ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

CLIMATIC CHANGES, SETTLEMENT DYNAMICS, RESOURCESCAPE, AND LANDSCAPE EVOLUTION IN THE DELICE VALLEY (ÇORUM) DURING THE EARLY AND MIDDLE HOLOCENE

Ph.D. THESIS

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Kemal KOÇAKLI
(601182009)

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Thesis Advisor: Prof. Dr. Bülent ARIKAN
Thesis Co-Advisor: Prof. Dr. Emin ÇİFTÇİ

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DELİCE VADİSİ'NDE (ÇORUM) ERKEN VE ORTA HOLOSEN DÖNEMİNDEKİ İKLİMSEL DEĞİŞİMLER, YERLEŞİM DİNAMİKLERİ, KAYNAK PEYZAJI VE PEYZAJ EVRİMİ

DOKTORA TEZİ

Kemal KOÇAKLI
(601182009)

İklim ve Deniz Bilimleri Anabilim Dalı

Yer Sistem Bilimi Programı

Tez Danışmanı: Prof. Dr. Bülent ARIKAN
Eş Danışman: Prof. Dr. Emin ÇİFTÇİ

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Kemal KOÇAKLI, a Ph.D. student of İTU Graduate School student ID 601182009, successfully defended the thesis/dissertation entitled "CLIMATIC CHANGES, SETTLEMENT DYNAMICS, RESOURCESCAPE, AND LANDSCAPE EVOLUTION IN THE DELICE VALLEY (ÇORUM) DURING THE EARLY AND MIDDLE HOLOCENE", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Bülent ARIKAN** İstanbul Technical University	....
Co-advisor :	**Prof. Dr. Emin ÇİFTÇİ** İstanbul Technical University	....
Jury Members :	**Prof. Dr. Bülent BAYRAM** Yıldız Technical University	....
	Prof. Dr. Dursun Zafer ŞEKER İstanbul Technical . University	....
	Assoc. Prof. Halil ZORER Van Yüzüncü Yıl University	....
	Assoc. Prof. Orkan ÖZCAN İstanbul Technical University	....
	Asst. Prof. Semih Sami AKAY Istanbul Topkapı University	....

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To my family,

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June 2025

Kemal KOCAKLI
(Geomorphologist)

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ABBREVIATIONS

ANN : Average Nearest Neighbor
cal. BP : Calendar Before Present
DEM : Digital Elevation Model
EBA : Early Bronze Age
EH : Early Holocene
GIS : Geographic Information Systems
IA : Iron Age
Ka : Thousand years ago
KDE : Kernel Density Estimation
LBA : Late Bronze Age
LH : Late Holocene
Masl : Meter Above Sea Level
MBA : Middle Bronze Age
MH : Middle Holocene
MCM : Macrophysical Climate Model
MML : MedLanD Modeling Laboratory
NAF : North Anatolian Fault
NDVI : Normalized Difference Vegetation Index
PPA : Point Pattern Analyses
RCC : Rapid Climate Change
RRIM : Red Relief Image Map
USPED : Unit Stream Power Erosion/Deposition

SYMBOLS

°C	: Degrees Celsius (temperature)
> / <	: Greater than / Less than (comparative operations)
±	: Plus-minus; standard deviation or error margin
∑	: Summation symbol (used in yield and population estimations)
$\delta^{13}C$	: Carbon-13 isotope ratio (used in paleoclimate studies)
$\delta^{18}O$	: Oxygen-18 isotope ratio (used in paleoclimate studies)
$kg/m^2/year$	: Kilogram per square meter per year (erosion rate unit)
km^2	: Square kilometers (area unit)
m^3	: Cubic meters (volume, e.g., silo/storage capacity)
mm	: Millimeters (typically for precipitation)
n	: Number of data points or storm events
P	: P-value (significance level in statistics)
r	: Pearson correlation coefficient
t/ha	: Tons per hectare (soil loss rate from surface)
Z	: Z-score (standard deviation from mean in spatial stats)

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CLIMATIC CHANGES, SETTLEMENT DYNAMICS, RESOURCESCAPE, AND LANDSCAPE EVOLUTION IN THE DELICE VALLEY (ÇORUM) DURING THE EARLY AND MIDDLE HOLOCENE

SUMMARY

Non-linear, complex, and feedback-driven interaction networks exist between archaeological communities and the landscapes they inhabit. These interactions are increasingly being explored and modeled by archaeologists, anthropologists, and other scholars through landscape archaeology and ecological anthropology, combined with computational methods and agent-based simulations. The strong interdisciplinary collaboration between archaeology and the geosciences has significantly contributed to this growing field of study.

This dissertation investigates how humans and landscapes co-evolved within the Delice Valley by adopting a theoretical framework rooted in ecological anthropology and landscape archaeology. To this end, an integrated methodological approach—combining Geographic Information Systems (GIS), remote sensing, and geomorphological analysis—was employed to spatially model, map, simulate, and interpret long-term socio-ecological processes.

The study area, Delice Valley, is located in north-central Anatolia and has been shaped since the Pleistocene by one of the major tributaries of the Kızılırmak River—the Delice River. At its confluence with the Kızılırmak (ancient Halys), the river forms a wide floodplain characterized by thick alluvial deposits. These alluvial zones constitute fertile lands with high agricultural potential for both modern and pre- and proto-historic farming communities.

The paleoclimatic history of the Delice Valley has been reconstructed using the CHELSA TraCE21k global circulation model, the synoptic Macrophysical Climate Models (MCM), and hydroclimatological proxy datasets. The findings indicate that cool and humid climatic conditions prevailed throughout the Early and Middle Holocene, while warmer and drier conditions became more prominent from the mid-Middle Holocene onward.

The settlement history of the Valley spans from the Chalcolithic period (ca. 6000 cal. BP) to the Iron Age (ca. 2600 cal. BP). Using advanced GIS-based spatial analysis tools, the spatial and temporal patterns of settlement were examined. During the Chalcolithic period (n=13), the dispersed settlement pattern reflects the early stages of socio-political organization. In the Early Bronze Age (ca. 5000–4000 BCE; n=107), the emergence of polity-like structures corresponds with a more clustered settlement pattern. During the Iron Age (ca. 3200–2600 BCE; n=60), following the collapse of the Hittite Empire, a return to dispersed settlement is observed. Notably, during the Early Bronze Age, settlements tend to cluster near fertile agricultural plains and key natural resources such as salt and copper.

Following the paleoenvironmental reconstructions, landscape evolution was modeled using the MedLanD model within a GrassGIS environment. The model assessed how archaeological agro-pastoral communities affected their surroundings—such as through erosion and land cover changes—under different land use strategies and climate change scenarios, as well as the resilience of these systems. The model was specifically applied to Resuloğlu Höyük (4300–4100 BCE), one of the prominent sites among 206 settlements in the study area. The MedLanD Modeling Laboratory (MML) yielded results that are consistent with Resuloğlu's archaeological record, geomorphological context, and socio-political organization.

Due to the badlands-like geological character of the region, rainfall was identified as the primary driver of natural landscape evolution. Under human-influenced conditions, livestock pressure and overgrazing dominated during dry periods, whereas agricultural activities became the main drivers under wetter conditions.

This study aims to safeguard the cultural memory and heritage of Resuloğlu Höyük through the use of integrated GIS, remote sensing, and geomorphological approaches. A comprehensive erosion modeling study was conducted using GeoWEPP (a GIS-based Water Erosion Prediction Project), supported by SPOT 7 satellite imagery, drone surveys, field observations, and expert interviews. The results demonstrate that archaeological excavations—particularly in a context of high erosion risk—have intensified erosion processes on the mound. These findings highlight the urgent need for local authorities to adopt immediate and effective conservation policies to prevent further degradation.

Ultimately, the research shows that socio-political organization, subsistence strategies, resource exploitation, and long-distance trade were critical factors influencing the long-term evolution of settlement systems in the region.

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ÖZET

Arkeolojik topluluklar ile yaşadıkları peyzaj arasında doğrusal olmayan, karmaşık ve geri beslemeli etkileşim ağları bulunmaktadır. Bu etkileşimler, günümüzde karmaşık sistemler kuramı, hesaplamalı bilimler ve yüksek başarımlı bilgisayar destekli simülasyon yöntemleri aracılığıyla; başta arkeologlar ve antropologlar olmak üzere çeşitli bilim insanları tarafından anlaşılmaya ve modellenmeye çalışılmaktadır. Arkeolojinin yer bilimleriyle kurduğu güçlü disiplinlerarası iş birliği, bu sürece önemli katkılar sağlamaktadır.

Bu tez, ekolojik antropoloji ve peyzaj arkeolojisi kuramsal çerçevesi doğrultusunda, insan ile peyzajın Delice Vadisi özelinde nasıl birlikte evrildiğini araştırmaktadır. Bu amaçla Coğrafi Bilgi Sistemleri (CBS), uzaktan algılama ve jeomorfolojik yaklasimlar gibi entegre yöntemler kullanılarak, uzun süreli sosyo-ekolojik süreçler mekânsal olarak modellenmiş, haritalanmış ve yorumlanmıştır.

Çalışma alanı olan Delice Vadisi, Orta Kuzey Anadolu'da, Kızılırmak Nehri'nin en büyük kollarından biri olan Delice Nehri'nin Pleistosen'den bu yana yatağını oyması sonucu oluşmuştur. Vadi, Delice Nehri'nin Kızılırmak'a (antik Halys) bağlandığı noktada geniş bir taşkın ovası ve zengin alüvyal birikimler ile karakterizedir. Bu alüvyonlar, hem günümüz hem de tarihöncesi tarım toplulukları için yüksek potansiyele sahip verimli alanlardır.

Delice Vadisi'nin iklimsel geçmişi, CHELSA TraCE21k küresel iklim modeli, Makrofiziksel sinoptik iklim modelleri (MCM) ve hidroklimatolojik proxy veri setleri kullanılarak yeniden yapılandırılmıştır. Bulgular, Erken ve Orta Holosen boyunca serin ve nemli iklim koşullarının etkili olduğunu, Orta Holosen'in ortalarından itibaren ise sıcak ve kurak iklim özelliklerinin belirginleştiğini göstermektedir.

Vadinin yerleşim tarihi, Kalkolitik Dönem'den (yaklaşık GÖ 6000) Demir Çağı'na (yaklaşık GÖ 2600) kadar uzanmaktadır. Gelişmiş CBS tabanlı mekânsal analiz araçları kullanılarak, yerleşim örüntüleri ve değişimleri dönemsel olarak incelenmiştir. Kalkolitik Dönem'de (n=13) dağınık yerleşim yapısı, sosyo-politik örgütlenmenin erken aşamalarına işaret etmektedir. Erken Tunç Çağı'nda (GÖ 5000–4000; n=107) beylik benzeri yapılanmaların ortaya çıkışı ile birlikte yerleşimlerin daha kümeli bir yapıya kavuştuğu gözlemlenmiştir. Demir Çağı'nda (GÖ 3200–2600; n=60) ise Hitit İmparatorluğu'nun yıkılması ile birlikte yerleşimlerde yeniden dağınık bir dağılım görülmüştür. Özellikle Erken Tunç Çağı'nda yerleşimlerin, potansiyel tarım düzlükleri ve tuz ile bakır gibi önemli doğal kaynaklara yakın bölgelerde yoğunlaştığı tespit edilmiştir.

Paleoçevresel yeniden yapılandırmaların ardından, peyzaj evrimini modellemek için GrassGIS tabanlı Mediterranean Landscape Dynamics Laboratory (MedLanD) modeli kullanılmıştır. Bu kapsamda, farklı arazi kullanım stratejileri ve iklim değişikliği

senaryoları altında, arkeolojik agro-pastoral toplulukların çevre üzerindeki etkileri (örneğin erozyon ve arazi örtüsü değişimleri) ve bu sistemlerin dayanıklılığı analiz edilmiştir. Model, araştırma alanındaki 206 yerleşim arasında öne çıkan Resuloğlu Höyüğü'ne (MÖ 4300–4100) uygulanmıştır. MedLanD, Resuloğlu'nun arkeolojik gerçekliği, jeomorfolojik evrimi ve sosyo-politik sistem içindeki konumu ile tutarlı sonuçlar üretmiştir.

Bu kapsamda yürütülen ajan tabanlı simülasyonlar, tarımsal, agropastoral ve pastoral geçim biçimlerinin farklı iklim senaryoları altında peyzaj üzerindeki etkilerini karşılaştırmalı olarak ortaya koymuştur. Özellikle %15 daha kurak ve %15 daha nemli senaryolar, geçim stratejilerinin ekolojik sınır koşullarda nasıl farklı sonuçlar doğurduğunu göstermiştir. Kurak koşullarda otlatma baskısı artarken, nemli senaryolarda tarımsal genişleme dikkat çekmiştir. Modelleme sonuçları, sosyo-ekolojik sistemlerin dayanıklılığının yalnızca çevresel faktörlerle değil, aynı zamanda insan topluluklarının karar alma biçimleriyle de şekillendiğini ortaya koymuştur.

Bölgenin badlands karakterli jeolojik yapısı nedeniyle, peyzajın doğal evriminde temel itici gücün yağış olduğu; insan etkili süreçlerde ise kurak iklim koşullarında hayvancılık ve meralardaki biyotik baskı, yağışlı iklimlerde ise tarımsal faaliyetlerin belirleyici olduğu tespit edilmiştir.

Bu çalışma, entegre Coğrafi Bilgi Sistemleri (CBS), uzaktan algılama ve jeomorfolojik yaklaşımlar kullanılarak, Resuloğlu Höyüğü'nün kültürel hafızasının ve mirasının korunarak gelecek nesillere aktarılmasını ele almaktadır. Araştırmada, geniş bir uzaktan algılama veri seti (SPOT 7 uydu görüntüleri ve drone operasyonları), arazi gözlemleri ve uzman görüşlerine dayanılarak GeoWEPP (Coğrafi Bilgi Sistemleri tabanlı Su Erozyonu Tahmin Modeli) uygulanmıştır. Model sonuçları, yoğun erozyon riski altındaki Resuloğlu Höyüğü'nde gerçekleştirilen arkeolojik kazıların höyükteki erozyon süreçlerini tetiklediğini ortaya koymaktadır. Bulgular, Resuloğlu Höyüğü'nün gelecekte ciddi bir erozyon tehdidi altında olduğunu göstermekte ve bu bağlamda yerel yönetimlerin acil koruma önlemleri alması gerektiğine yönelik politika önerileri sunmaktadır.

Bununla birlikte, bu tez yalnızca geçmişi anlamakla kalmayıp, günümüz arkeolojik uygulamalarına yönelik koruma odaklı çıkarımlar da sunmaktadır. Resuloğlu Höyüğü örneğinde gösterildiği üzere, yüksek erozyon riski altındaki alanlarda gerçekleştirilen kazılar, peyzajda geri dönülmesi güç tahribatlara neden olabilmektedir. Bu bağlamda, GeoWEPP modeli ile yapılan analizler, kazı sonrası arazi şekillendirme süreçlerinin doğal drenaj sistemlerini ve yamaç stabilitesini bozarak erozyonu hızlandırdığını ortaya koymuştur. Bu durum, kültürel miras alanlarının korunmasında jeomorfolojik planlamanın zorunlu bir bileşen olarak değerlendirilmesi gerektiğini vurgulamaktadır.

Sonuç olarak, bu araştırma; iklim değişikliği, kaynak kullanımı, yerleşim dinamikleri ve arazi yönetimi gibi faktörlerin uzun vadede nasıl etkileşimli bir sistem oluşturduğunu bütüncül bir yaklaşımla ortaya koymaktadır. Arkeolojik veri setleri, iklim modelleri ve sayısal simülasyonların birlikte kullanıldığı bu entegre metodoloji, gelecekte benzer araştırmalara yol gösterici niteliktedir. Aynı zamanda bu çalışma, sürdürülebilir kazı uygulamaları ve kültürel peyzajların korunmasına yönelik stratejik politika önerileriyle, sadece akademik bir katkı değil, uygulamaya dönük bir rehber işlevi de görmektedir.

Bu tez kapsamında elde edilen bulgular, özellikle sosyo-politik örgütlenme biçimleri, geçim stratejileri, kaynak kullanımı ve uzun mesafeli ticaret gibi ekonomik etkenlerin yerleşim sistemlerinin uzun vadeli evriminde belirleyici rol oynadığını ortaya koymaktadır.

Bu tezde geliştirilen bütünleşik yöntemsel çerçeve—paleoklimatoloji modellemesi, jeomorfolojik analiz, uzaktan algılama, CBS tabanlı mekânsal analiz ve ajan tabanlı simülasyonlar—uzun vadeli insan–çevre etkileşimlerini incelemek için başka bölgelere de uyarlanabilir ve ölçeklenebilir bir yaklaşım sunmaktadır. Özellikle yeterli arkeolojik yerleşim verisi, paleoklimatik proxy kayıtları ve yüksek çözünürlüklü topoğrafik veri setlerine sahip alanlar bu yaklaşımdan fayda sağlayabilir. MedLanD ABM ve GeoWEPP gibi simülasyon modelleri, farklı geçim stratejileri ve iklim senaryolarının peyzaj evrimi, toprak erozyonu desenleri ve yerleşim sürdürülebilirliği üzerindeki etkilerini değerlendirmeye olanak tanır. Bu yönüyle, çalışmada uygulanan yöntemler Delice Vadisi dışındaki karmaşık sosyo-ekolojik sistemlerin analizinde yol gösterici bir şablon işlevi görmektedir.

Farklı bölgelerde uygulanabilirlik için, temel veri setleri arasında coğrafi koordinatlandırılmış arkeolojik yerleşim kayıtları, yüksek çözünürlüklü sayısal yükseklik modelleri (DEM), detaylı toprak ve arazi örtüsü haritaları, paleoklimatik yeniden yapılandırmalar (örneğin CHELSA-TraCE21k, MCM) ile tuz ve bakır gibi doğal kaynakların konum verileri yer almalıdır. Bu veri setleri arasındaki mekânsal ilişkiler, Kernel Yoğunluk Tahmini, arazi tercihi modellemeleri ve yakınlık analizleri gibi CBS tabanlı araçlarla tanımlanmalıdır. Bu bütüncül veri yapısı, gerçekçi ve bölgeye özgü simülasyon ortamlarının inşasını destekler. Uygun biçimde kalibre edildiğinde, bu araçlar farklı coğrafyalardaki eski toplulukların çevresel değişkenliğe nasıl uyum sağladığını anlamaya katkı sunar; böylece bu tezin yöntemsel yaklaşımı, farklı arkeolojik ve jeomorfolojik bağlamlara da uygulanabilir hale gelir.

1. INTRODUCTION

In archaeological research, the dynamic interactions among the landscape, past climate, natural resources, and social organization have always been the source of attention. As civilizations go through environmental crises, they seek mitigating strategies to alleviate the socio-economic problems that stem from natural environmental change or human-induced degradation. Such ecosystemic changes also threaten the complex social systems that we have been constructing. How did past cultures and civilizations that faced similar natural or anthropogenic perturbations deal with these threats? Can we trace these responses from long-term archaeological settlement patterns in a given area? To what extent did the availability of natural resources contribute to the evolution of settlement patterns under environmentally challenging conditions?

In recent years, a growing number of studies from around the world have explored comparable research questions across different archaeological periods by employing a range of methodologies. Examples of these interdisciplinary efforts include paleoenvironmental reconstructions (Sharifi et al., 2015; Zimmerman and Wahl, 2020), investigations into temporal transformations in societal structures (Cullen et al., 2000; Batiuk, 2013), and analyses of the co-evolution of multiple variables to understand human adaptive strategies (Gauthier, 2016; Robinson et al., 2018).

The spatial and temporal scales of these studies differ based on the nature of the datasets and methodologies used. Despite this variation, a unifying aspect of these approaches is the recognition that archaeological evidence captures long-term patterns of human adaptation. These adaptive responses may arise from abrupt climatic changes driven by natural phenomena (Kutzbach et al., 2014; Morin et al., 2018), or from a complex interplay of factors, including human-induced environmental impacts (Büntgen et al., 2016; Flohr et al., 2016; Gogou et al., 2016). Consequently, integrating archaeological data (e.g., surveys and excavations) with the paleoenvironmental data sets and resource distribution allows us to understand how ancient societies might have adapted to changing environmental conditions and the range of impacts these environmental conditions had on the socio-political organization as reflected in the long-term evolution of settlement patterns in a specified region.

This dissertation explores the co-evolution of landscape and human society in the Delice Valley (Çorum) during the Early (11.7-8.3 cal. yr. BP) to Middle Holocene (8.3-4.2 cal. yr. BP). The fragmented nature of the archaeological record from this period limits our ability to fully understand the complex interplay between environmental dynamics and human activity through traditional archaeological methods alone. To address these challenges, this study employs a Complex Adaptive Systems (CAS) framework. The Complex Adaptive Systems (CAS) describe dynamic systems which contain multiple agents that interact while adapting to changing conditions to produce unpredictable emergent behavior (Holland, 1992; Mitchell, 2009). Within this approach, agent-based simulations of land use by agropastoral communities are integrated with dynamic, spatially explicit environmental models developed using Geographic Information Systems (GIS). This methodological integration allows for the modeling of long-term trajectories of the region's socio-environmental systems. As a result, fragmented archaeological datasets, along with the region's natural landscape, cultural organization, and socio-ecological structure, are reconstructed within a comprehensive and systemic framework.

