results that are more a function of analysts’ choices than is often acknowledged. Considering what has (or has not) been learned about ancient peoples often becomes subservient to producing models with statistically significant results as demonstrated, for instance, by applications of predictive modeling that conflate prediction with explanation. Quantitative geomatics methods including predictive and other forms of spatial modeling can and do make substantive (and still unexhausted) contributions. For instance, the finding that even in hyper-arid Wadi Sana irrigation structures were constructed in areas of moderate flow potential would have been difficult to convincingly substantiate without geomatics analyses. However, the pitfalls and biases of quantitative GIS analyses in archaeology (including MAUP) need to be addressed not only by critics who dismiss predictive modeling methods and results because they are incompatible with their preconceptions about the efficacy of technological, environmental, and economic factors in human choices, but by practitioners of predictive modeling who can more rigorously appraise both the strengths and weaknesses of their analyses.
GIS and geomatics are traditionally marked by tendencies toward materialism. But interpretive, qualitative GIS methods including visualization are themselves forms of analysis. Graphics that facilitate visual interpretation, including satellite imagery maps used for this study, are powerfully informative tools for understanding spatial dimensions of ancient life (McCorriston and Harrower 2005). The etic picture derived from GIS necessarily differs from perceptions of indigenous peoples including those of Wadi Sana. But in contrast with arguments that maps provide inherently western, ethnocentric views that misrepresent indigenous perspectives (e.g., Bender 1993), imagery maps are not so remote to indigenous peoples that they are antithetically incomparable. Given a satellite image map, badu in Wadi Sana enthusiastically recognized the intricate network of šīgha, šh’ab, and wādī drainages that after four years RASA surveyors are just beginning to know, indicating that just as some archaeologists do, local badu find satellite image maps usefully informative. The answer is not to disregard satellite imagery and potential quantitative analyses, but instead to critically consider how GIS frames analyses, how discretionary scale and categorization choices delineate outcomes, and combine quantitative methods with qualitative techniques that can arguably better address more enigmatic social and ideological relations that are more difficult to address via scientific quantification. Landform classifications have helped depict the wider-scale distribution of landform types that RASA Project archaeologists and geologists recognize, and have prompted ongoing discussions regarding how landscapes could be, and should be, represented in GIS with the longer-term goal of further comparing and integrating what we learn from discussions with local peoples.

In addition to geomatics analyses that helped demonstrate the influences of hydrological conditions on ancient human choices, ethnoarchaeology offered means of better understanding the social and socio-logistical parameters of ancient irrigation. While quantitative spatial analyses might also address social factors, including the role of irrigation structures and tombs in territoriality, The Ecological Fallacy (see pp. 42-43) cautions against indiscriminate reliance on even quantitative evidence of spatial association. Future analyses, including RASA investigations that specifically focus on tombs and other monuments, will explore how geomatics can further address social dimensions of life in ancient Wadi Sana. However, like other methods, geomatics analysis techniques have drawbacks; locations and spatial distributions provide a useful perspective but one that may mask other important factors that are more difficult to conceptualize and represent spatially. Rather than attempting to squeeze evidence into a spatial GIS box, applying methods in combination with geomatics (in this case
ethnoarchaeology) provides means to include observations that are more challenging to represent and address with GIS.

Ethnoarchaeological analyses, including inter-regional and local perspectives, show that new perceptions and ideologies of social landscapes were vital to irrigation’s origins. Irrigation involved dramatically new types of claims to land. While exclusive rights to naturally flowing water would be dangerous in hyper-arid environments where nomadic peoples and their animals require water to survive, water harnessed for irrigation requires special claims to irrigation water and its products to make irrigating worthwhile. Knowledge about irrigation, including how to design effective water diversion installations required intimate familiarity with patterns and velocities of runoff during monsoon rains. Ancient forager-herders in Wadi Sana developed and applied this knowledge amidst changing and competing claims to territories. Design, construction, operation, and maintenance tasks for the earliest irrigation systems were probably accomplished at the domestic group or extended family level. Irrigation structures served as symbolic landesque capital (cf. Sheridan 2002) that spawned and legitimized sociocultural affiliations. As increasing large-scale irrigation systems developed new organizational/managerial challenges required culturally and ideologically negotiated solutions. Ethnoarchaeology identifies irrigation managers and water users associations as potential organizational alternatives.