This research focuses on the long-term dynamics of socio-ecological systems in the Delice Valley (north-central Anatolia) during the Early and Middle Holocene, through the lens of complex adaptive systems theory, combining perspectives from landscape archaeology and ecological anthropology. The study uses advanced spatial analysis tools within a GIS framework to examine the settlement history and spatial patterns of archaeological sites in the valley, spanning from the Chalcolithic Period (ca. 6000–5000 cal. BP) to the Iron Age (ca. 3200–2600 BP).

To reconstruct the region's paleoclimate and landscape evolution, the research integrates high-resolution global climate data (CHELSA TraCE21k), Macrophysical Climate Models (Hereafater MCM), and multi-proxy environmental datasets. Based on this reconstructed environmental context, human–landscape interactions were modeled using the MedLanD simulation framework, focusing on the case of Resuloğlu Höyük (4300–4100 cal. BP). The model explores how different climate change scenarios and land use strategies may have influenced the resilience and environmental impact of agro-pastoral communities in the region.

The paleoclimate model and proxy-based paleoenvironmental reconstructions indicate that, in north-central Anatolia, the end of the Early Holocene (11.7-8.3 cal. yr. BP) represents the major paleoclimatic shift from cooler and wetter conditions to warmer and drier conditions. The Delice Valley experienced arid conditions as its permanent climate pattern starting from approximately 6200 cal. BP until the present day. The combination of aridification and the braided river system of the Delice River and human activities in the Valley led to the development of badlands in this region.

This dissertation, using an integrated approach that combines GIS, remote sensing, and geomorphological analyses, focuses on the preservation of the cultural memory and heritage of the Resuloğlu Mound and its transmission to future generations. The research applies the GeoWEPP model by utilizing an extensive remote sensing dataset including SPOT 7 satellite imagery and drone surveys–, complemented by field observations and expert assessments. The model results reveal that archaeological excavations conducted at the erosion-prone Resuloğlu Höyük have triggered significant erosion processes. The findings indicate that the mound faces a serious threat of future degradation, and policy recommendations are proposed, emphasizing the urgent need for local authorities to implement immediate conservation measures.

1.1 Study Area and Regional Settings

The Delice River functions as a major tributary of the Kızılırmak (ancient Halys) which connects north-central Anatolia to the Black Sea (Fig. 1). The Basin contains Pliocene and Quaternary continental clastics as its dominant geological formations. The North Anatolian Fault (NAF) operates as Turkey's biggest strike-slip fault which runs through the northern part of the Basin (MTA, 2016). The research area shows intense tectonic activity while its terrain features a challenging and intricate landscape that has experienced elevation.

A large portion of the gypsum-rich areas, which are particularly widespread in Central Anatolia, are drained by the Kızılırmak River and its tributaries (Akkan, 1970). In this context, the Delice River is the largest tributary of the Kızılırmak. Within the Kızılırmak's extensive drainage basin, the plains of Central Anatolia are primarily drained by the Delice River. According to Erol (1959), the waters of the Kızılırmak and its largest tributary, the Delice River, acquire their physical and chemical properties from the gypsum series through which they have flowed for a long time.

The Delice River's main course and its tributaries originated during the Quaternary period, encompassing both the Pleistocene and Holocene epochs. Elevations within the basin range from a maximum of 2580 meters above sea level to a minimum of 14 meters below sea level. The presence of eroded peneplains at higher elevations highlights the region's geologically complex and dynamic evolution. Broad flatlands are predominantly found in the central section of the basin, to the east of Çankırı Province (Figure 1.1). The region has a continental climate dominated by northerly winds. According to the empirical data from Çorum Meteorology Station, located in the central part of the basin, the annual average temperature is 10.7 ◦C and the annual total precipitation is 441 mm based on the 2023 observations of the State Meteorological Service of Türkiye. This study primarily focuses on the lower reach of the Delice River (Figure 1.1), an area characterized by broad agricultural terraces, concentrated salt and copper deposits, and a meandering, slow-flowing river system. These features consistently made the region attractive for prehistoric human settlement.

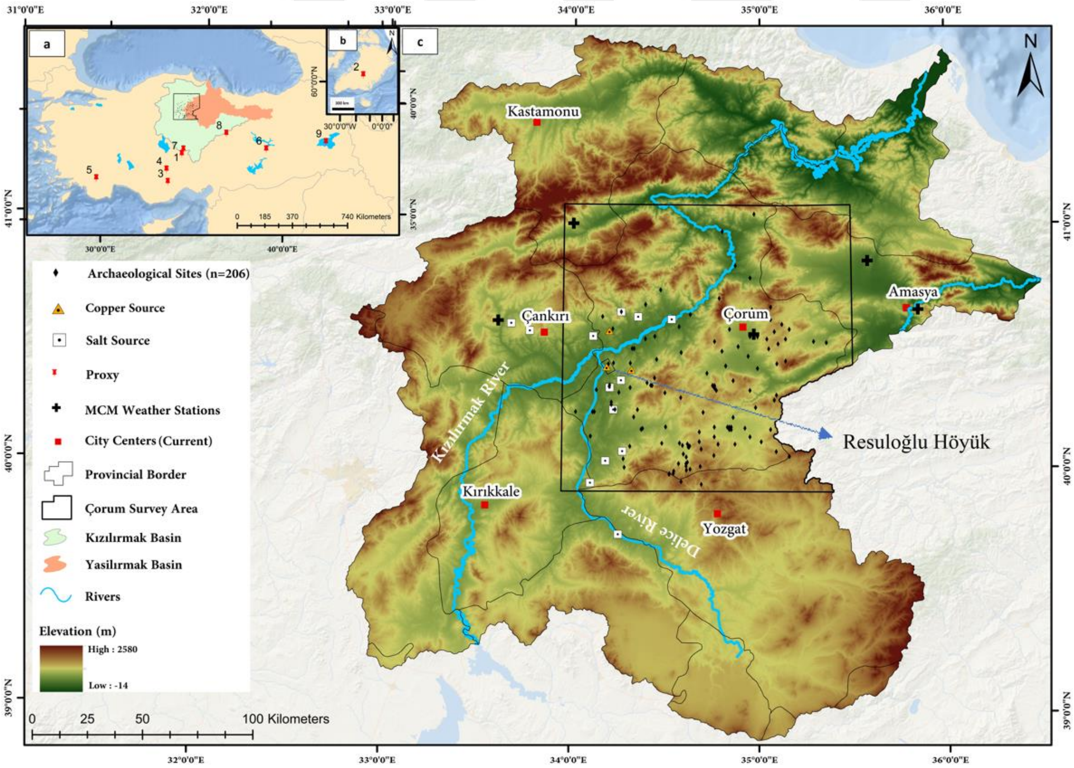

Figure 1.1: a) Location of the study area with basin borders and proxy points. b) Map of Greenland and GISP2 Ice core sample. c) Digital elevation map (5 m resolution) of Delice Basin with the archaeological sites (n = 206) and the meteorological stations (bold plus sign) used for the Macrophysical Climate Model. Copper sources are indicated by orange triangles and white squares represent salt sources in the region.

1.2 Purpose of the Dissertation

This dissertation investigates human-environment interactions in the Delice Valley from ca. 6000 to 2600 cal. BP by examining economic aspects. The research investigates how anthropogenic impacts together with shifting paleoclimatic conditions affected surface processes and societal structures including community organization and subsistence strategies and adaptation through detailed temporal and spatial analysis. The research implements agent-based modeling as a method to model these complex interactions.

The Holocene period, which began around 12,000 cal. BP, presents significant challenges in distinguishing the effects of climate change from those of human-induced geomorphic processes. The effects of climate change and human activity create complex interactions through multiple feedback mechanisms that strengthen each other. Knox (2001) points out that efforts to separate human influences from natural changes often fail to generate useful or significant findings. This research adopts a socio-ecological systems framework to emphasize the continuous and dynamic interdependence between human communities and their environmental contexts.

This study uses agent-based modeling (hereafter ABM) to study the relationship between human actions and landscape evolution. It explores how ancient communities adapted to climatic variability and changing land-use patterns by studying their environmental impact and resilience. The simulated results are evaluated against limited archaeological records to identify extended patterns. The research aims to establish how landscapes and societies developed together through an integrated perspective. By linking past and present, it also seeks to inform sustainable excavation strategies and promote the geomorphological preservation of vulnerable cultural heritage sites such as Resuloğlu Höyük.

1.3 Hypotheses and Research Questions of Thesis

This dissertation explores the long-term socio-ecological dynamics of the Delice Valley (north-central Anatolia) between 6000 and 2600 cal. BP, from the perspective of complex adaptive systems theory (CAS). It adopts an interdisciplinary approach supported by high-resolution spatial and temporal datasets and multiple lines of environmental and archaeological evidence.

The first research question investigates the general climatic structure of the Early and Middle Holocene in the Delice Valley and examines whether abrupt climate shifts known from the Near East—such as the 8.2 and 4.2 ka events—can be identified in this region. The hypothesis is that Abrupt climate events such as the 8.2 and 4.2 ka shifts had measurable and regionally specific impacts on the Delice Valley, which can be detected through high-resolution climate modeling, proxy data, and geomorphological evidence. This hypothesis assumes that the Delice Valley did not remain climatically isolated during the Early and Middle Holocene and that regionally significant climatic events left discernible traces in the valley's paleoenvironmental record. It posits that a combined approach—using mesoscale climate models (MCM, CHELSA), published multi-proxy data, and local geomorphological indicators—can reveal evidence of these shifts and their environmental consequences at a valley scale.

The second question focuses on the relationship between environmental change and socio-political organization. It examines how climate-driven transformations in the physical landscape may have influenced the forms and hierarchies of past communities in the Delice Valley. The central hypothesis is that hierarchical political formations likely emerged during climatically stable and agriculturally productive phases, while heterarchical or less centralized/socially more flexible structures developed under environmentally unstable conditions characterized by dispersed and flexible subsistence strategies. This hypothesis is tested through spatial analysis of settlement distributions using GIS-based statistical tools such as Average Nearest Neighbor and Kernel Density Estimation, which help identify clustering or dispersion patterns in settlement systems over time.

The third question addresses the impacts of land use practices on the natural landscape and the extent to which agricultural methods introduced in the Early Holocene contributed to anthropogenic change. Hypothesis states that; Agent-based modeling can evaluate and simulate how different agropastoral land use intensities between extensive and intensive systems create unique landscape changes and erosion patterns. The proposed hypothesis shows that extensive land use practices including low-density grazing and fallow-based agriculture cause gradual landscape changes which spread across space but intensive land use practices with continuous cultivation and high stocking rates create localized severe anthropogenic changes that result in accelerated erosion and soil degradation. The MedLanD ABM framework enables researchers to assess human-caused transformations against natural geomorphological processes through simulations that compare different land use intensity scenarios.

MedLanD ABM, developed by Arizona State University which runs natively in GRASS GIS. Two key modules—r.landscape.evol and r.agropast.adaptive—are used to simulate agropastoral production at varying levels of intensity while calculating and mapping natural erosion processes. Consequently, the results of ABM simulations reveal the combined effects of human land use decisions and environmental dynamics. The testing of this hypothesis also reveals the resilience of communities (i.e., sustaining their populations through different subsistence strategies) and how human activities influenced erosion and land use changes across multiple scenarios. MedLand has proven to be highly effective in previous studies, successfully modeling complex socio-ecological interactions and landscape transformations over time.

The final component of this research seeks to identify appropriate conservation strategies for erosion-prone archaeological sites, with a specific focus on Resuloğlu Mound. Situated in a geomorphologically fragile region dominated by highly erodible badlands, Resuloğlu appears to be under increasing threat due to both past land use and modern archaeological excavations. The hypothesis tested here is that grazing-related biotic pressure in the modern era and excavation activities have contributed significantly to local erosion dynamics. To assess this, the GeoWEPP model is employed. The ultimate goal is to generate site-specific management recommendations that can guide archaeologists and local authorities in protecting vulnerable cultural heritage under current and future environmental conditions.

1.4 Scientific Contributions and Impacts

It is now well established that the expansion of agriculture during the Middle Holocene significantly transformed the natural landscape in Anatolia (James, 2013). However, the relationship between the scale of agricultural practices and the magnitude and timing of their environmental impacts remains poorly understood (Marsh and Kealhofer, 2014). This research combines paleoenvironmental records with archaeological evidence from the Delice Basin to analyze extended human-environment interactions across time. This research uses long-term coupled socio-ecological systems perspective to present new data which demonstrates how Delice Valley settlement patterns relate to climate change and anthropo-geomorphic processes in surrounding regions. The research uses human beings as agents of geomorphic change to develop a distinctive method for understanding human-caused effects on surface processes. The use of computational science methods in the social sciences—particularly in archaeology and history—is a relatively recent development (De Marchi, 2005). The research combines regional settlement records with basin geomorphology to build detailed landscape evolution models that demonstrate environmental changes and settlement system interactions throughout time.

The GIS applications in archaeological research across Türkiye exist at a low level of adoption. The technical requirements and quantitative reasoning needed to use GIS have prevented the tool from becoming standard in Anatolian archaeological practice. The study employs GIS to analyze settlement patterns in the Delice Valley through spatial and temporal methods, which makes it stand out from traditional archaeological approaches.

In summary, this dissertation examines the evolution of coupled socio-ecological systems from past to present through the lens of complex systems theory. The research uses high-performance computer-based agent-based ABM method to combine extensive and varied datasets. By drawing extensively on GIS and geomorphological science, the study models the spatial and temporal dynamics of socio-natural interactions. In doing so, it offers original contributions—both theoretical and methodological—to the disciplines of archaeology, history, environmental sciences, and geography.

1.5 Organization of the Dissertation

This dissertation is structured in chapters to match its multidisciplinary orientation and diversity of methodology. Every chapter begins with an introduction outlining the scope of the subject and concludes with an account of key conclusions. In total, nine chapters constitute this dissertation.

Chapter 2 establishes the archaeological context of the Anatolian Peninsula in the Early to Middle Holocene. With an emphasis on socio-political development and organization forms of archaeological communities—both in overall Anatolia and in particular within Delice Valley— it is sought to construct theoretical apparatus for interpreting such processes. In so doing, Chapter 2 ultimately examines and seeks to analyze the position and importance of the Resuloğlu Mound in relation to such larger changes as well as enhance available data's spatial and temporal resolution for this site.

Chapter 3 applies GIS-based geostatistical methodology to examine in detail the intricate interrelation of landscape and society. With its conclusions and hypotheses set out in the last chapter as its foundation, Point Pattern Analysis is used in this chapter to determine in what ways and under what circumstances GIS can be used in archaeological research. Chapter 4 is concerned with paleoenvironmental reconstruction. The introduction of datasets and methodology for reconstructing former environmental conditions and describe how such input—derived from paleoenvironmental and geoarchaeological research in the Delice Valley—was prepared and incorporated into the MedLanD modeling system.

Chapter 5 discusses the natural resource potential in the Delice Valley, particularly salt and copper deposits. This chapter discusses how these commodities were utilized, in what ways settlements were organized around them, and how exchange of those commodities might have influenced interaction zones and exchange networks in the area. Chapter 6 presents agent-based modeling methodology and its foundational principles. Subsequently, an in-depth description of MedLanD has been provided. In this chapter, various simulation experiments for simulating various climate scenarios and different land-use strategies (subsistence strategies) were tested based on how such dynamics occurred in and surrounding Resuloğlu Mound.

Chapter 7 discusses long-term landscape evolution, influenced by natural processes and human activities. In the area surrounding Resuloğlu Mound, the sequence of landscape changes over time has been documented, along with geomorphology-based recommendations for the conservation of cultural remains and the management of at-risk archaeological sites.. Chapter 8 synthesizes the research questions and hypotheses in the context of a complex socio-ecological systems approach. Based on the insight and outcome of the foregoing chapters, this chapter presents a comprehensive assessment of landscapes and human societies' co-evolution over extended temporal periods.

In chapter 8, the focus is on the geomorphological disturbances caused by archaeological excavations at Resuloğlu Höyük and how these activities have accelerated erosion processes. High-resolution datasets—including SPOT 7 satellite imagery, digitized 1990 aerial photographs, drone data, and daily excavation records—

were integrated to run soil loss simulations using the GeoWEPP model under various land use and climate scenarios. The findings reveal that excavation activities, especially in the cemetery area situated on sloped and geologically sensitive terrain, have significantly increased erosion. Based on these results, the chapter evaluates post-excavation landscape changes and proposes conservation strategies such as sustainable excavation practices, site management plans, and GIS-based monitoring systems.

In Chapter 9, all findings, results, and research questions are examined from a relational systems perspective in an effort to understand how the landscape evolved in the Delice Valley throughout the Early and Middle Holocene, and how human influence contributed to this transformation.

2. ARCHAEOLOGICAL BACKGROUND: SOCIO-POLITICAL TRANSFORMATIONS IN NORTH-CENTRAL ANATOLIA

2.1 Chapter Introduction

This chapter focuses on the settlement history of the region and the socio-political organization of its communities over time in the Central Anatolian Plateau with special emphasis on the Delice Valley from the beginning of the Holocene (11.7 cal. yr. BP) to the end of the Middle Holocene (4.2 cal. yr. BP). The aim is to interpret the periodical oscillations in the density of archaeological settlements in the Delice Valley from the perspective of coupled socio-ecological systems. Then, each archaeological period is assessed individually, from the Chalcolithic period (ca. 6000 cal. BP) to the end of the Iron Age (ca. 2600 cal. BP). This chapter also aims to explain the settlement history and environmental conditions of the Resuloğlu Höyük (4300-4100 cal. BP); in particular, why this site was selected for the application of MML ABM experiments.

2.2 Contextualizing the Delice Valley within Central Anatolia

The Central Anatolian Plateau has a rich and deep-rooted history of human settlement, dating all the way back to the Neolithic period—around the beginning of the Early Holocene. However, Delice Valley, a smaller region within this broader landscape, presents a slightly different view.The first clear signs of human habitation do not appear until the Early Chalcolithic period (ca. 6000 cal. BP). This gap in timing raises some important questions. Why was the Delice Valley settled much later than other parts of the Central Anatolian Plateau? To understand this, we need to take a closer look at the unique environmental, cultural, and historical factors that may have shaped the region's settlement patterns.

The earliest Neolithic communities (ca. 10,000 cal. BP) such as Aşıklı Höyük demonstrate the transition to fully domesticated economies (Düring, 2010). Çatalhöyük (ca. 9000 cal. BP) represents the continuum of technological and symbolic achievements in the region (Hodder 2014; 2019). By the end of the Neolithic period (ca. 8000 cal. BP), human groups in the central Anatolian Plateau established a fully sedentary and mainly agro-pastoral way of life in large villages (Sagona and Zimansky

2009; Düring 2010). In the Delice Valley, however, there has been no sign of Neolithic sites. The lack of Neolithic sites may be due to natural and/or cultural formation processes (Binford, 1981; Schiffer, 1996). Natural processes such as alluvial deposition, erosion, or geomorphological transformations could have buried or erased earlier settlements. The Neolithic communities might have stayed away from the valley because of environmental limitations or social preferences about settlement locations, or subsequent human activities might have destroyed previous archaeological evidence (Binford, 1981; Schiffer, 1996).

2.2.1 Emergence of the Chalcolithic (c. 6000–5000 cal. BP)

The Chalcolithic period (ca. 6000–5000 cal. BP, Figure 2.1a) comes with its archaeological problems; very little is known from archaeological settlements about this technologically (e.g., copper metallurgy, architectural techniques, and settlement planning) and socio-politically (i.e., concentrated population at fewer number of sites, the first signs of social organization) transformative phase. The only Chalcolithic site that was excavated in proximity to Delice Valley is Çamlıbel Tarlası, which is situated on top of a ridge that overlooks a stream (Schoop 2008; 2010). The excavations revealed pits, slags, and other remains, indicative of seasonal intensive metal smelting and working activities.

The architectural remains at the site revealed several houses with terracing walls, the rectilinear structures were built on stone foundations with mud-brick. The floors showed signs of renewal aside a few courtyards, storage bins, and other installations indicative of the seasonal nature of the site rather than permanent settlement (Schoop 2008; 2009; 2010). Only 13 archaeological settlements associated with the Chalcolithic period have been identified in the Delice Valley. These settlements appear to be randomly distributed across the landscape. They do not exhibit any clear pattern of clustering—either around water sources, natural resources such as copper and salt, or in proximity to one another (Figure 2.1a).

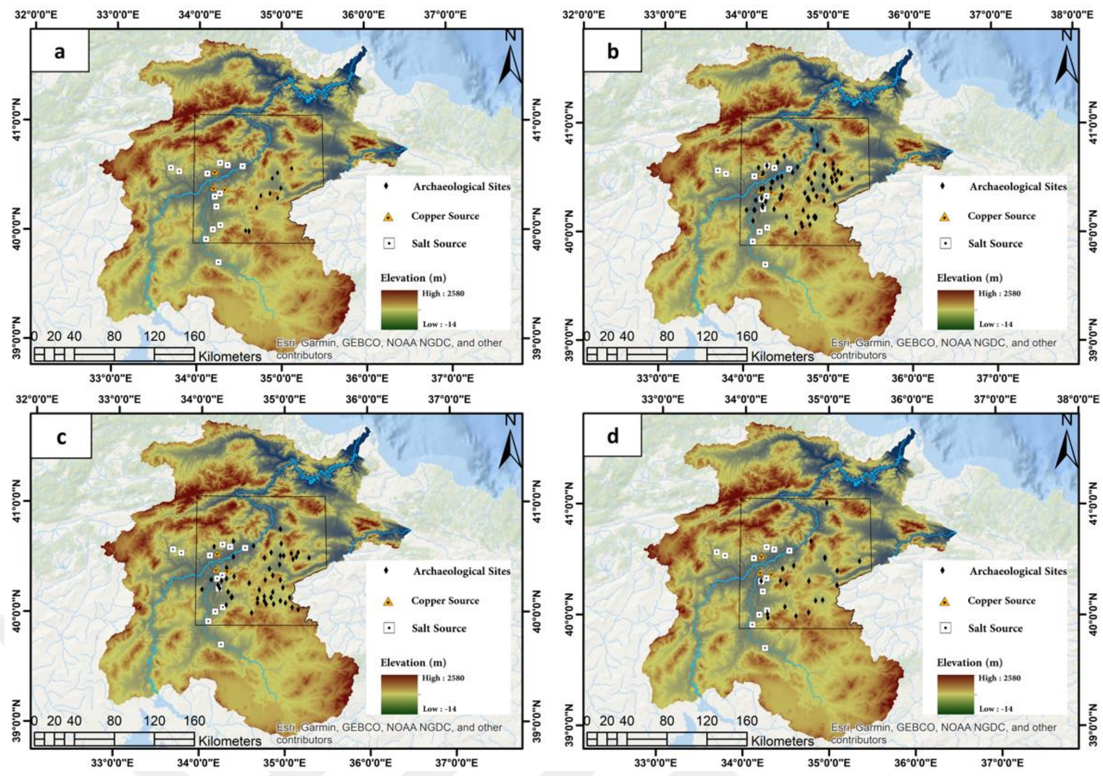

Figure 2.1: Spatiotemporal distribution of settlements, copper and salt, from (a) Chalcolithic (c. 6000–5000 cal. BP), (b) Early Bronze Age (5000–4000 cal. BP), (c) Iron Age (3200–2600 BP), and (d) sites with unknown temporal associations on 5-meter resolution digital elevation model.

2.2.2 Emergence of the Bronze Age (5000–3200 cal. BP)

Early Bronze Age (hereafter EBA, ca. 5200–4000 cal. BP, Figure 2.1b) represents an additional series of transformations for the north-central Anatolian settlements. Metallurgy continued to develop with the onset of alloying arsenic, antimony, tin, and copper while settlement planning and social organization showed further signs of complexity (Dardeniz, 2020). The number of sites increased exponentially (Figure 2.1b). Even though this situation may be attributed to their visibility or, biases in archaeological research design, it is clear that the EBA settlements were higher in number (n=107) and they were widely spread across the landscape (i.e., incorporating diverse landforms). The social complexity reached its peak during the Late Chalcolithic in Mesopotamia with the rise of city-states however, due to topographic, economic, and demographic differences, central Anatolia only witnessed the formation of chiefdoms in the EBA (see Sagona and Zimansky for a comparative assessment for different regions of Anatolia). These central Anatolian chiefdoms exerted some level of centralization over their territories to maintain their access to raw materials and resources while building extensive long-distance trade networks (Dardeniz, 2020). In the research area, the best example of the EBA settlement system is Resuloğlu Höyük (ca. 4300–4100 cal. BP).

By the onset of the Middle Bronze Age (MBA, circa 4000–3500 cal. BP), the Old Assyrian Trading Colonies had become firmly established at numerous locations throughout the central Anatolian Plateau. The circulation of commodities—such as tin, gold, silver, wool, and textiles—along with the transmission of technological expertise, played a pivotal role in the sociopolitical transition from chiefdoms to localized kingdoms. This process also intensified competition among these emerging polities as they sought to secure greater portions of the wealth brought in by Assyrian merchants. By 3800 cal. BP, the competition among these local kingdoms led to a series of conflicts, which coincided with an Indo-European group entering north-central Anatolia. The newcomers found a political vacuum in the region, and subdued the rival kingdoms, establishing the Hittite Kingdom around ca. 3650 cal. BP, which evolved into the Hittite Empire (ca. 3450 cal. BP) that controlled much of the Anatolian Peninsula as well as northern Levant and northern Syro-Mesopotamia until its collapse around the end of the Late Bronze Age (3200 cal. BP). Hattusha (Boğazköy) is arguably the best site in the research area, exemplifying the socio-political changes in the Middle and Late Bronze ages.

Boğazköy started as a hilltop Chalcolithic settlement that overlooks a spring, which expanded during the Early Bronze Age and it was integrated into the Old Assyrian Colony trade system in the MBA. With the arrival of the Indo-European group and their intermingling with the local population, also known as Hatti, Hattusha became the capital of the Hittites. The expansion of the site, its elaborate fortification systems, the urban sprawl around the site, multi-tiered settlement hierarchies, sectors of the site with specialized functions such as temples, workshops, and other elements all point to increasing complexity and the peak of centralized administration in north-central Anatolia during the time of the Hittites (Seeher 2002). The end of the Late Bronze Age (LBA hereafter, ca. 3500–3200 cal. BP) in the eastern Mediterranean brought chaotic events that destabilized the Hittite, Egyptian, Assyrian, and Mycenean empires. Although the exact pattern remains unclear, these major powers of the region were in turmoil and eventually, the Hittite and the Mycenean empires came to an end by 3200 cal. BP (Manning et al. 2023).

2.2.3 Emergence of the Iron Age (3200–2600 cal. BP)

The collapse of imperial systems during the Late Bronze Age led to the formation of local kingdoms during the Iron Age. The north-central Anatolian region experienced minimal central control which resulted in settlements that focused on particular land features while adopting self-reliant farming and ovicaprid herding practices during the first half of the Iron Age (ca. 3200–2600 cal. BP. Figure 2.1c). This phase represents a temporary disruption in the long-distance trade networks of central Anatolia as local kingdoms attempted to reconstruct the political system in the region. In the research area, Resuloğlu reflects the changes that took place during the Early Iron Age. Resuloğlu was re-settled after it was abandoned at the end of the EBA. Iron Age re-settlement was ephemeral at this hilltop site; as a single row of stone foundations with a mudbrick superstructure and small habitation units organized around a central courtyard (Arıkan and Yıldırım 2018). A similar situation also emerged at Hattusha where the settlement shrank considerably in size and its character changed from an imperial capital to a local town.

2.3 Resuloğlu Mound

Resuloğlu Mound, an Early Bronze Age-III settlement (ca. 4300–4100 BP) located in north-central Anatolia, at the junction where Delice River meets Kızılırmak River (ancient Halys) (Figure 2.2a). The site, inhabited by a farming community, lies in a semi-arid badland topography. Resuloğlu offers an ideal case for studying how past communities interacted with and adapted to their environment, especially under changing climate conditions. The settlement and cemetery are the two primary components (Figure 2.2c) of the site, currently divided by a valley formed by extensive erosion.

Erosion has been one of the primary threats to the Resuloğlu Mound and its immediate surroundings, both in ancient and under modern time conditions (Figure 2.2b). In this context, the future of the site is at considerable risk. One of the key motivations of this study is to understand the past and present condition of Resuloğlu primarily from a geomorphological evolution perspective and to contribute to the development of policies aimed at preserving cultural heritage for future generations by providing guidance to archaeologists (how to make sustainable archaeological excavation in erosion-prone areas) and local authorities (how to manage cultural land).

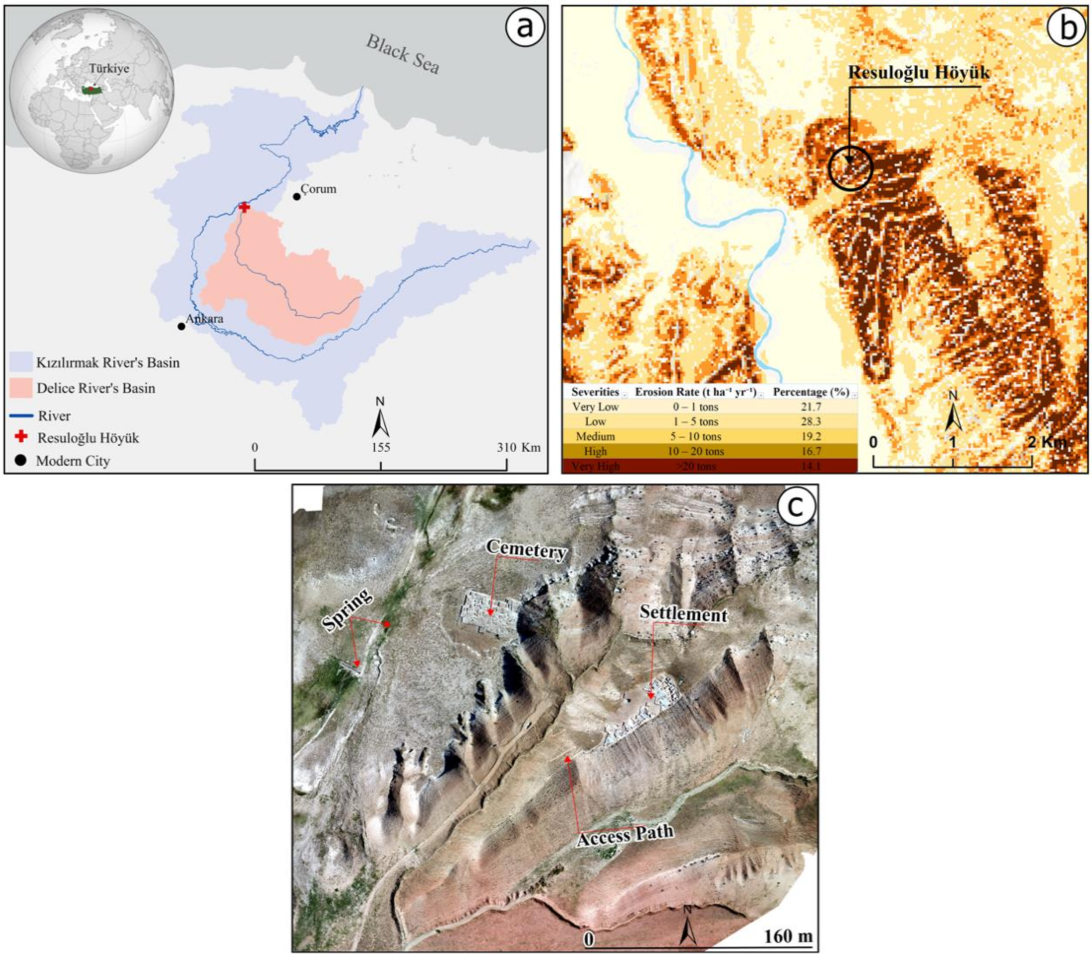

Figure 2.2: a) The location of Resuloğlu Höyük within Türkiye and its position in the surrounding hydrological systems. b) Present-day soil erosion rates in and around the Resuloğlu Höyük, calculated using the RUSLE (Revised Universal Soil Loss Equation) model (30 m resolution; source: GD-CDE, 2023). c) High-resolution (1 m) orthophoto image acquired by drone, showing the Resuloğlu Höyük settlement area and the associated cemetery.

Resuloğlu first came to public attention in the early 2000s, when looters discovered and damaged burials that had been exposed due to severe erosion. In response, the site was placed under official protection in 2003 through a collaboration between Ankara University and the Çorum Museum. Archaeological excavations began the same year and continued uninterrupted until 2019 (Yıldırım & Ediz, 2005, 2006, 2007, 2008; Yıldırım & İpek, 2010, 2011; Yıldırım, 2011a, 2011b, 2012, 2013; Yıldırım et al., 2017).

With its strategic location overlooking the Delice Valley, its architectural layout, and large grain storage facilities, Resuloğlu provides key insights into the socioeconomic structures and political organization of communities in central Anatolia (Dardeniz & Yıldırım 2022). Material culture remains from the excavations indicate that the community maintained cultural and commercial connections with other regions and had easy access to items that reflected contemporary trends (Dardeniz et al. 2021). While numerous metal artifacts were recovered from the cemetery (Figure 2.3a), no evidence of metal production—such as tools or workshop remains—was found in the settlement. This suggests that metal objects were likely acquired in finished form, possibly through a barter economy based on grain. The presence of large-scale grain silos, particularly in the southeastern part of the site, supports this interpretation (Figure 2.3b and 2.3c).

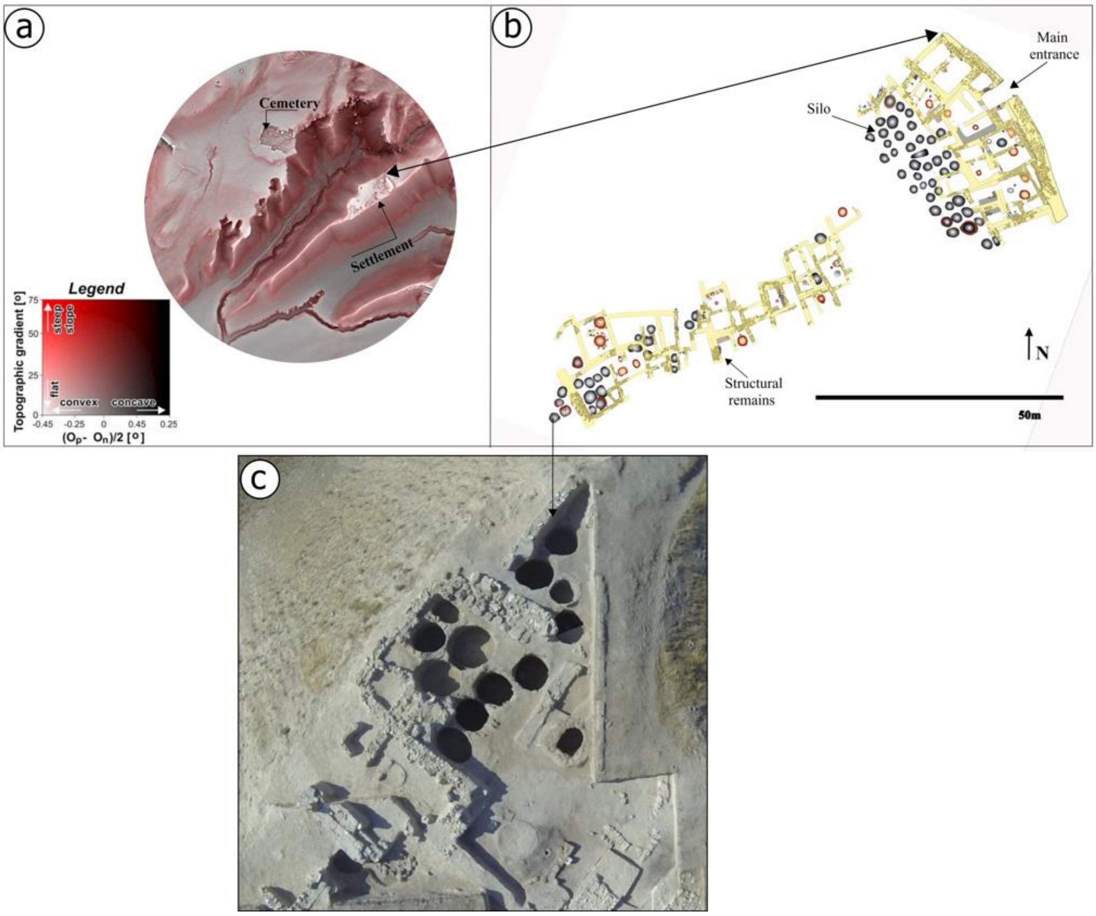

Figure 2.3: a) A 1-meter resolution three-dimensional Red Relief Image map of Resuloğlu Höyük and the associated cemetery area. b) Architectural plan of the settlement area (Source: Resuloğlu Höyük excavation archives). c) Aerial view of the grain silos located at the southwestern edge of the settlement (Source: Yıldırım et al., 2016).

In the northeastern sector of the settlement, architectural remains of 22-room complex—likely belonging to a local elite—have been documented (Dardeniz &

Yıldırım, 2022). This area features a northern gate, fortification walls, segmented residential zones, and several grain silos (Figure 2.3b). Many of the walls are not well preserved because they have been exposed to erosion for a long time.

As in other Early Bronze Age communities, agriculture and animal husbandry were the main subsistence strategies at Resuloğlu. Estimates based on the settlement's size and land use potential suggest that the surrounding environment was suitable for small, self-sufficient yet complex communities. More developed polities—such as regional kingdoms—however, would have required broader and more fertile agricultural lands (Arıkan & Yıldırım, 2018).

The alluvial floodplain of the Delice Valley was one of the most important agricultural zones for the Resuloğlu community. The intensive farming took place at the site as indicated by the presence of 70 well-preserved grain silos, which points to a small-scale economy based on grain storage and exchange (Arıkan & Yıldırım, 2018). Stone tools for grain processing were found in nearly every household, and large communal silos in the central court (Figure 2.3b) confirm the central role of agricultural production in daily life at Resuloğlu.

2.4 Chapter Summary

This chapter gives an overview of the socio-political changes in the Delice Valley and Central Anatolian Plateau from the beginning of the Holocene to the end of the Middle Holocene. It examines the absence of Neolithic settlements in the Delice Valley and tries to understand why the settlements began only in the Chalcolithic period. The known Neolithic sites of Aşıklı Höyük and Çatalhöyük mark early domestication and sedentism in Central Anatolia but there are no Neolithic sites in the Delice Valley, which may suggest some kind of environmental or cultural formation processes that led to this gap. Only 13 settlements have been identified in the valley during the Chalcolithic period (ca. 6000–5000 cal. BP), which are not clustered around water sources, natural resources, or each other. The closest excavated site, Çamlıbel Tarlası, indicates seasonal occupation with evidence of metalworking but lacks permanent architectural features. The Early Bronze Age (ca. 5000–4000 cal. BP) marked a major shift when the number of settlements dramatically increased (n=107). The settlements are now more concentrated around arable lands and key resources like salt and copper. This period saw the rise of more complex social structures and chiefdom-level polities.

Resuloğlu Höyük, a key site from this period, exemplifies these developments. During the Middle Bronze Age (ca. 4000–3500 cal. BP), the Assyrian Trade Colonies facilitated the flow of goods and technology, leading to intensified competition among local kingdoms. This rivalry, combined with the arrival of Indo-European groups, set the stage for the emergence of the Hittite Kingdom (ca. 3650 cal. BP), which later expanded into an empire controlling much of Anatolia and beyond. The Iron Age (ca. 3200–2600 cal. BP) began with the collapse of these imperial systems, ushering in a period of localized political organization. The settlements became smaller and more self-sufficient, reflecting a break from the earlier centralized systems. During this period, Resuloğlu was briefly reoccupied, with small, modest dwellings replacing the earlier monumental architecture.

The chapter concludes with a detailed discussion of Resuloğlu Höyük, an Early Bronze Age settlement located near the confluence of the Delice and Kızılırmak rivers. Its strategic position, abundant storage facilities, and architectural layout provide valuable insight into the economic and political organization of early farming communities. Today, the site faces severe erosion threats, positioning it as a critical case for the development of sustainable archaeological practices and effective heritage preservation strategies.

3 THEORETICAL FRAMEWORK

3.1 Chapter Introduction

The third chapter provides a detailed discussion of the two main approaches that form the theoretical foundation of this research: Landscape Archaeology and Ecological Anthropology. This chapter examines the emergence and development of both frameworks, their core assumptions, the types of datasets they utilize, and the critiques they have received, drawing on key studies and the scholars that contributed to the development of these theoretical approaches. This section also explains why and how these approaches have been adopted within the context of this dissertation.
Both frameworks offer a strong theoretical foundation for understanding the long-term evolution of socio-ecological systems, human responses to environmental changes, and the impacts of human activities on landscapes. In complex and dynamic systems such as the Delice Valley, applying such frameworks is crucial for analyzing the interactions between humans, society, and the environment. This enables a multidimensional and systematic analysis of settlement dynamics, resource use strategies, and landscape evolution, and facilitates a deeper understanding of the defining characteristics of complex adaptive systems.

3.2 The Role of Theoretical Approaches in Understanding Coupled Socio-Ecological Systems

This study examines how human societies and their environments have evolved together over long temporal spans, shaped by dynamic interactions and feedbacks within complex socio-ecological systems. The research combines multiple theoretical frameworks because its multidisciplinary nature requires integrating diverse data sets.

The research combines two integrated approaches which are landscape archaeology and ecological anthropology. The physical and cultural landscapes transform through the simultaneous actions of natural forces and human-made processes (Wells, 2001). The study of socio-ecological systems (SES) requires robust theoretical models to explain human-environment interactions that are complex and dynamic. Landscape

Archaeology together with Ecological Anthropology serve as essential analytical tools to study long-term human-environment interactions and resource management strategies and landscape evolution.

Through Landscape Archaeology, researchers study how past human activities created spatial and material features that result in the ongoing transformation of landscapes across time (Anschuetz, Wilshusen, and Scheick 2001; David and Thomas 2008). Ecological Anthropology on the other hand, investigates how people create adaptive responses to environmental limitations and modifications by establishing systematic connections between cultural and ecological systems (Orlove 1980; Moran 2006). These two complementary approaches provide essential knowledge about how coupled socio-ecological systems adjust to environmental changes through resistance and adaptation mechanisms and transformation processes. Assessing these patterns in the Delice Valley requires integrated theoretical frameworks due to the complex and non-linear aspects of social and natural co-evolution.