While Southwest Arabia remains a sparsely investigated region and continued investigations will allow more conclusive evaluations of factors posited by general models, some preliminary observations can be made about transitions to agriculture in Southwest Arabia. Rather than a peripheral hinterland of the Middle East to which crop agriculture simply diffused, ancient Southwest Arabia was a diverse geographic crossroads that experienced a plethora of early African, Levantine, Mesopotamian, and South Asian influences shaped by local ingenuities. Even though crops may have been foreign, transitions to plant agriculture involved far more than simply transplanting previously domesticated species. Environmental and social contingencies, including tropical, monsoon climates, preexisting foraging-herding adaptations, perceptions of landscapes, territory, and conceptualizations of nature played important roles in shaping new lifeways. While Roberts (1977) suggestion that the southern Levant down the coast of the Red Sea to Southwest Arabia was a zone of runoff agriculture (where irrigation was a necessary component of crop agriculture) cannot yet be indisputably confirmed because direct-rainfall-reliant (dryland) farming may have appeared in the highlands of western Yemen as early as irrigation, irrigation’s early appearance further calls into
question presumptions that dry-farming invariably precedes irrigation agriculture. Although irrigation was likely inspired (to some degree) by the prosperities irrigation afforded in regions surrounding Southwest Arabia, irrigation did not diffuse as soon as it was known. Cultivation techniques and coevolved crops needed to be incorporated and shaped to fit local environmental and social circumstances. Like ancient Africans (Marshall and Hillebrand 2002), peoples of ancient Southwest Arabia adopted domesticated cattle (and possibly ovicaprids) before crops. Climatic conditions, including late 6th millennium BP aridification, constricted feasible subsistence options. Although it is not yet clear whether the earliest irrigation occurred immediately prior to, concurrent with, or just after late 6th millennium aridification, results of this study show close connections between physical landscape characteristics and irrigation structure locations demonstrating (more proximately) that environmental conditions were important in shaping human choices. Even given parameters delineated by environments, agriculture was not a compulsory eventuality. Long after some groups began cultivating, others (like badu of Wadi Sana today) remained nomadic herders. But prior to the establishment of villages and towns reliable trade for plant food was not an option, leading some groups (including those of Wadi Sana) to pursue a combination of transhumant foraging, herding, and irrigation that exemplifies the continuum between traditionally prescribed categories of mobile foraging, nomadic herding, and crop agriculture (Smith 2001). Although long-term, millennia-scale population pressure (possibly exacerbated by aridification) played an important role in delimiting increasingly circumscribed territories, we presently have little evidence to suggest that increased local mobility was not an option and that irrigation was therefore instigated by demographic stress. When ancient Southwest Arabians began irrigating they became less residentially mobile but not fully sedentary showing that village-life and year-long sedentism were not prerequisites of agriculture. Social factors including changing perceptions of relations with nature, land, and water-use were vital to convincing cohorts that irrigation was a viable, advantageous strategy. Small fields in Wadi Sana could have produced enough for nuclear families, but we have no evidence for mass storage or accumulation that would indicate surplus was controlled or redistributed beyond immediate-kin domestic groups by persons of elevated status.

In addition to their importance for understanding transitions to agriculture, the findings of this research have important significance for understanding the longer-term role of irrigation in the trajectories of ancient Southwest Arabian societies. It is difficult to envision a region with more potential to provide new evidence of irrigation as both a
stimulus and reflection of long-term changes in social, cultural, and political relations. The technological, environmental, social, and ideological factors that shaped ancient irrigation practices in Southwest Arabia had long and diverse histories prior to the rise of large-scale floodwater irrigation systems. Better understandings of irrigation’s origins in Southwest Arabia helps chart irrigation’s role among subsequent Southwest Arabian societies including Iron Age kingdoms. Although irrigation has long remained a topic of scholarly interest in ancient Southwest Arabia, studies have traditionally focused on describing the technology of ancient state systems and have been conducted with little consideration of what archaeologists and anthropologists have learned about irrigation elsewhere. Although the hydraulic hypothesis in its original and most simplistic formulation is seriously (if not terminally) flawed, its faults do not necessarily discredit the view that irrigation (in conjunction with other factors such as population pressure, trade, and warfare) was crucially important in instigating economic and social change. In Southwest Arabia, Iron Age kingdoms are well known for wide trade contacts and high-productivity floodwater irrigation strategies were critical to enabling and sustaining such relations. Southwest Arabia’s earliest kingdoms developed along the Ramlat as-Sab’atayn Desert’s margins where sophisticated irrigation technologies were necessary, rather than in western highlands where less labor-demanding rainfed farming was possible. Harnessing massive sayl water flows before they reached the desert not only generated food surpluses to sustain ancient Southwest Arabian cities, but additionally afforded political leaders the ideological prestige of commanding transformation of the wadi outlets into regional centers of civilization. More detailed reconstructions of irrigation’s origins and subsequent development are crucial to understanding how irrigation became such an important economic and social force among these complex societies.