3.2.1 Landscape archaeology

Landscape archaeology shows that spaces which include natural features also become culturally shaped meaning-rich social environments through human experience (Tilley, 1994; Ingold, 1993). This perspective encourages us to look past the physical aspects of hills and valleys and pathways by examining how people both interpreted and used and assigned meaning to these spaces throughout history.

David L. Clarke established the theoretical base for this approach through Analytical Archaeology (1968) before Eric Higgs and Grahame Clark developed environmental approaches. According to Clarke archaeology needs to study both environmental data and human activities to reveal comprehensive spatial patterns and settlement dynamics beyond artifact sites.

The research of Christopher Tilley in A Phenomenology of Landscape (1994) built upon existing thought by showing that landscapes should be studied as living environments that contain symbolic value and human experiences in addition to their economic resources. This phenomenological perspective created a major influence on the evolution of landscape archaeology.

The study by Hodder and Orton in Spatial Analysis in Archaeology (1976) introduced essential statistical and GIS-based methods for interpreting archaeological landscape spatial patterns. The framework presents landscapes as active entities which transform through ongoing interactions between settlements and topography and climate and resource availability. In a similar vein, at Delice valley, the GIS-based terrain preference analysis of 206 sites reveals essential information about long-term spatial changes. The Chalcolithic period (ca. 6000–5000 BCE) saw communities primarily residing on ridge-tops before settlement patterns moved to flatlands during the Early Bronze Age (ca. 5000–3200 BCE) and then returned to valley floors during the Iron Age (ca. 3200–2600 BCE). Human communities adapted to environmental changes while their landscape engagement patterns shifted throughout history, as shown by the settlement preference changes.

3.2.2 Ecological anthropology

Through his Theory of Culture Change in 1955 Julian Steward established the foundation for cultural ecology which recommends studying cultures through their environmental adaptations. Steward introduced a fundamental perspective which stated that "environment does not determine people, it conditions them" as a vital yet adaptable replacement for absolute environmental determinism. Roy Rappaport's Pigs for the Ancestors (1968) demonstrated through his research that environmental adaptation depends on rituals and social organization to show the complex ways human societies respond to ecological pressures. Carole Crumley's Historical Ecology method showed how human-environment relationships transform through time by examining multiple temporal levels.

Ecological anthropology shares strong similarities with landscape archaeology because it investigates human-environment relationships as cultural and reciprocal processes. This method based on cultural ecology studies how communities adjust to environmental limitations by developing knowledge systems and making subsistence choices and land-use decisions (Steward, 1955; Rappaport, 1968). The fundamental belief of ecological anthropology states that environmental knowledge exists in a socially constructed form which becomes embedded within shared memories and institutional frameworks (Orlove, 1980; Crumley, 1994). This approach delivers exceptional value for understanding the "resourcescape" concept which explains how communities interact with their natural resources by seeing them managing them and reshaping them (Dardeniz and Arıkan 2025).

The settlement evolution of the Delice Valley during Early and Middle Holocene shows the survival strategies that local communities used to adapt to changing environmental conditions. Researchers found more than seventy storage silos at the Resuloğlu Mound which serves as an example of local adaptation. The structures most likely functioned to provide food security as well as increase resistance to environmental uncertainties especially during times of environmental stress like the 4.2 ka event. The silos demonstrate both sophisticated long-term planning abilities and show how adaptive strategies became integral to social organization systems and collective risk management approaches.

The combination of landscape archaeology and ecological anthropology enables complete understanding of natural and human-caused changes in the Delice Valley. The research uses archaeological evidence together with geomorphological and paleoenvironmental information to establish the Valley as a socio-ecological system that transforms continuously because of human-environmental feedback processes spanning thousands of years.

4 GEOSPATIAL ANALYSES

4.1 Chapter Introduction

The following section details the process of gathering archaeological data and transferring it into GIS for the application of spatial analysis techniques that align with the research questions.

The first step is gathering archaeological settlement data while building the regional archaeological chronology through a systematic evaluation of excavation reports and archaeological conference results and relevant literature. The process sought to include all past archaeological excavations and surface surveys that took place in the study area. A GIS database was prepared which contained all archaeological sites spanning from the Chalcolithic period through the Iron Age. The dataset contained an extensive attribute table for each settlement which included information about location and elevation and settlement type and discoverer(s) and discovery method, and other contextual details. The GIS-based geostatistical analysis methods which were appropriate for the research questions have been identified such as the Average Nearest Neighbor (ANN), Kernel Density Estimation (KDE), and the r.geomorphon (for terrain preferences) module.

4.2 Archaeological Settlements

The analysis relies on data collected through systematic archaeological surveys which two different teams performed in Delice Valley. The chronology system in this study depends on systematic excavations at major archaeological sites including Hattusha where dating methods are supported by solid archaeological textual and scientific evidence. The creation of a regional chronology through typological comparisons between materials from various archaeological projects proved essential for dating the surface finds from survey areas. The first round of Delice Valley surveys was conducted between 1996 and 2010 (Sipahi and Yıldırım, 2000). A total of 206 settlements dating between 6000 and 2600 cal. BP were recorded, consisting of mounds, hilltop sites, and cemeteries. The settlements are distributed over a large area (16.695 km^2).

The second research conducted in the same region by Arıkan, Dardeniz, and Yıldırım (Dardeniz et al., 2021; Arıkan and Yıldırım, 2018) between 2016 and 2018 focused on the past environment, human activities (i.e., agriculture, livestock, and mining), and environmental change. Geological samples aside other empirical data were gathered during this survey. The distribution of the settlements was then interpreted in light of the paleoclimatic conditions and the observed geomorphological changes. The geo-statistical analyses presented here combined settlement data from both surveys. There are 13 (6.3 %) Chalcolithic, 107 (51.9 %) EBA, and 60 (29.1 %) Early Iron Age sites. There are 26 sites (12.6 %) of unknown (Figure 2.1) character due to inconclusive reading of surface materials; these sites are also included in statistical and geospatial analyses below. The assessment will use settlement data and other relevant information (i.e., landforms) gathered through surveys to evaluate long-term changes, resource use patterns, and mitigating strategies.

4.3 GIS-Based Geospatial Analysis (Distribution Pattern)

The research evaluates long-term settlement pattern changes in Delice Valley through geographical information systems and statistical methods. Specifically, the use of average nearest neighbor analysis together with kernel density estimation and r.geomorphons to determine whether each archaeological period displayed distinct settlement patterns. The mapping of geomorphic features to explore if settlements targeted specific landforms was performed. The researchers documented all settlement geological and morphological features together with unmanned aerial vehicle photographs. The project established an extensive database which contains archaeological site information including their boundaries and geological and topographical characteristics.

4.3.1 Average Nearest Neighbor (ANN)

Various methodological frameworks for Point Pattern Analysis (PPA) have been developed to assess whether a given spatial distribution of points arises from a random pattern, forms clusters, or exhibits a regular spatial arrangement (Hartmann et al., 2018). One commonly used method, the Average Nearest Neighbor (ANN), calculates

the distance from each settlement to its closest neighboring point and then computes the mean of these distances to evaluate the spatial arrangement of settlements, ranging from clustered to dispersed. The ANN ratio is obtained by dividing the observed average nearest-neighbor distance by the expected average distance. A ratio below 1 indicates a clustered pattern, while a value above 1 reflects a dispersed distribution (Mitchell, 1999: 88, 90). In ArcGIS, the ANN tool computes five key metrics (Equation, 4): observed mean distance, expected mean distance, nearest neighbor index, z-score, and p-value (Source: Mitchell, 1999, p. 88).
The ANN ratio is given as;

$$ANN = \frac{\bar{D}_O}{\bar{D}_E} \quad (4.1)$$

Where $\bar{D}_O$ is the observed mean distance between each feature and its nearest neighbor.

$$\bar{D}_O = \frac{\sum_{i=1}^{n} d_i}{n} \quad (4.2)$$

And where $\bar{D}_E$ is the expected mean distance for the features given in a random pattern.

$$\bar{D}_E = \frac{0.5}{\sqrt{n/A}} \quad (4.3)$$

In the above equations; d_i is equal to the distance between the features I and its nearest neighboring feature, n corresponds to the total number of features, and A is the area of a minimum enclosing rectangle around all of the features, or any user-specified area value.
The average nearest neighbor z-score for the statistic is calculated as;

$$z = \frac{\bar{D}_O - \bar{D}_E}{SE} \quad (4.4)$$

where

$$SE = \frac{0.26136}{\sqrt{n^2/A}} \quad (4.5)$$

Inferential statistics is primarily concerned with testing the initial hypothesis. This initial hypothesis is also known as “Complete Spatial Randomness” in spatial statistics, i.e., what is the likelihood that this pattern is random, and what is the probability that this probability is random? I use the P-value (a measure of probability) and the Z score (standard deviation) to answer these questions. A P value of 0.01 suggests that the pattern represents a meaningful, not random – pattern with 99 % probability. Z scores indicate how far the result deviates from the mean. Positive Z scores indicate a high rate of aggregation (e.g., hot spots), whereas negative Z scores indicate minimal aggregation (Esri, 2021a) (see Figure 4.1).

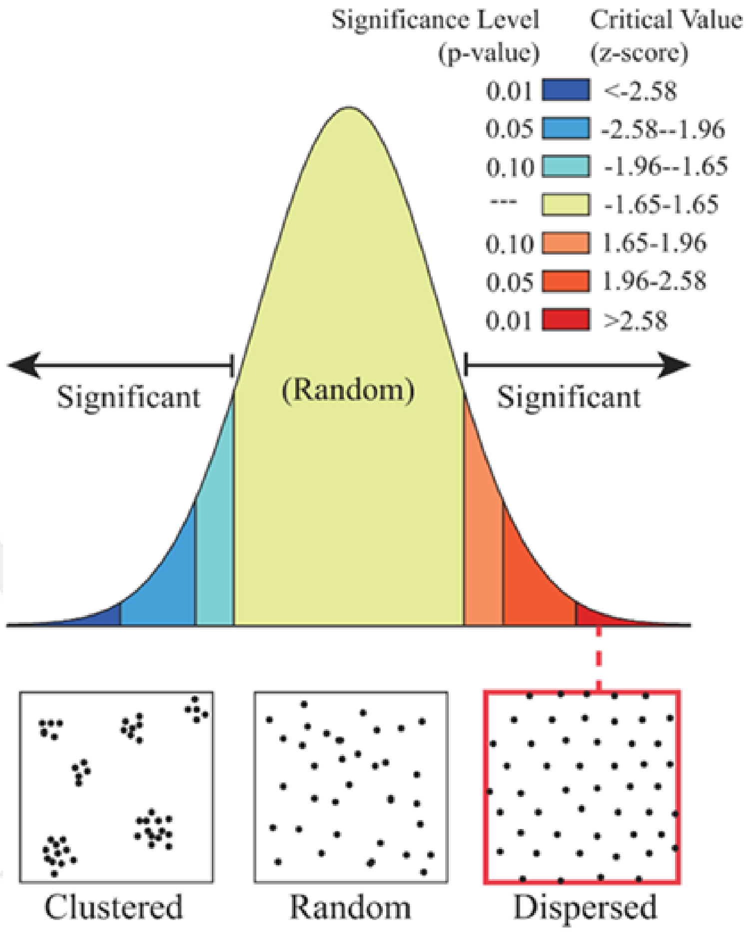

Figure 4.1: The bell curve showing the statistical difference between settlement groups (Esri, 2021a).

4.3.2 Kernel Density Estimation (KDE)

The GIS module accepts vector data as input while producing raster data as output. The point pattern representation through KDE produces intensity levels at different radii which form a flattened output (Baxter et al., 1997, Conolly and Lake, 2006, Carrero-Pazos, 2019, Kempf, 2020). This method determines the size per unit from point or polyline features by fitting each point or polyline onto a precisely tapered surface using a kernel function. The default search radius (i.e., bandwidth) in ArcGIS 10.2.1 and later is calculated based on the spatial configuration and the number of entry points. This method ensures that the search radius is not excessively large by grouping input points based on their proximity to each other. In defining the coverage of KDE, one has to pay attention to the number of points and arrange the scale of analysis accordingly (i.e., use square meters instead of square kilometers if necessary). In most circumstances, the geodetic approach is preferable (Esri 2021b) as this method requires accurate distance and area calculations. Larger search radius values result in a smoother, more generalized density raster. Smaller values produce a raster with greater detail. The default search radius calculation method in ArcGIS 10.2.1 has been enhanced. The kernel density model was applied separately for each archaeological period, and the results were presented by overlaying multiple criteria for each period onto the base topography (Figure 4.2).

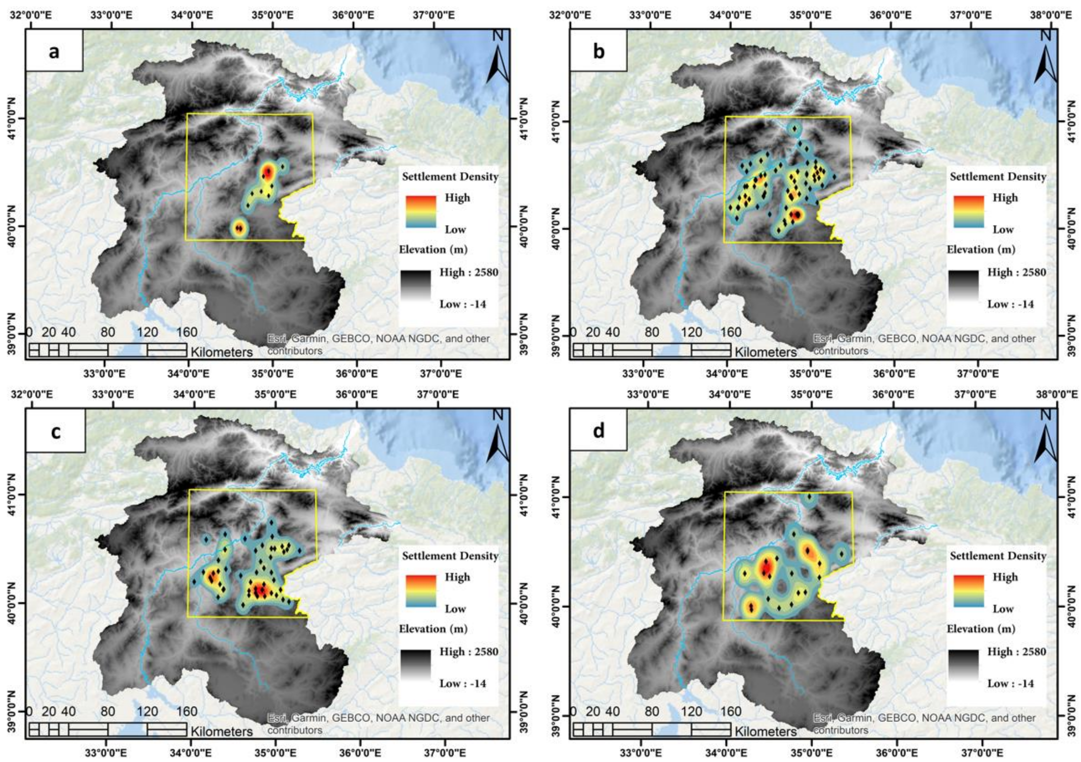

Figure 4.2: Settlement density results of all archaeological periods. The search radius has been adjusted to account for the average distance from the ANN analysis**.**

4.3.3 Terrain preference

This study employs an innovative method for landform classification and mapping. The geomorphon technique, based on pattern recognition, offers a fresh perspective for identifying and categorizing landforms (Jasiewicz and Stepinski, 2013; see also GrassGIS, 2021). The geomorphon method uses a DEM as input and compares the elevation of a target cell in the DEM with surrounding cells along eight compass directions to the maximum search radius, then employs a triplet model to characterize the landform at a target cell location. The pattern originates from a comparison of a focus pixel with its eight neighbors, beginning with the one in the east and progressing counterclockwise by generating a ternary operator. The high position is red, the same position is green, and the low position is blue in Fig. 4. Then, it allocates a geomorphon to each cell in the raster.

The r.geomorphon module operated on a 5-meter resolution Digital Elevation Model (DEM) which came from the General Directorate of Mapping. The resulting data were exported in GeoTIFF format and used to classify the terrain into six (flat, peak, ridge, slope, and pit) distinct geomorphological landform types (Figure 4.3). Then, the settlement dataset was overlaid onto this map and using the Extract Multi Values to Points tool in ArcGIS, the specific geomorphological unit on which each settlement was established.

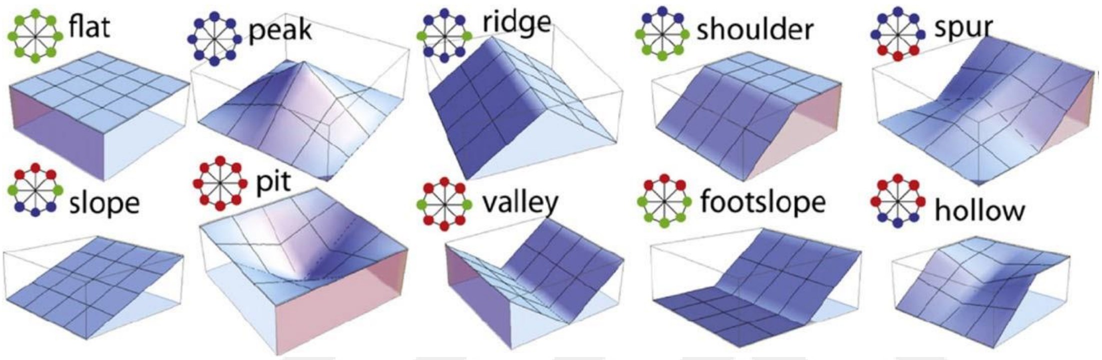

Figure 4.3: The 10 most common geomorphon patterns found in nature and their symbolic 3D morphological representation. Figure after Jasiewicz and Stepinski (2013).

4.4 Chapter Summary

In this section, the study applied GIS-based geo-statistical methods to evaluate the spatial patterns of archaeological settlements in the Delice Valley, ranging from the Chalcolithic to the Iron Age. First, a comprehensive database was created by combining data obtained through archaeological excavation reports, surface surveys and literature review, including information such as the location, elevation, settlement type and exploration method of each settlement.

Three basic analysis methods were selected to examine the settlement patterns: Average Nearest Neighbor (ANN) analysis, Kernel Density Estimation (KDE) and terrain preference analysis performed with the r.geomorphon module. ANN analysis will be used to determine whether the settlements are random or clustered and will reveal settlement densities that change over time. KDE will analyze the spatial trends of the settlement in certain regions by mapping the settlement densities in different periods. The r.geomorphon module, on the other hand, performs morphological classification on the Digital Elevation Model (DEM) at 5-meter resolution and determines which geomorphological units the settlements are located on.

As a result of these analyses, it has been understood how the settlement systems in the Delice Valley evolved in terms of time and space; the effects of environmental conditions, topographic preferences and human activities on long-term landscape dynamics have been revealed. The section provides important contributions to the understanding of the spatial dimension of socio-ecological systems by showing how GIS-supported spatial analyses are an effective tool in the interpretation of archaeological data.

5. PALEOENVIRONMENTAL RECONSTRUCTION

5.1 Chapter Introduction

The current environment exists as a result of extensive human-environment interactions that span thousands of years under different climatic conditions (Ullah, 2012). This chapter presents all available paleoenvironmental datasets recorded to date across the Delice Valley, along with findings from personal field observations, to reconstruct the landscape in which local communities may have lived during the Early and Middle Holocene. Using an inductive approach, the aim is to understand and model the characteristics of the past landscape in the research area. Topography, climate, and land use –particularly vegetation– are key components of the paleo-landscape that are closely linked to archaeological communities and therefore require robust modeling and reconstruction. This chapter outlines the methodology followed to reconstruct the Early and Middle Holocene landscape and evaluates the reliability of these approaches using a broad range of datasets and diverse modeling techniques.

5.2 Paleoclimate Models

Paleoclimate models function as mathematical and physically based tools which help scientists understand past climate systems. The models analyze how the atmosphere interacts with oceans and land surfaces and ice sheets to generate prehistoric climate simulations (Joussaume & Taylor, 1995; Braconnot et al., 2007). The importance of paleoclimatic modeling becomes evident when reliable proxy data are scarce or non-existent because it bridges spatial and temporal gaps to show long-term climate patterns (Harrison et al., 2014). These models use various climate forcings including solar radiation and volcanic activity and greenhouse gas concentrations to study essential climate periods like the Last Glacial–Holocene transition and the Mid-Holocene Climatic Optimum and the 4.2 ka event.

Modern paleoclimate models operate across multiple scales with varying levels of resolution. Large-scale models like General Circulation Models (hereafter GCMs) generate global climate system features yet regional models produce detailed outputs for particular regions which makes them ideal for archaeological and environmental research (Kutzbach et al., 2008; Otto-Bliesner et al., 2016). The recent global paleoclimate research relies on high-resolution datasets including WorldClim (Fick & Hijman, 2017), PaleoClim (Brown et al. 2018) and CHELSA TraCE21k (Karger et al., 2021) which offer various climate variables through open-source access. This research uses two models to reconstruct Delice Valley paleoclimate: the Macrophysical Climate Model (MCM) at synoptic scale (Bryson and DeWall, 2007) and the global-scale CHELSA-TraCE21k model.