Explanations of transitions to agriculture are frequently dominated by perspectives that emphasize environmental or social factors without applying perspectives and methods that comparatively address both natural and cultural contingencies. In addition to tracing the chronology of irrigation’s origins, one primary goal of this dissertation was to provide a case study that examines how a critical realist, landscape-oriented perspective that draws on both processual-materialist and postprocessual-idealist approaches could produce a more comprehensive and rich explanation than either ontological/epistemological perspective independently. Exclusively quantitative geomatics analyses of associations between irrigation structure locations and hydrological factors would have neglected sociocultural parameters of
irrigation’s origins. While on the other hand, exclusively qualitative considerations of sociocultural factors would have unduly disregarded environmental challenges. The dichotomy drawn here between environmental and social factors is not intended to contend that they are independent sub-components that comprehensively encompass human life, but a heuristic distinction drawn between them emphasizes their combined importance and helps clarify conflicts between processual and postprocessual perspectives in ways that enable more accurate explanations of prehistory.
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218
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240

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APPENDIX A

WATER MANAGEMENT SITE RECORDING FORM
<table>
<thead>
<tr>
<th><strong>IDENTIFICATION</strong></th>
<th>visited by___________</th>
<th><strong>GPS (Lat)___________ N</strong> (Lon)___________ E (شرق)</th>
</tr>
</thead>
</table>
| Survey Unit        | _________________ | RELATED SITES _______________ |}

**SITE** ________________

**DATE** ________________

**DESCRIPTION**

a) **Type**
   - Canal
   - Shrill
   - Basin
   - Cistern
   - Other [__________]

b) **Plan**
   - Linear [__________]
   - Curvilinear [__________]
   - Rectilinear [__________]
   - Oval/Rounded [__________]
   - Irregular [__________]


c) **Slope**
   - 0-5° [__________]
   - 5-15° [__________]
   - 15-30° [__________]
   - >30° [__________]

b) **Materials**
   - A) Large Boulder (75-100cm) [__________]
   - B) Medium Boulder (50-75cm) [__________]
   - C) Small Boulder (25-50cm) [__________]
   - D) Cobble (6-25cm) [__________]
   - E) Pebble (<6cm) [__________]
   - F) Mud/Clay [__________]
   - G) Plaster [__________]
   - H) Mortar [__________]
   - I) Cement [__________]
   - J) Paint [__________]
   - K) Other [__________]

b) **Diagnostics**

- Courses surviving [__________]
- Deflated [__________]
- Protrusive [__________]
- Hidden/in section [__________]
- Intact surface [__________]

**COLLECTIONS**

- Designated [__________]
- All tools [__________]
- Tools, flakes & cores [__________]
- Diagnostics only [__________]

- Spaced: # transects (m apart) [__________]
  # transects (m) [__________]
  # areas (m²) [__________]
  # items (units) [__________]
  Other [__________]

**BAG NUMBERS**

- RASA 2004 __________ -- -- 00
- RASA 2004 __________ -- -- 00
- RASA 2004 __________ -- -- 00
- RASA 2004 __________ -- -- 00

**SURVEY UNIT# __________ SITE# __________ PAGE _______**
FIELD DATES:

MATERIAL
 Lithic/Ceramic

# of
 ITEMS
 عدد العينات

TYPE
 نوع

DATE/COMMENTS
 تاريخ التعليقات

BAG #
 عدد الأكياس

---

REMARKS/INTERPRETATION

ملاحظة / التفسير

---

SKETCH

Plan [ ]
Section [ ]
Quadrat [ ]
Multiple Structures [ ]

---

PHOTOS:

Digital Cam ______ # _______
Color roll ______ # _______
B&W roll ______ # _______

DRAWINGS/MAPS (ref #’s/drawn by):

Theodolite mapping [ ]
Tape and Compass [ ]
GPS Mapping [ ]

---

SURVEY UNIT #:

SITE #:

PAGE:

267