5.2.1 Macrophysical Climate Model (MCM)

The research implements the Macrophysical Climate Model (MCM) to synoptically model local precipitation and temperature changes at centennial resolution (Bryson and DeWall, 2007) from the beginning of the Holocene to the late Holocene.
The MCM uses orbital forcing (i.e., Milankovitch Cycles) to calculate heat budgets while it estimates surface albedo from glacier volume and atmospheric transparency through radiocarbon-dated volcanic eruption calibration during the past 40,000 years (Bryson et al., 2006). This model includes periodic changes in major atmospheric circulation systems which include subtropical anticyclones and the Intertropical Convergence Zone (ITCZ) and jet stream which are called centers of action. The model uses algorithms to convert cumulative forcing effects into predicted changes of key climatic variables such as precipitation and temperature and number of rain days at specific meteorological stations across a standard 30-year reference period (e.g., 1960–1990 climate normal) (Bryson and Bryson, 2000; Bryson and DeWall, 2007). The model achieves reliable results through multivariate regression analysis which requires an R^2 value above 0.97 to demonstrate 97% accuracy between observed and modeled variables (Bryson and DeWall, 2007).

5.2.2 CHELSA-TraCE21k Climate Model

The CHELSA-TraCE21k model delivers temperature and precipitation data through GeoTIFF format at 1 km spatial resolution and 100-year intervals from the Last Glacial Maximum (~21,000 cal. BP) to the present. The dataset provides high-resolution data which enables researchers to assess both the direction and intensity of climatic change as well as its spatial distribution. The dataset contains 19 climate variables in raster format across the entire globe from the Last Glacial Maximum (LGM) through to the present day (Karger et al., 2021). The dataset is designed to be easily accessible and compatible with all common data processing tools (Figure 5.1).

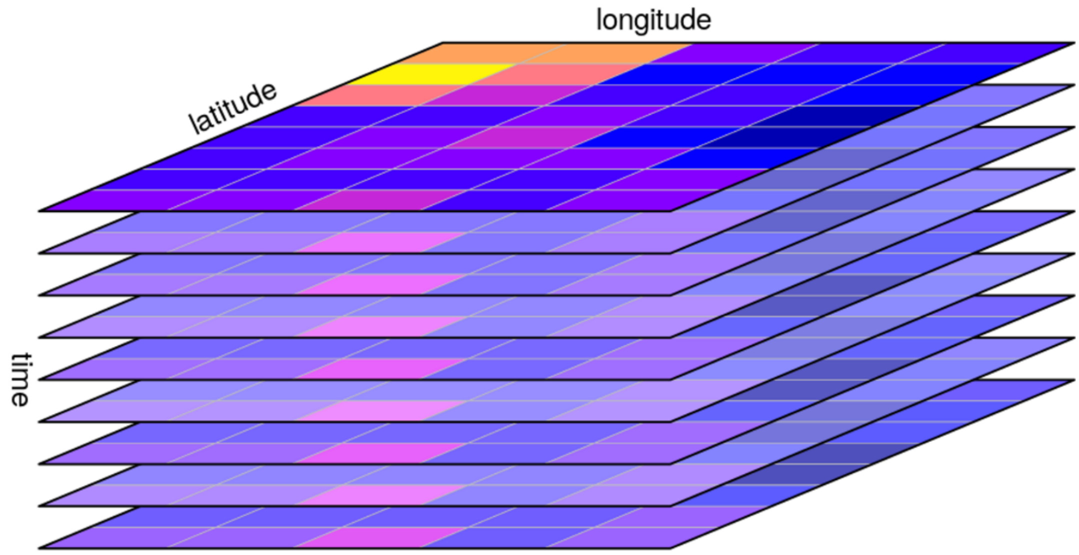

Figure 5.1: Representation of CHELSA-TraCE21k paleoclimate outputs data (GIS Stack Exchange, 2019).

5.2.3 Similarities and differences between the paleoclimate models

The MCM and the CHELSA-TraCE21k climate models differ significantly in terms of their design approaches, areas of focus, spatial resolution, and fields of application. Both models are aimed at reconstructing past climates, but they differ in their methodological frameworks, temporal coverage, spatial resolution, and specific use cases (Table 5.1).

MCM is focused on reconstructing large-scale and long-term climate trends by simplifying complex climate processes to highlight broad climatic changes and general patterns across extensive geographic regions and long time spans. This approach is particularly useful for understanding macro-level shifts and trends within a broad temporal context. In contrast, the CHELSA-TraCE21k model stands out for its ability to produce high-resolution paleoclimatic reconstructions. It integrates the detailed spatial resolution of the CHELSA dataset with the extensive temporal coverage of the TraCE-21k simulations, enabling more nuanced and fine-grained analyses of past climate conditions. This integration allows for the assessment of historical climate dynamics with a much higher degree of precision.

Table 5.1: Comparison of the Macrophysical Climate Model (MCM) and the CHELSA-TraCE21k model.

Variable	Macrophysical Climate Model	CHELSA-TraCE21k
Spatial resolution	Synoptic/regional	30 arc-seconds (~1 km)
Temporal Coverage	40,000 BP-present	21,000 BP-present
Temporal resolution	100-years	100-years
Outputs material	Excel files; variables like temp, precip.	Downscaled raster (GeoTIFF); variables like temp, precip.
Climate variables	Temp, Precip, Radiation etc.	Tmin, Tmax, precipitation, etc.
Purpose and focus		
Application areas	Paleoecology, archaeology, species distribution modeling	Paleoecology, archaeology, species distribution modeling
Modeling framework	Coupled general circulation models (GCMs)	Downscaled from TraCE-21ka + CHELSA V2
Downscaling method	N/A or basic interpolation	CHELSA V2 statistical downscaling (orographic precipitation modeling)
Data accessibility	Climate Data source from meteorological stations.	Opensources; https://chelsa-climate.org
Structure	Complex coupled modules	Downscaled output, not a full coupled model
Strengths & Limitations	Robust for large-scale dynamics; low spatial detail	High-res, spatially detailed, but inherits uncertainties from GCM

5.3 Supra-regional Proxy Records

Local proxy data combined with climate model outputs generates results that increase both accuracy and reliability in paleoclimatic studies. The validation of global climate models depends on large-scale proxy data including ice cores and deep-sea sediment cores and sea-level changes yet these models lack detailed spatial resolution and fail to capture complex local environmental conditions. The failure to detect local environmental complexities presents a significant challenge for archaeological research because microclimatic dynamics play a crucial role. The best approach to understand climate model results requires integrating them with local proxy records within these specific regions.

This research uses paleoclimate model outputs to analyze regional climate change patterns by examining multiple previously published proxy data sets (Table 1). The analysis compares model predictions with paleoclimate records spanning the Holocene period to detect any extrem climate shifts that occurred in the Delice Valley. The GISP2 ice core from Greenland serves as my first analysis because it delivers trustworthy paleoclimatic data for the Northern Hemisphere. The GISP2 record serves as the core selection because the Mediterranean basin exists in a transitional climatic region that experiences westerly winds from the Northern Hemisphere during winter and subtropical anticyclonic belt winds during summer (Bolle, 2003).

The North Atlantic climate fluctuations that affect the Mediterranean region make the GISP2 record suitable for comparison purposes. The second step involves matching model predictions against proxy data collected from different locations on the Anatolian Peninsula which vary in their distance and hydrogeological characteristics from the study area. The comparisons help determine if Holocene abrupt climatic events (e.g., the Bond Events) affected Delice Valley communities and establish a foundation for quantitative and objective interpretations of regional paleoclimatic patterns. Visualization and tabulation of Bond cycles using R packages reveal their patterns in MCM, CHELSA, and proxy datasets, with results presented in the discussion section.

Table 5.2: List of paleoclimate proxy record locations mentioned in the text and references.

Map no.	Site name	Archive	Proxy	Lat.	Long.	Elev. (masl)	Reference
1	Eski Acı Göl	Lake Sediments	$\delta^{18}O$	38.55	34.54	1270	Roberts et al. (2001, 2008, 2016)
2	GISP2	Ice Core	°C	72.61	-38.5	-	Alley (2000)
3	İncesu Cave	Speleothem	$\delta^{18}O$	37.06	33.66	1615	Erkan et al. (2022)
4	Lake Akgöl	Lake Sediments	$\delta^{18}O$	37.63	33.58	1002	Roberts et al. (2008)
5	Lake Gölhisar	Lake Sediments	$\delta^{18}O$	37.11	29.63	930	Eastwood et al. (2007); Roberts et al. (2008)
6	Lake Hazar	Lake Sediments	$\delta^{18}O$	38.47	39.33	1239	Ön et al. (2018)
7	Lake Nar	Lake Sediments	$\delta^{18}O$	38.33	34.45	1369	Dean et al. (2015, 2017); Roberts et al. (2016, 2019)
8	Lake Tecer	Lake Sediments	Grain size	39.25	37.05	1393	Kuzucuoğlu et al. (2011)
9	Lake Van	Lake Sediments	$\delta^{18}O$	38.63	42.81	1648	Roberts et al. (2008)

5.4 Geology and Geomorphology

Through the Delice Valley's extensive badlands topography, Delice River has carved its channel since the Late Miocene-Pliocene period (Doğan & Şenkul 2016). The Early and Middle Holocene landscape evolution of the valley needs understanding beyond past climate changes since it requires thorough examination of geological structure, geomorphic processes and environmental and anthropogenic dynamics.

The Holocene period witnessed the valley's topography transformation through the interaction of climatic fluctuations with tectonic activity and human-induced changes to land use. The Chalcolithic period onwards continuous valley occupation with multiple land-use strategies demands detailed mapping of the Delice Basin's lithology and structural geology and terrain patterns across both spatial and temporal scales.

The valley's micromorphological variation was captured through a combination of GIS, remote sensing techniques, and high-resolution Digital Elevation Models (DEMs) for interpretation. An integrated methodology enables researchers to detect historical land-use patterns and track sediment movements and fluvial system evolution with high precision. The MCM and CHELSA-TraCE21k global paleoclimate models helped evaluate how different climatic conditions and land-use scenarios influenced geomorphological features. The analysis of the valley's resourcescape transformation throughout time becomes possible through this multi-layered and data-rich framework.

The integration of geological and geomorphological data from different disciplines provides complete understanding of both landscape physical evolution and socio-ecological systems evolution throughout time. The research area received geological and geomorphological analysis through assessments of different scales which spanned from basin-wide to fine-resolution mapping at archaeological sites. The study combines datasets of different resolution levels including geological maps and topographic data and paleoclimate reconstructions and proxy records to produce an integrated spatial and temporal model.

The General Directorate of Mineral Research and Exploration (MTA) provided the 1:100,000-scale geological map that served as the primary reference for the entire Delice Basin (see Figure 5.2). The dataset helped to identify major geological units and build a generalized chronostratigraphic sequence of the valley. The geological formations of the Delice Basin extend across time from the Mesozoic to the Quaternary periods, thus demonstrating extensive geological evolution (see Figure 5.2).

The geological structure of the area is primarily composed of Miocene-aged carbonate and evaporite sequences, along with Quaternary alluvial deposits (see Figure 5.3). Gypsum, sandstone, and conglomerate formations from the Miocene have contributed to the development of a badlands-type terrain, characterized by steep slopes, sparse vegetation cover, and high erosion potential. This highly erodible landscape holds significant value for both reconstructing ancient environments and assessing present-day land capabilities.

The research centers on the fluvial confluence located in the lower basin where the Delice River merges with the Kızılırmak River (Figure 1.1). The region experienced multiple prehistoric settlements while serving as an essential settlement center. This area has been selected primarily due to the presence of the Resuloğlu Mound, a key archaeological site that holds significant importance within the region (Figure 5.3). The 1:25,000-scale digital geological maps provided sufficient information for the investigation of Resuloğlu together with its adjacent terrain. The researchers could only produce this level of geological detail for this particular sub-region because high-resolution geological data remain unavailable for the entire basin.

5.4.1 Geological formations

A more detailed geological map was then produced for the lower reach of the Delice Valley, which includes the Resuloğlu Mound (Figure 5.3b). Using the H23a1 geological sheet, the area was mapped at a scale of 1:25,000 to support a focused analysis of landscape evolution in this specific part of the basin.

The geological formations in the lower part of Delice Valley, listed from oldest to youngest, are shown in Figure 5.3b.

İncik Formation (Tomi): First described by Birgili et al. (1975), this unit consists of volcaniclastic and clastic sediments, including tuffite, conglomerate, mudstone, andesite, and shale, often interbedded with pumice and tuff layers. The formation extends across the northeastern sector of the valley along a southeast–northwest axis.

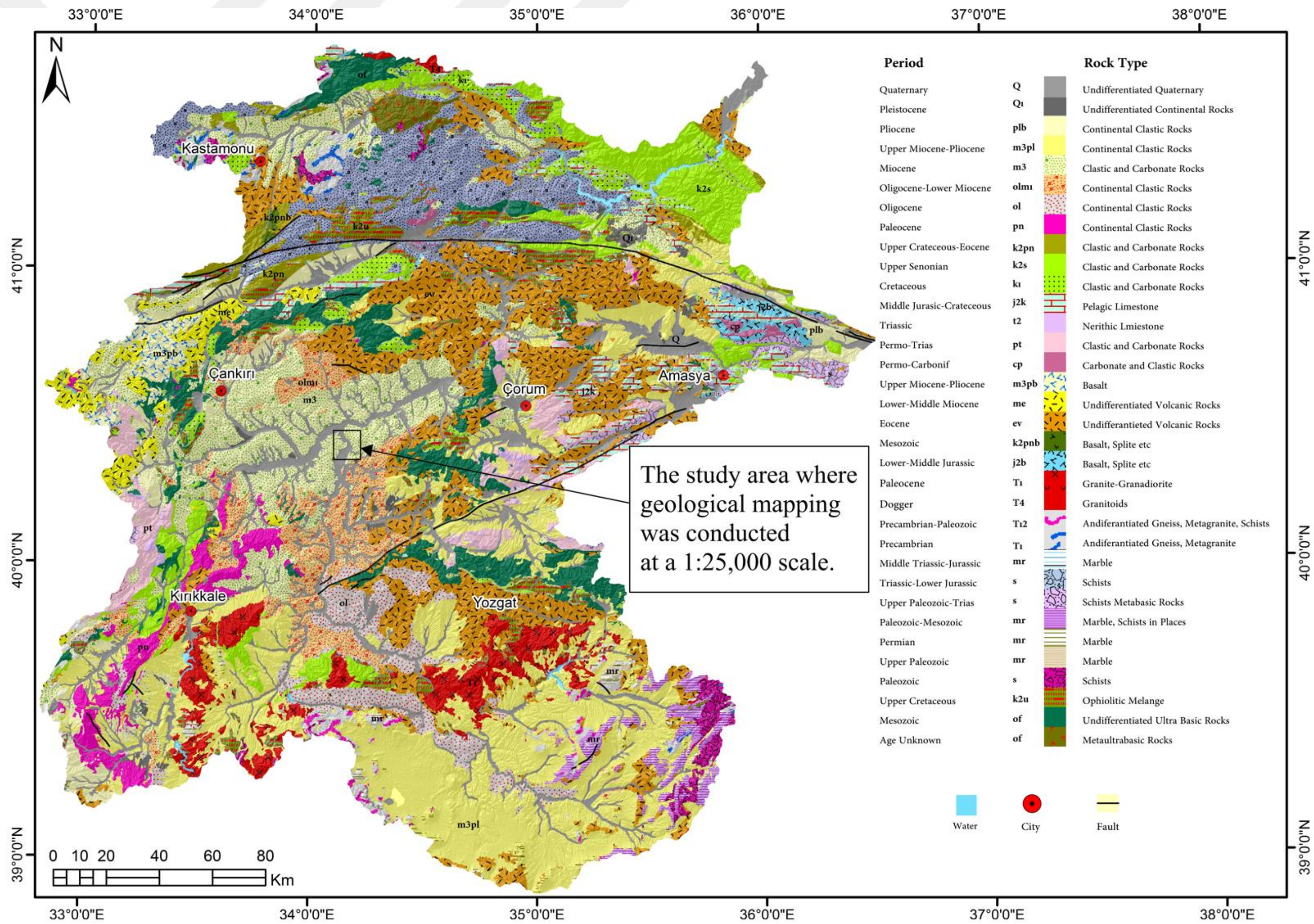

Figure 5.2 1:100,000 scale geological map of the Kızılırmak Basin and its largest tributary, the Delice Basin. The square indicated by the arrow refers to the area covering Resuloğlu and its surroundings, which was mapped at a 1:25,000 scale and is shown in detail in Figure 5.4b.

Resuloğlu Höyük is situated on this unit, lying directly atop the İncik Formation (see Figure 5.3b). The unit has an estimated thickness of 2200–3000 meters (MTA, 2016) and is characterized by medium- to thick-bedded strata with localized angular unconformities.

Bayındır Formation (Tmb): Also identified by Birgili et al. (1975), this formation is composed of gypsum, mudstone, and sandstone sequences. Gypsum dominates the lithology, with mudstone and sandstone occurring as interbeds. The Bayındır Formation conformably overlies the İncik Formation (see Figure 5.3b) and is interpreted as having formed in semi-arid, semi-enclosed basins. The estimated thickness is 600–700 meters.

Kızılırmak Formation (Tmk): Primarily composed of reddish-colored mudstone, conglomerate, and sandstone, with intermittent gypsum and tuff layers, this unit forms the dominant substrate of the valley's western (left) bank (see Figure 5.3b). It is stratigraphically positioned between the Bayındır and Bozkır formations and has a thickness ranging from 80 to 250 meters.

Alluvium (Qal): These are unconsolidated fluvial deposits—comprising gravel, sand, silt, and clay—formed by meandering and braided streams and floodplain processes. They are distributed along the course of the Delice River and represent potential arable land that may have been used by prehistoric agricultural communities (see Figure 5.3b).

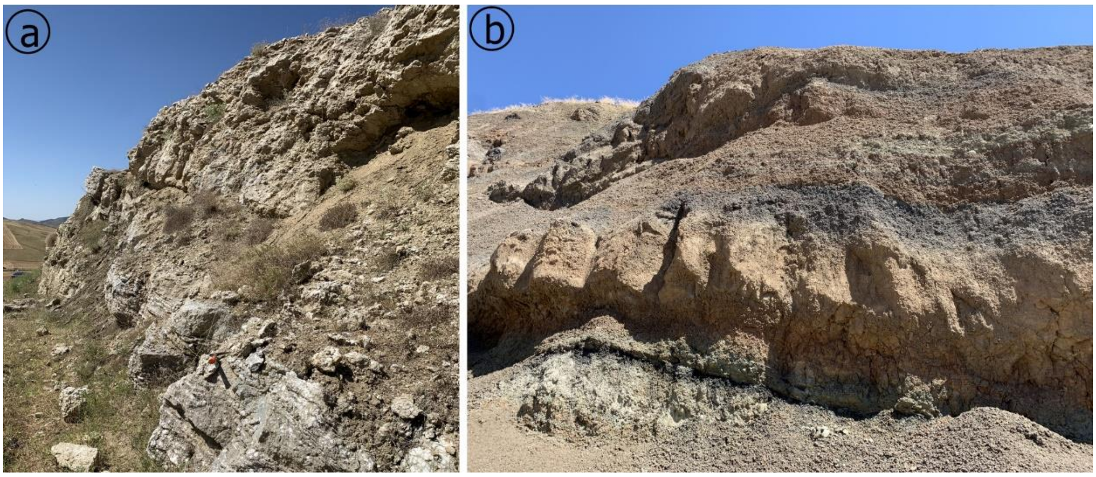

Figure 5.3: Geological formations based on our field observations. a. Gypsum-bearing sequences of the Bayındır Formation from the basin margin. b. Quaternary alluvium deposits in the valley floor. (Photo credit: Emin Çiftçi)

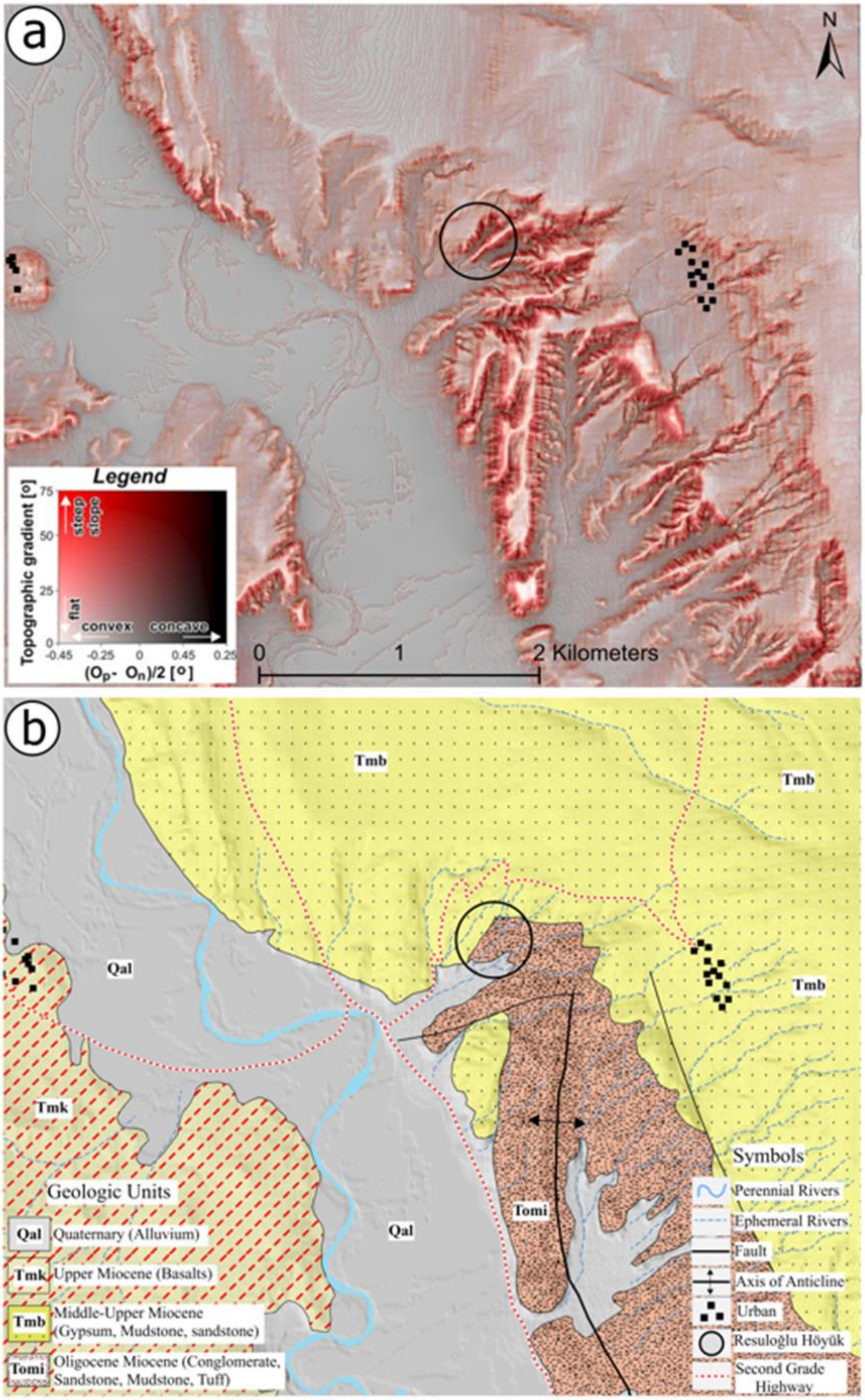

Figure 5.4: Topographic Red Relief Image (RRI, 5 m resolution) and 1:25,000-scale geological map of Resuloğlu Höyük and its surrounding area (Geological data source: MTA, 2016).

5.4.2 GIS-based geomorphometric analyses

5.4.2.1 Red Relief Image Map (RRIM)

Red Relief Image Maps (RRIM) were employed not only to enable the precise delineation of morphological units, but also to better understand the geomorphological context in which archaeological sites are situated. This method specifically addresses and minimizes the visual distortions in three-dimensional depth perception that are often encountered in hillshade and other DEM derivatives (Chiba et al., 2008).

RRIM is based on the I value layer, which is produced by combining a red-toned slope raster with positive and negative openness indices, collectively referred to as the topographic openness.

The I value is calculated using the following formula:

$$I = (Op - On) / 2$$

Where:

- Op (Positive Openness Index) represents the visibility of concave surfaces from a fixed observation point on the landscape.
- On (Negative Openness Index) represents convex surfaces in the terrain.
- I is the resulting raster layer, exported in GeoTIFF format, representing the contrast between concave and convex landforms.

The resulting I value raster is overlaid on a red-toned slope base map in ArcGIS Pro, where transparency settings are adjusted to optimize visual interpretation. This process produces the final RRIM map, the step-by-step creation of which is illustrated in Figure 5.3.

This methodology has been found to be highly effective in geosciences, especially for the detection of geomorphological units, as well as for the identification of the intensity, spatial extent, and orientation of natural or anthropogenic disturbances in the landscape. The main purpose of this method in the current study is to create a clearer and more analytically legible representation of the modern topography in order to gain insights into how archaeological communities may have transformed the landscape over time.

5.4.2.2 Morphometric analyses

The study of archaeological communities' environmental interactions demands thorough analysis of topographic modifications because these physical features directly show past human activities. The material expressions of human–landscape interaction and long-term socio-ecological adaptation strategies appear through anthropogenically altered landforms including agricultural terraces and artificial embankments which were originally created for cultivation and habitation and water management purposes.

A multi-source analytical approach was used to properly detect and document morphological features. The systematic integration of RRIM with supplementary datasets including orthophotos and contour lines and geomorphological unit maps and hillshade renderings was performed. The integration of multiple data layers provided detailed spatial information about landscape morphology which improved the accuracy of feature classification. Through this integrative methodology researchers can both analyze the physical landscape's formal properties and understand how ancient communities transformed their environment through lasting topographic features that demonstrate their environmental adaptation.

5.5 Chapter Summary

The chapter provided a complete reconstruction of Early and Middle Holocene environments in the Delice Valley by using paleoclimate models together with geomorphological analysis and proxy records. Two paleoclimate models—the synoptic-scale MCM and the high-resolution CHELSA dataset—were compared and cross-validated with local and regional paleoclimatic proxies in the Results section.

The geological and geomorphological data combined with basin-wide and high-resolution site-specific mapping allowed researchers to develop a complete picture of the valley's long-term landscape evolution. The RRIM together with morphometric techniques were used to identify terraces and artificial slopes and other anthropogenic modifications of the landscape. The chapter combined multiple datasets to create a detailed paleoenvironmental baseline which supports agent-based modeling and provides insights into settlement dynamics and resilience strategies in the Delice Valley.

6. THE RESOURCESCAPE of NORTH-CENTRAL ANATOLIA

6.1 Chapter Introduction

This section focuses on the utilization of natural resources in the Delice Valley. By examining the geological evolution of the region, it is also possible to understand the potential exploitation of these geological resources. The central goal is to explore the relationship between resource availability, modes of consumption, settlement distribution, and forms of social organization.

Particular attention is given to key raw materials and minerals such as salt, copper, antimony, and clay; how these were used, processed, and circulated by communities within the Delice Basin. The analysis investigates how social organization and economic practices were structured around these resources.

Within this framework, the Resuloğlu Mound serves as a case study to assess the community's access to valuable ores, its role in the trade of prestige goods, and its integration into long-distance exchange networks. In doing so, the chapter aims to reveal how a single settlement's geographic hinterland, resource base, and interaction with broader trade systems contributed to its socio-economic organization and regional significance.

6.2 Resource Distribution

The study of resource distribution patterns provides crucial knowledge for analyzing the organizational structure of archaeological societies and their sustainability and transformation processes. The geological differences combined with transitional environmental areas of Central Anatolia have created fundamental conditions that formed the development and survival methods and settlement patterns of human communities from Neolithic to Iron Age periods. The accessibility of resources across space and time created different cultural development pathways throughout the region.

An analysis of Central Anatolia's geological history serves as a useful guide for assessing its natural resource potential. During the Miocene (ca. 23.03–5.33 million years ago) the region existed as shallow endorheic (A closed drainage system describes a geographic region where waters do not drain into oceans or seas but instead end in lakes, swamps or underground flows) lake environments which were limited to a continental setting. Geomorphological processes combined with tectonic activity transformed this landscape into an open drainage system after its initial closure. The region produced massive quantities of fine-grained lacustrine sediments and evaporitic minerals, especially halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$), which accumulated on lakebeds to form vital mineral deposits.

Active tectonic processes in the region increased the number of available resources. The combination of fault zones and geothermal activity with lithological boundaries enabled hydrothermal processes that created polymetallic ore deposits containing copper, lead, zinc and arsenic. Central Anatolia possesses exceptional exploitable geological resources because of its two major geodynamic features which include evaporitic basins and hydrothermal mineralization.

Prehistoric and historical communities have consistently chosen the shallow lake systems of the Central Anatolian Plateau as their main ecological, economic and symbolic centers because of its enclosed continental lakes and hypersaline marshes and pluvial basins. The lakes produced salt deposits along with sodium and potassium-rich evaporites and gypsum and numerous clay minerals which became vital to the material culture and social activities of the local inhabitants (Erol 1978; Kazancı & Gürel 1999; Kürçer et al. 2012).

The evaporitic environment of these basins allowed the creation of commercially valuable minerals such as halite, gypsum and carnallite ($KMgCl_3 \cdot 6H_2O$) with recorded amounts in Lake Tuz, Lake Seyfe and Acıgöl (Özsayın et al. 2018; Demirbaş 2001). The lakebed clays and wetland clays were essential because they provided materials for ceramics and waterproof construction materials (Courty & Roux 1995).

During the Early Bronze Age evaporites including salt and gypsum proved essential for food preservation as well as livestock management practices. Nomadic and semi-nomadic agropastoral communities spent their seasons in mineral-rich environments by constructing temporary settlements near natural salt licks and saline springs (Vigne et al. 2011).

Clay served as a vital resource, supporting both building practices and a wide range of craft activities. The fine silts and clays from shallow lakebeds and marshes made ideal materials for crafting long-lasting ceramic forms. Petrographic examinations of artifacts from Alişar and Eskiyapar and Resuloğlu sites within the Niğde, Yozgat and Çorum basins show that lacustrine clays were chosen specifically for ceramic production (Whitbread 1995; Arıkan & Dardeniz 2023; Dardeniz, 2023).

6.3 An Overview of the Delice Valley

Delice Valley has rich natural reserves, among which metals and salt are the most significant for the pre- and protohistoric settlers of the region. Copper, arsenic, antimony, and silver are among the available (poly)metallic ores in the area (orange triangles in Figure 2.1).

6.3.1 Salt

Salt plays a multifaceted role in human societies, serving as an essential mineral for maintaining health. It is a key component in the processes of pickling, flavoring, and curing vegetables, fruits, meat, and fish—activities vital for long-term food preservation. Beyond its dietary value, salt has been extracted and exchanged for consumption, utilized in various crafts such as leather production and metalworking, and held considerable ritual significance in the cultural practices of ancient Anatolian communities (Dardeniz, 2023). In north-central Anatolia, rock salt, lacustrine, and spring saltpans are readily available for human and animal consumption and these high-quality salt reserves must have been in use at the Delice Valley as early as 6000 BP. While there is no evidence of centralized control over salt through the EBA in the region, based on cuneiform tablets of the Old Assyrian Colony period, there seems to a limited control over salt to guarantee the amount required for palatial consumption. The trade of salt in low quantities and the presence of professions like 'salt dealer' and 'chief of salt dealer' mirror the monitoring of salt, yet the exact palatial involvement is unknown. During the subsequent Hittite period, the rise of centralized governance led to state control over salt resources (Carnevale and Torri, 2023). Salt is used for leather, wool, and metal crafting and saltpans were controlled and shared between rulers which is related to the animal economy. Animals and secondary products from the animals were one the pillars of Hittite's sustainable economy.

6.3.2 Copper

Rich copper reserves extend toward the Küre Mountains at the western Black Sea coast. There are arsenic occurrences at Durağan (Sinop) and Bakırçay (Amasya). Massive silver and lead deposits in the form of galena were documented nearby –NE of the research area– (i.e., Merzifon/Gümüşhacıköy). Evidence from archaeological, mineralogical, chemical, and isotopic analyses confirms that these metallic resources were already being utilized during the Early Bronze Age (Dardeniz, 2020; Dardeniz and Yıldırım, 2022). Exploitation, trade, and consumption of north-central Anatolian copper continued in the following periods under the control of merchants and palaces as indicated in archaeological and textual records. The ancient site Durmitta situated in north-central Anatolia served as a significant copper and salt source according to Old Assyrian Colony and Hittite textual records.

6.4 Resuloğlu's Role in Natural Resource Utilization and Trade

Resuloğlu is a compelling example of a middle-range society in Bronze Age Anatolia—one where metal consumption, rather than production, takes center stage. The archaeological findings at this site show that every metal artifact came from graves within the cemetery rather than domestic areas during the settlement period. The burial site at the site contained 288 graves and over 400 metal objects (Dardeniz & Yıldırım 2022).

To investigate these materials, Dardeniz and Yıldırım performed portable X-ray fluorescence (pXRF) analysis on 307 artifacts and lead isotope analysis on 45 of them. Remarkably, there is no evidence of metal production at the site—no slag, crucibles, or furnace remains—indicating that Resuloğlu's inhabitants acquired finished or semi-finished metal goods from external sources.

Research conducted by Dardeniz and Yıldırım revealed that Resuloğlu's metal diversity stemmed from non-elite community-level decision making rather than elite-driven centralized control. Instead, it suggests horizontal, community-level decision-making. The lead isotope analysis demonstrates that metals originated from close and faraway locations because the community took part in trading networks that transformed agricultural products into valuable commodities. At Resuloğlu metal functions as an exchange-oriented material as well as a symbolic and ceremonial item which fails to support social inequality. Funerary use of metal artifacts indicates its significance for social rituals while ruling out elite control and practical uses. The wide range of metal sources stretching from Black Sea coast to Taurus Mountains demonstrates Resuloğlu's active participation in elaborate trade networks. Resuloğlu functioned as a socially dynamic settlement which was embedded in a broader landscape of interaction and resource circulation rather than being an isolated village. The site challenges straightforward classification between egalitarian and hierarchical systems. The concept of "middle-range society" provides a precise framework to describe the social dynamics at Resuloğlu since power and resources and value distribution occurred through systems that moved beyond vertical control structures.

6.5 Chapter Summary

This chapter examines the geological processes in the Delice Valley that formed resources and their use by prehistoric and early historic communities. It is concerned with the interaction between the geological evolution of the area, the possible ways of resource utilization and the types of socio-economic systems that were formed around these resources.

During the Miocene, the area was a closed basin where evaporitic minerals such as halite and gypsum precipitated from lake waters. Tectonic activity and geothermal systems then led to the creation of polymetallic ore deposits containing copper, arsenic, antimony and lead. This made Central Anatolia an advantageous location for resource extraction.

Early communities used Lake Tuz, Lake Seyfe, and Acıgöl as shallow lake systems not only for ecological and economic activities but also as symbolic landscapes. The salt, carnallite, gypsum, and clay minerals that were found in these basins were used in food preservation, animal husbandry, ceramic production and construction. Petrographic analysis of Çorum, Yozgat, and Niğde sites revealed that lacustrine clays were deliberately chosen for pottery production.

Resuloğlu Höyük in the Early Bronze Age is unique because it is a society where the consumption of metal goods rather than metal production was emphasized. The excavations produced more than 400 metal items that were found mostly in a cemetery that included 288 graves but no sign of metallurgical production such as slag, crucibles or furnaces was observed. This means that the metals were purchased from other societies.

According to Dardeniz and Yıldırım (2022), the metal use variability at Resuloğlu indicates horizontal, community-level decision-making rather than elite-controlled hierarchical decision-making. Lead isotope data demonstrate that the community had access to both local and distant ore sources, suggesting participation in broad exchange networks through which agricultural surplus could be converted into prestige goods.

At Resuloğlu, metal was not a tool for maintaining social inequality but a symbolic, ceremonial, and exchange-oriented material. The variety of metal sources from the Black Sea coast to the Taurus Mountains shows that the settlement was part of extensive and complex trade networks.

Hence, Resuloğlu cannot be placed in either egalitarian or hierarchical societies. This is particularly appropriate for this study since it describes the complex social structure and material relations observed at the site. The chapter discusses how a settlement's position, resource availability, and integration into the wider trade networks determined its socio-economic status in the region.

7. EXPLORING THE EVOLUTION OF SOCIO-ECOLOGICAL SYSTEMS THROUGH AGENT-BASED MODELING

7.1 Chapter Introduction

This chapter investigates the long-term interactions between archaeological communities and their environment in the context of Early Bronze Age north-central Anatolia, using agent-based modeling (ABM) as an integrative approach. The focus is on Resuloğlu Mound, a middle-range settlement dating to ca. 4300–4100 cal. BP, located at the confluence of the Delice and Kızılırmak rivers (Figure 1.1b). The site is situated within a semi-arid badland landscape, characterized by high surface erodibility and climatic sensitivity—conditions that make it an ideal case study for examining socio-ecological resilience.

The research presented in this chapter builds upon high-resolution archaeological and paleoenvironmental data collected from over 15 years (from 2003 to 2019) of systematic excavation and survey at Resuloğlu. These data were integrated with topographic, geological, and paleoclimatic information through GIS-based tools and process-based simulation. The agent-based modeling platform MML was used to explore the feedback dynamics between land use strategies, surface processes, and population sustainability under different climate scenarios.

Three primary subsistence strategies were simulated: agricultural, agropastoral, and pastoral. Each strategy was evaluated across three climate scenarios: normal, 15% drier, and 15% wetter than baseline conditions. The model outputs were analyzed across multiple variables, including population dynamics, cumulative erosion rates, and land cover variability (measured via the Coefficient of Variation, CV hereafter). These outputs were assessed in terms of both ecological impact and demographic sustainability.

This chapter contributes to a growing body of interdisciplinary research that seeks to understand ancient human adaptation through computational modeling. It also responds to theoretical questions in landscape archaeology and ecological anthropology by addressing how pre- and proto-historic communities organized their subsistence systems in response to environmental and climatic stress. In particular, the chapter highlights the role of rainfall variability—especially in badlands settings—as a critical driver of landscape evolution, and examines how different livelihood strategies modulated this effect through either mitigation or amplification of surface processes. Beyond its case-specific insights, the Resuloğlu simulations provide a replicable framework for evaluating long-term socio-ecological feedbacks and for assessing the resilience of ancient communities. By embedding archaeological knowledge within a formal modeling environment, this chapter advances a methodological bridge between empirical data and theoretical constructs such as complex adaptive systems, resilience theory, and coupled human-natural systems.

7.2 Overview of the Mediterranean Landscape Modeling Laboratory (MML)

The MML represents an agent-based modeling system that evaluates past land use patterns and population dynamics together with environmental consequences across the Mediterranean region. (Barton et al. 2010; Ullah 2013; Barton et al. 2015). The system models natural and social processes in parallel by using GIS-based landscape evolution modules for natural processes and agent-based modeling techniques for social processes (Mayer & Sarjoughian, 2007). The combined methodology creates possibilities to examine long-term human-environment interactions through dynamic analysis.

Agent-based modeling serves as the core social simulation mechanism within MML to analyze the non-linear patterns of complex socio-ecological systems. The framework presents autonomous agents that have decision-making abilities and environmental adaptation capabilities (Lake 2015). Agents interact with each other to produce macroscopic social and environmental patterns through their individual decision-making.

The agent-based modules of MML operate natively in GRASS GIS platform through Python scripts (Mayer et al., 2006). The technical framework enables researchers to modify agent actions dynamically while integrating complex social and environmental elements for scenario testing. The system allows the creation of decision-making models that simulate human behavior responses to different environmental stressors.

This dissertation presents simulation scenarios where each agent functions as an agropastoral household that contains a fixed population size with no internal distinctions between members (Arıkan 2023; Arıkan et al., 2020). Households primarily interact with their environment rather than directly with one another. The interactions produce dynamic models that track population trends alongside soil degradation and vegetation patterns through time.

MML functions as a powerful experimental system to simulate processes while filling gaps in archaeological data and improving historical interpretations through enhanced spatial and temporal precision (Arıkan, 2017). Through its ability to simulate different land-use and climate scenarios MML allows researchers to better understand how past communities responded to environmental change.

7.2.1 Model parameterization and input data

MML operates as a coupled system in which landscape evolution is driven by feedback mechanisms between natural and anthropogenic components (Barton et al., 2015, 2017). It is composed of two main modules: *r.landscape.evol*, which simulates natural surface processes, and *r.agropast.adaptive*, which simulates anthropogenic impacts on land cover and land use. Both Python modules run on the GRASS GIS platform (Barton et al, 2010).

The r.landscape.evol module is a surface process model designed specifically to simulate erosion and sediment deposition based on topography. It is built on the Unit Stream Power Erosion/Deposition (USPED) and Stream Power equations (Mitas & Mitasova, 1998). For each raster cell, it calculates erosion or deposition values by taking into account the two-dimensional variation in surface transport capacity. These values are then applied to the DEM, resulting in a dynamically evolving terrain. In this way, the model is dynamic and produces a new digital landscape (i.e., an updated DEM) at the end of each annual simulation cycle.

The r.agropast.adaptive module simulates village-scale agricultural and pastoral decision-making. The main purpose of MML is to simulate the long-term environmental impacts of human settlement in a rapid yet meaningful way rather than employing complex individual-level agent-based models. Each year, the effects of human activities on the landscape (such as soil loss or vegetation decline) are calculated and passed back to the r.landscape.evol module. This creates a feedback mechanism between human land use and topographic evolution. Together, these components allow the model to simulate a socio-ecological system that evolves dynamically through the combined effects of natural processes and human behavior.

These modules operate annually in a coupled manner. Human activities (e.g., farming, grazing, firewood use) alter vegetation cover and soil properties, which in turn feed into surface hydrology and geomorphology, producing a dynamic feedback loop over simulation cycles (Barton et al., 2015).

The ABM experiments in archaeology focuses on the testing of various hypotheses. The model demands a set of input data consisting of a variety of raster layers as well as parameter sets. The r.landscape.evol module, responsible for simulating landscape evolution, computes erosion and sediment deposition based on a set of key inputs such as topography (Digital Elevation Model – DEM), rainfall erosivity factor (R-factor), soil erodibility (K-factor), and vegetation cover (C-factor). For a complete list of input parameters used in the natural landscape evolution module (r.landscape.evol), see Appendix Table 1A in Barton et al. (2015, p. 599).

For the ABM simulations, the single climatic input was annual mean precipitation (mm/year). These values were obtained by applying the MCM to the study area. The operation of this synoptic-scale paleoclimate model has been explained in detail by Arıkan (2014, 2015) and is thus not reproduced here.

The study area's annual mean precipitation, based on the paleoclimate model, is around 431 mm/year. For the simulation of varied climate conditions, this value was increased by 15% to get 495 mm/year (wet climate condition) and it was reduced by 15% to get 366 mm/year (dry climate condition). The higher values are used for simulation of wet climate conditions, lower values are used for simulation of dry conditions, while the original value is used for simulation of ‘normal’ conditions (Figure 7.1).

The *r.agropast.adaptive* module enables the selection of suitable cells based on village-level agricultural and pastoral needs by activating built-in decision-making mechanisms. MML requires the explicit definition of both agricultural and pastoral catchment areas (Arıkan, 2023). To define these catchments around a known settlement location, the *r.catchment* module is used (Ullah, 2011).

First, a cost surface map was generated using the *r.walk* module in GRASS GIS, which calculates walking costs along the least-cost paths (Figure 7.2a). Then, based on this cost surface and slope threshold values, agricultural and grazing catchments were delineated. Agricultural zones were selected from areas with a slope of less than 10% and located within a 30-minute walking distance from the settlement (Figure 7.2b). In contrast, grazing areas were defined independently of slope and were allowed to extend over much larger distances as ovicaprids are capable to roam the landscape.

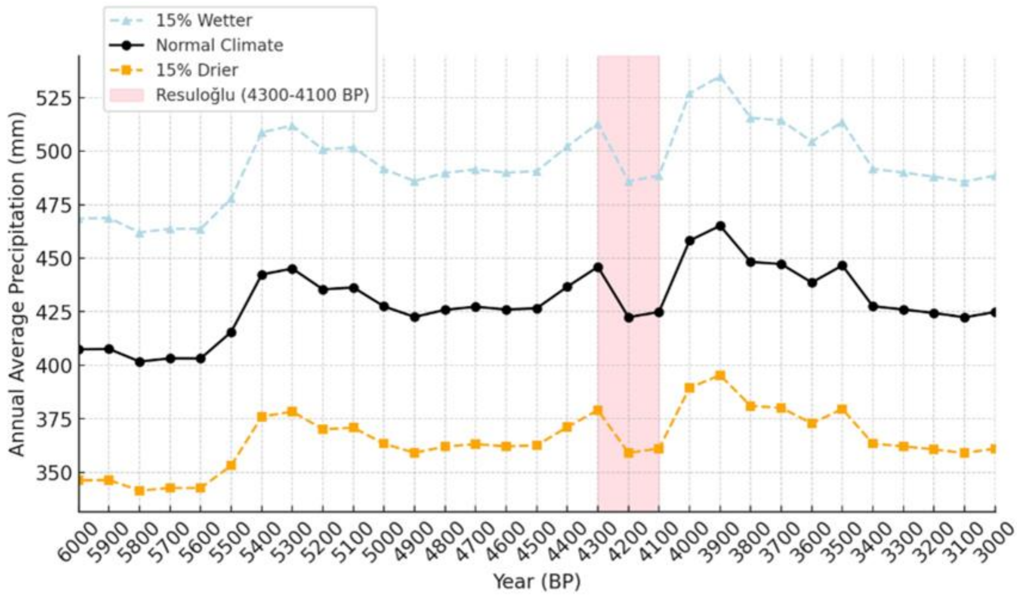

Figure 7.1: Annual average precipitation values (mm/year) are between 6000 and 3000 years before present, based on the Macrophysical Climate Model (MCM). The black line represents the reconstructed annual average precipitation. The blue and orange lines indicate precipitation values increased and decreased by 15%, respectively, as used in the climate scenarios. The pink band marks the chronological timeframe of the Resuloğlu Höyük settlement (4300–4100 cal. years BP).

In MML, population change is calculated at the end of each simulation year based on the caloric gain or loss of individuals resulting from agricultural and pastoral activities. Population is updated annually according to these energy balances. In this study, the initial population was set at 115 individuals, based on previous ethnographic and archaeological estimates (Arıkan & Yıldırım, 2018). This estimate is further supported by archaeological evidence such as the presence of grain storage facilities and communal structures.

The model allows the user to either keep population constant or allow it to change dynamically over time. In all scenarios presented here, population was permitted to fluctuate in response to the outcomes of subsistence strategies and environmental factors. MML calculates the total calories gained from agriculture (based on annual crop yields) and pastoralism (based on herd size) for each individual. After subtracting the energy expended on these activities, a net gain or loss is determined per agent.

Births occur when there is a caloric surplus of 10% or more, while deaths occur when there is a 10% deficit (see Arıkan et al., 2021, Table 2).

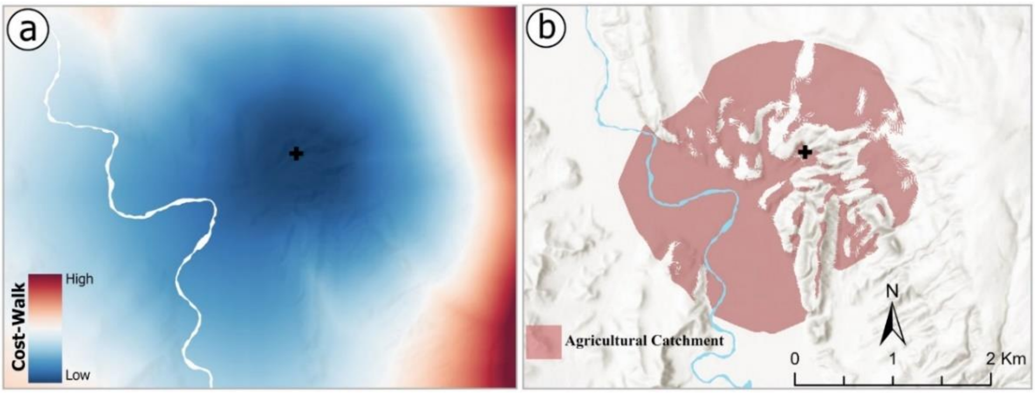

Figure 7.2: a.) Cost-walk (walking cost) map. b.) Agricultural catchment map of Resuloğlu Höyük and its surrounding area. The spatial resolution for both maps is 10 meters.

The vegetation cover was entered into the model as grassland, in accordance with archaeological data (Arıkan & Yıldırım, 2018). Land use / land cover (LULC) changes, which represent anthropogenic impacts, were incorporated into the landscape evolution module as model inputs. For a detailed list of input parameters used in the land use and agent decision-making module (r.agropast.adaptive), see Appendix Table 2A in Barton et al. (2015, p. 601).

7.2.3 Experimental design and simulation scenarios

The experiments using agent-based modeling assess multiple scenarios through repeated iterations to validate the statistical stability of generated patterns. The research examined nine different scenarios (Table 7.1) through three climate types and three subsistence strategies. The ABM experiments underwent 10 iterations for each run. The analysis of all simulation runs showed that results achieved stability during the tenth iteration. The pattern consistency together with output values showed no changes throughout the simulation. The results presented in this study derive from ten iterations per scenario which are shown in Table 7.3. The 200-year-long agent-based simulations conducted at Resuloğlu between 4300 and 4100 cal. BP deliver important findings about how the society interacts with its environment through complex feedback systems.

The model produced outputs which were analyzed through three primary evaluation themes. The model evaluated three main output variables which included population changes across time (2) cumulative erosion-deposition (kg/m²/year) and (3) land cover change through the Coefficient of Variation (CV). The CV value served as an indicator to assess long-term land use sustainability and its effects on habitat diversity and ecological resilience. The research implemented three subsistence strategies which included agriculture and agropastoral (mixed) and pastoral practices (Table 1) under three climate conditions (drier, normal, and wetter) while displaying all associated variables through visualizations and evaluations (Figures 7.3, 7.4, and 7.5).

7.3 Application of MML

In this study, the MML was successfully applied across different subsistence strategies (agricultural, agropastoral, and pastoral) and various climate scenarios (normal, 15% drier, and 15% wetter) to simulate a 200-year period between 4300 and 4100 BP. The model effectively captured the dynamic interactions between human settlements and environmental processes over the long term and served as a powerful tool for analyzing the impacts of each strategy-climate combination on demographic sustainability and environmental outcomes.

7.4 Chapter Summary

This chapter investigates the long-term interactions between Early Bronze Age communities and their environment through an agent-based modeling (ABM) approach, using Resuloğlu Mound in Central Anatolia as a case study. The study integrates high-resolution archaeological and paleoecological datasets—collected from systematic excavations and surveys conducted between 2003 and 2019—into Geographic Information Systems (GIS) and process-based simulation frameworks.

Within the scope of this chapter:

- A detailed database of topographic, geological, and paleoclimatic data specific to the Resuloğlu region has been compiled.
- These datasets were integrated into the Mediterranean Landscape Dynamics Modeling Laboratory (MedLanD) platform, and systematic agent-based simulations were conducted under three different subsistence strategies (agricultural, agropastoral, pastoral) and three climate scenarios (15% drier, normal, and 15% wetter conditions).
- Each experimental run simulated a 200-year period (4300–4100 cal. BP) and was iterated ten times to ensure the statistical robustness of the results.

Table 7.1: Attribute table of the scenarios generated in MML based on combinations of subsistence strategies (farming-to-herding ratio) and climate types

Scenario	Starting population	Subsistence strategy	Percentage (%)	Climate type (avr. ann. precipitation)	Long simulation	Iteration
1	115	Agrarian Economy	80%	15% Drier	4300-4100 cal. BP	10
2	115	Agrarian Economy	80%	Normal	4300-4100 cal. BP	10
3	115	Agrarian Economy	80%	15% Wetter	4300-4100 cal. BP	10
4	115	Agropast Economy	50%&50%	15% Drier	4300-4100 cal. BP	10
5	115	Agropast Economy	50%&50%	Normal	4300-4100 cal. BP	10
6	115	Agropast Economy	50%&50%	15% Wetter	4300-4100 cal. BP	10
7	115	Pastoral Economy	80%	15% Drier	4300-4100 cal. BP	10
8	115	Pastoral Economy	80%	Normal	4300-4100 cal. BP	10
9	115	Pastoral Economy	80%	15% Wetter	4300-4100 cal. BP	10

8. INTEGRATED GIS AND REMOTE SENSING AND GEOMORPHOLOGICAL APPROACHES FOR CULTURAL HERITAGE PRESERVATION

8.1 Chapter Introduction

The chapter examines the historical development of the Delice Valley area with special attention to the Resuloğlu Mound. The main objective of the research aims to understand the role of this archaeological site in forming regional historical memory while developing protection plans for future generations. The chapter provides policy recommendations which assist local governments in their cultural heritage protection and sustainable land management initiatives.

The confluence of the Delice and Kızılırmak rivers creates a geomorphically important setting for Resuloğlu which currently suffers from major erosion problems (Fig.? The site faces dual threats from erosion and archaeological importance which establish Resuloğlu as a distinctive critical research subject. The archaeological excavations from 2003 to 2019 revealed deep architectural features and graves at three-meter depths in the cemetery area. The archaeological excavations disturbed the sensitive geomorphic systems thus making erosion worse and speeding up the destruction of the landscape.

The chapter stresses the immediate need to develop sustainable excavation methods that focus on archaeological sites that face erosion risks. The research discusses various approaches to minimize the erosion caused by excavation activities while maintaining cultural landscapes for extended periods.

With the support of the American Research Institute in Turkiye (ARIT), during my tenure as a visiting doctoral researcher for one year at the National Soil Erosion Research Laboratory (NSERL) at Purdue University, I applied GeoWEPP model to the research area for simulating soil erosion and runoff under different land use and climate conditions.

The GeoWEPP model allows researchers to evaluate current erosion at Resuloğlu and determine how archaeological operations increased erosion while determining the main factors behind landscape deterioration in the site area. This chapter presents work packages which aim to expand knowledge about archaeological intervention effects on geology while creating scientific principles for sustainable cultural heritage management.

The chapter examines the geomorphological development of Resuloğlu Mound throughout different historical periods. This chapter applies the QGeoWEPP model to simulate erosion rates from past to present based on the results of MML discussed in the previous chapter. The resuşts from QGeoWEPP model are important to calculate the excavation-induced erosion acceleration while detecting main erosion generators in the current situation and developing measures for Resuloğlu Mound preservation. This chapter provides specific recommendations for the site's long-term protection which will enable its transmission to future generations.

8.2 Modeling Soil Erosion and Risk Mitigation Strategies in Archaeological Sites: Insights from Resuloğlu Höyük

Five essential steps (Figure 1) are involved in cultural heritage preservation efforts. The first and most essential step is the recognition and understanding of risks that threaten cultural heritage, and the final step is implementation and monitoring of risk mitigation strategies. This chapter emphasizes the need for sustainable excavation methods throughout archaeological research pre-and post-excavation phases. The research aims to address an important knowledge gap about risk by using soil erosion simulations for cultural heritage protection. Soil erosion represents a major geological hazard which affects cultural and natural heritage sites because of climate changes and human activities that modify land use and cover (UNESCO, 2007). Cultural heritage managers can establish preventive measures and risk mitigation methods by identifying archaeological sites that face high soil erosion risks (Polykretis et al., 2021). Geomorphology and geoarchaeology offer tools for site investigations and anthropogenic landscape identification, process identification, heritage assessment and scientific investigation planning (Forti et al., 2023). The development of geospatial technologies such as GIS and spatial modeling techniques in the last three decades have brought numerous advantages in soil erosion quantification and spatial-temporal erosion prediction for various future conditions. The use of these approaches in cultural heritage preservation and monitoring activities is still restricted.

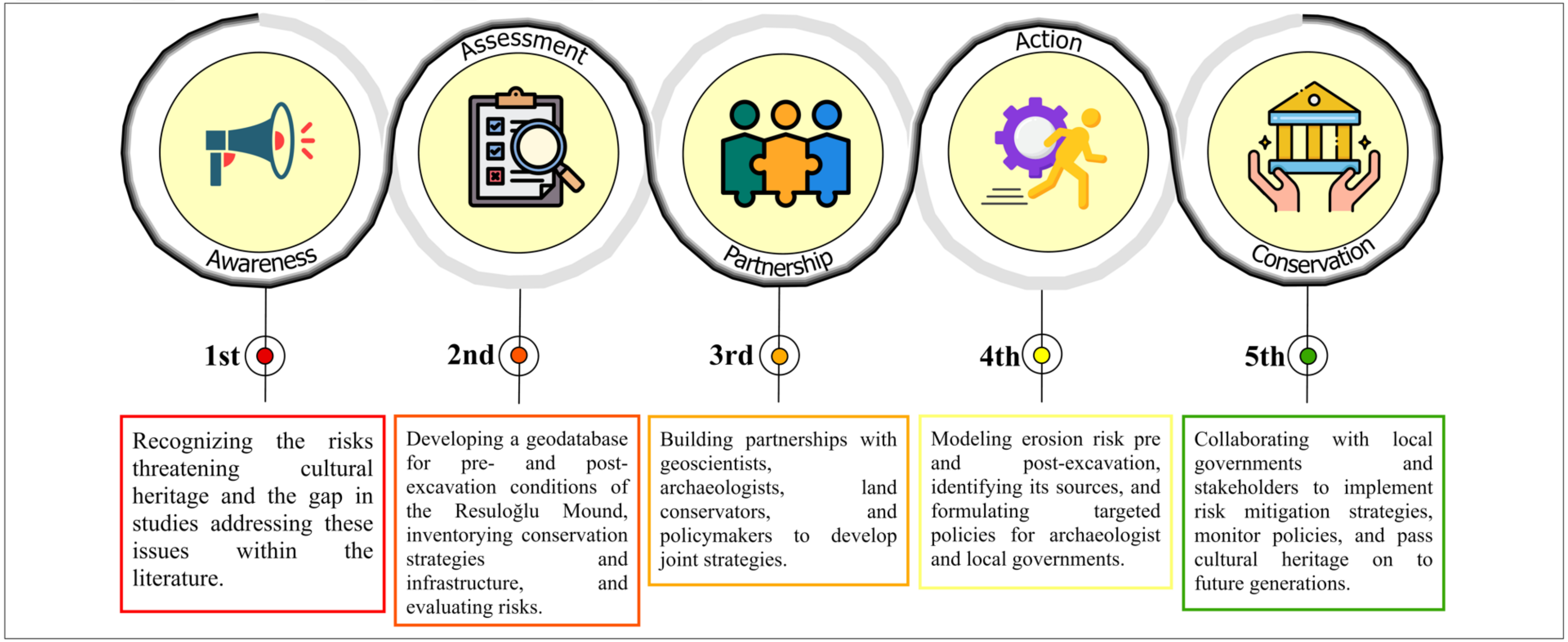

Figure 8.1: An Integrated Framework for Cultural Heritage Preservation in Resuloğlu Mound.

QGeoWEPP has the ability to predict soil erosion across pre- and post-excavation scenarios at the Resuloğlu Mound. This site is a significant socio-ecological and bio-geomorphic interaction and the work is positioned well to provide information for future cultural heritage preservation efforts.

The use of computer simulation models has become the norm in the assessment of sediment yield and soil loss under different land use and management practices (Pandey et al. 2009). WEPP provides the ability to calculate spatial and temporal erosion and deposition patterns and predicts erosion location and time at watershed and hillslope scales. (Flanagan and Nearing, 1995). Several geospatial platforms for WEPP users exist based on different software which includes GeoWEPP (Renschler, 2003), GEMSE (Baigorria and Romero, 2007), WEPPcloud (Lew et al., 2022), QWEPP (Miller et al., 2022) and QGeoWEPP (Zhang and Renschler, 2024).

The WEPP model has a simple user interface that is used for the prediction of the impacts of both natural and human disturbances. It has been widely used in various applications such as road design and infrastructure services (Grace, 2005; Elliot et al., 1995; Elliot et al., 1998), forest applications (Srivastava et al., 2018; Srivastava et al., 2020; Dun et al., 2009; Elliot, 2013), land use management (Luetzenburg et al., 2019; Laflen et al., 1994; Anache et al., 2018; Renschler, 2020) and mine excavation (Zemke et al., 2019) with the main goal of reducing soil erosion risks. Nonetheless, its use in sustainable excavation practices—specifically for erosion reduction, cultural heritage preservation, and infrastructure planning—is still not studied. This study aims to address this gap.

- The main aim of this research was to introduce a multidisciplinary approach in assessing soil erosion risks, taking into account climate and weather pattern variations and human activities, in relation to cultural heritage. To address these objectives, the following questions were formulated:
- i) Were the excavations carried out at the Resuloğlu Mound between 2003 and 2019 likely to trigger changes in erosion?
- ii) Is it feasible to differentiate between natural and human-induced (anthropogenic) erosion at this archaeological site?

- iii) Are there erosion mitigation strategies that can be applied at the Resuloğlu Mound, that consider future climate change scenarios as part of considering how cultural heritage at this site can be preserved for future generations?

This archaeological monument will be conserved and the following generations will have a better understanding of the resilience of cultural heritage in the face of anthropogenic effects and climate and weather pattern variability.

The mound was excavated every summer (July-September) from 2003 to 2019. Soil erosion has caused major changes to the landscape as shown in the current morphology of the Resuloğlu Mound (Figure 8.2a and 8.2b). The mound is located at the boundary of two distinct geological formations (Figure 8.2c). The settlement area sits on top of the older Miocene and Oligocene conglomerate, sandstone, and mudstone units and the cemetery area lies on the younger Upper Miocene gypsum, mudstone and sandstone units (MTA, 2016). The latter units are thinner than the former and belong to a geological formation that is more prone to erosion.

The present time the direct passage between the settlement and the cemetery is not possible. However, hand, 4300 years ago, Resuloğlu residents would put food and valuable items next to their deceased loved ones as a part of their belief systems, which would have necessitated frequent visits to the cemetery, implying that the gully between the cemetery and the settlement (Figure 8.2b) was either much smaller or even non-existent during the period of occupation. Other than creating a large gully in the area between the cemetery and the settlement, erosion has also caused the collapse of walls and rooms of architectural features on the steep slopes of the Resuloğlu settlement. Therefore, this destabilization and the ongoing erosion means that the Resuloğlu Mound has to be preserved with urgency.

This chapter reviews the rates of erosion during the period before and after the archaeological excavation. Before the excavation, the site was subjected to heavy biotic pressure due to grazing and there was no conservation plan in place. After excavation, the soil properties of the excavation areas and deposition slopes in terms of depth, texture, and permeability underwent significant changes. In conclusion, the excavation has led to considerable changes in the site's soil properties, vegetation cover, conservation methods and morphology. These changes are major factors that affect the results from erosion models.

The Resuloğlu Mound thus presents a suitable case for simulating erosion rates as a function of landscape dynamics before and after excavation. There is no current active excavation at the Resuloğlu Mound. However, the site presents an important archaeological data set, indicators of Early Bronze Age weather patterns and climate changes, and information on how past communities adapted and coped with climate change and its associated impacts (Koçaklı et al., 2024). Given the fact that the strategies should be passed on to future generations and the mound's current high risk of erosion, the Resuloğlu Mound is an interesting case to study.

8.3 GeoWEPP (Geospatial Interface for the Water Erosion Prediction Project) Model

The Water Erosion Prediction Project (WEPP) model is a physically based continuous simulation erosion model (Nearing et al., 1989; Laflen et al., 1991; Flanagan & Nearing, 1995; Flanagan et al., 2007). Model (WEPP) is built on the fundamentals of hydrology, plant science, hydraulics, and erosion mechanics (Flanagan and Nearing, 1995).

GeoWEPP was developed as a collaborative project by the USDA Agricultural Research Service and Purdue University at the USDA National Soil Erosion Research Laboratory (Renschler et al. 2002; Renschler 2003). GeoWEPP was developed as an extension to the proprietary ESRI software packages ArcView and ArcGIS, addressing issues with ESRI GIS software updates and compliance. Currently, GeoWEPP supports only ArcGIS 10.4 and earlier versions. The discontinuation of ESRI technical support for these older versions has created challenges for users in maintaining compatible computing environments, as the stand-alone Windows-based GeoWEPP software is increasingly difficult to operate on modern systems. Therefore, the user-friendly, accessible, shareable, and open-source QGeoWEPP software, which operates on a Quantum GIS platform, was developed by Zhang and Renschler (2024).

The QGeoWEPP requires DEMs together with land use maps and soil maps and climate data as its input information. The Universal Transverse Mercator (UTM) system requires all spatial data for processing which needs to be converted into ASCII file format.

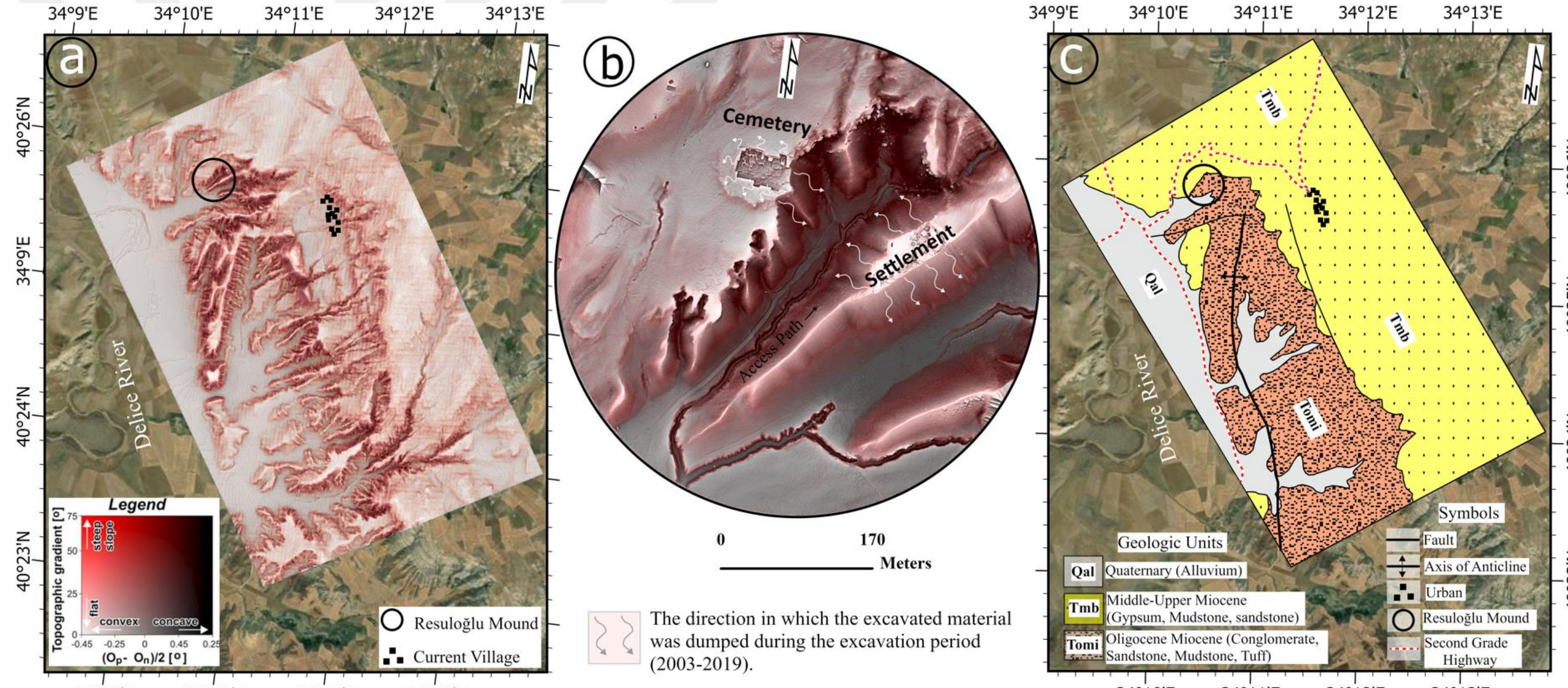

Figure 8.2: a.) The location of Resuloğlu Mound and its surroundings with Red Relief Image (resolution 5 m) b.) Topography map of the Resuloğlu Settlement area and Cemetery (Latitude: 40.429870°N, Longitude: 34.175682°E,) with Red Relief Image (resolution 1 m). c.) Geologic map of the study area (Scale: 1:25,000).

8.3.1 GeoWEPP input files preparation

8.3.1.1 Climate data

The WEPP climate input file has 10 parameters, including day, month, year, the number of daily precipitations, daily maximum and minimum air temperatures (tmax, tmin), as well as solar radiation (rad), wind velocity (w-vel), wind directions (w-dir) and dew-point temperature (dew). From among the meteorological stations within ~ 50 km from the Resuloğlu Mound site, data from the Çankırı station, which includes all climate variables required by the model over an extended period and specifically for the years 2000 to 2024, were used. Based on monthly average precipitation and temperature data from the Çankırı station for 1979-2023 (Figure 8.3), the area has a semi-arid continental climate (Turkish State Meteorological Service [TSMS], 2024).

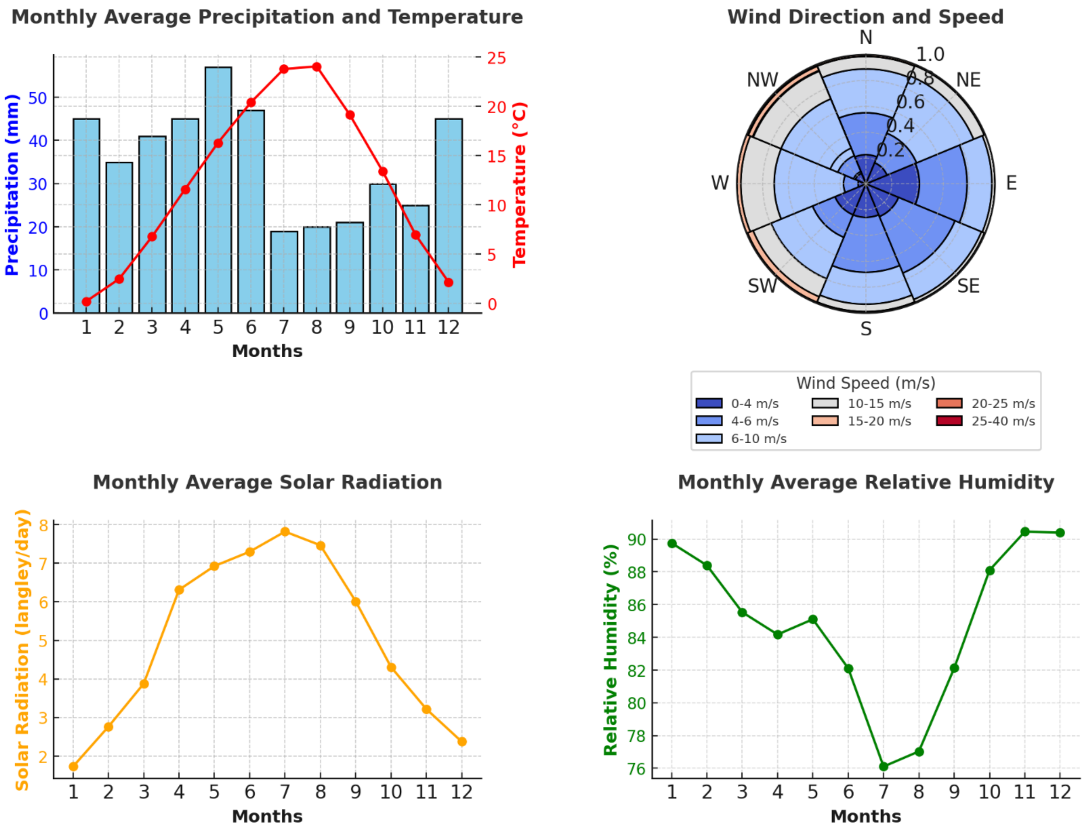

Figure 8.3: Monthly climate variables—precipitation, temperature, solar radiation, wind direction and speed, and relative humidity—recorded from 1979 to 2024 at the Çankırı Meteorology Station, marked as a black plus sign in Figure 2. (Source: Turkish State Meteorological Service.)

8.3.1.2 Slope data

To support regional-scale analysis, 5-meter resolution DEM data has been obtained from the Turkish General Directorate of Mapping, covering the Resuloğlu Mound and its surrounding area within a 50-kilometer radius (Figure 2a). This dataset served as the baseline topographic reference for the study.

This research investigates whether archaeological excavations have contributed to increased erosion by generating and comparing high-resolution digital elevation models from before and after the excavations. For the pre-excavation period, analog aerial photographs taken in 1990 by the General Directorate of Mapping was scanned. These were processed with Agisoft software to produce a 1-meter resolution DEM (Figure 8.4). For the post-excavation period, we conducted a high-resolution UAV (Unmanned Aerial Vehicle) survey over the Resuloğlu Mound in September 2019. The collected imagery was processed with Pix4Dmapper software to create a detailed 1-meter resolution DEM (Figure 8.4). However, since the dataset I derived from the black-and-white analog aerial photographs taken in 1990 contained a high level of noise, and corrections had to be applied using morphometric analysis techniques such as the RRIM and Geomorphon.

A multi-source dataset (Figure 8.5) was used to evaluate the morphological changes that occurred before and during excavation activities. The dataset consisted of satellite imagery, UAV-derived models, and historical military archive materials. The high-resolution SPOT 7 satellite images enabled us to observe surface disturbances and study their spatial distribution in relation to excavation areas. The orthophotos from military archives together with daily reports from the excavation archive provided essential contextual details. The available resources improved our knowledge about the geomorphological processes which affected the site. The detailed analysis through this method provides an enhanced understanding of the landscape transformation at Resuloğlu which results from archaeological activities.

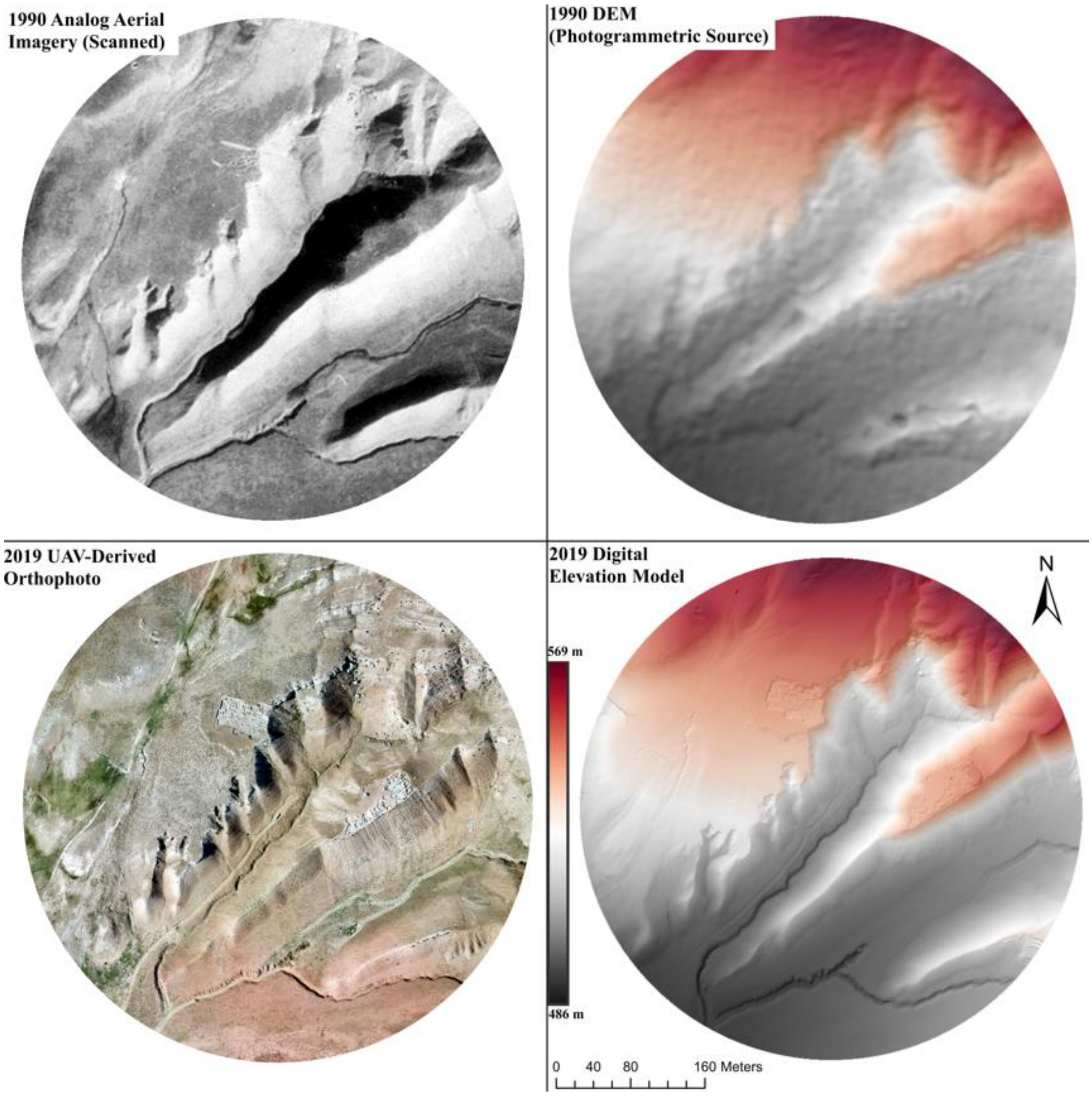

Figure 8.4: Pre-excavation analog aerial photographs and high-resolution drone orthophotos of Resuloğlu Höyük, alongside 1-meter resolution digital elevation models generated from these datasets.

The noise in the DEM data produced in 1990 originates from analog aerial photographs that were taken in black and white, scanned, and archived. In these images, especially in shadowed and highly reflective areas, the derived slope values often fail to provide the expected level of accuracy and reliability. To mitigate this type of noise, I applied a GIS-based statistical surface smoothing method. This technique compares each cell value with its neighboring cells to reduce abrupt variations and enhance topographic continuity. As a result, random errors in the DEM are minimized and more realistic slope values are obtained.

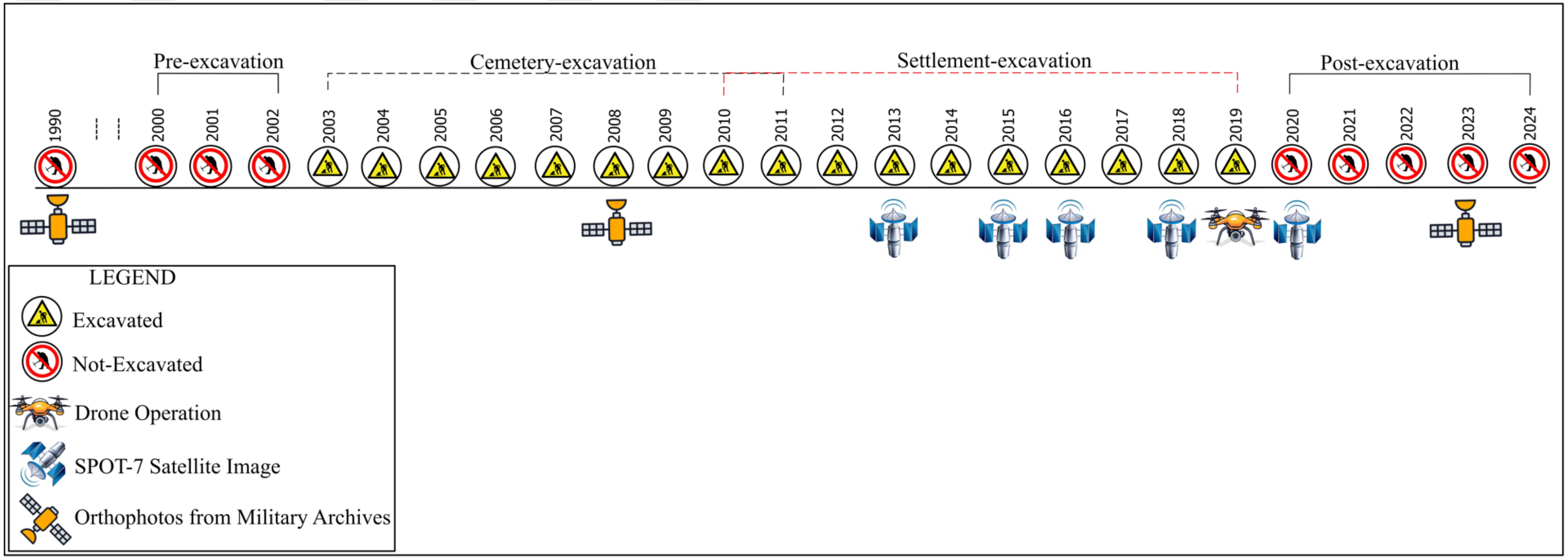

Figure 8.5: Chronology of the Resuloğlu excavations and the source and acquisition timeframe of the remote sensing data used.

8.3.1.3 Soil data

The WEPP model requires precise soil property values to predict sediment yield and runoff. The WEPP model evaluates soil characteristics through texture analysis and albedo assessment and hydraulic conductivity measurement and rill and interrill erodibility evaluation and critical shear determination. The Republic of Türkiye Ministry of Agriculture and Forestry (2023) supplied the necessary soil data for the model. The dataset provided by them included extensive details about the pre-excavation characteristics of the Resuloğlu Mound and its adjacent region including soil texture and depth and drainage properties and salinity and other relevant factors.

8.3.1.4 Management data

I used a 2017–2023 dataset from ESA Sentinel-2 imagery at 10-meter resolution which we accessed through ESRI's Sentinel-2 Land Cover Explorer (ESRI, 2023) for the land use and land cover (LULC) time series input files in the model. I added SPOT 7 satellite images together with orthophotos from military archives to enhance the dataset for capturing time-based land use changes. The extra resources enabled better detection of land use transformations which improved the model's precision.

The Resuloğlu Mound maintained consistent land use patterns during the entire observation period. Before the excavation started the area functioned mainly as grassland where local herders kept their sheep and cattle for grazing. The beginning of excavation work led to the establishment of protected zones which limited animal access to specific sites within the mound. The change in land use established a distinctive setting to analyze soil erosion rates between grazing periods before excavation and post-excavation restricted access.

Analysis will compare these scenarios to determine the effects of different land use practices on soil erosion rates. This methodology enables researchers to study both natural erosion mechanisms and human-caused changes from excavation and land management on geomorphological processes.

Table 8.1: General characteristics of the data to be used.

Data	Operator	Global/Local	Extracted Information	Spatial Resolution (m)	Source
Meteorological measurements (daily)	Turkish State Meteorological Service	Local	Precipitation, max temp, min temp, solar rad, wind speed, wind direction, relative humidity	-	https://www.mgm.gov.tr/eng/forecast-cities.aspx (accessed on 3 March 2024)
Resuloğlu Mound excavation archives	General Directorate of Cultural Heritage and Museums	Local	All archaeological findings	-	https://kvmgm.ktb.gov.tr/ (accessed on 3 March 2024)
Air photos	DJI Drone (Pix4D)	Local	Elevation	1 m	Personal data
Digital Elevation Model	Republic of Türkiye General Director of Mapping	Local	Elevation, RRIM, and topographic profiles.	5 m	https://www.harita.gov.tr/ (accessed on 3 March 2024)
SPOT 7 Satellite	ESA (European Space Agency)	European continent	Landuse, and NDVI	1.5 m	https://www.esa.int/ (accessed on 3 March 2024)
Geology	Republic of Türkiye Mineral Research and Exploration General Directorate	Local	Age, rock type, fault locations.	1:25,000	https://www.mta.gov.tr/en/ (accessed on 3 March 2024)
Soil	Republic of Türkiye Ministry of Agriculture and Forestry	Local	Soil texture, depth, salinity, etc.	1.25.000	https://www.tarimorman.gov.tr/TAGEM (accessed on 3 March 2024)
Land/use	ESRI	Global	Landuse/cover	10 m	https://livingatlas.arcgis.com/landcover/
Annual Crop Yield	Turkish Statistical Institute	Local	Annual Average Winter Wheat	-	https://www.tuik.gov.tr/ (accessed on 3 March 2024)

8.3.2 Experimental design and scenarios

The WEPP (Water Erosion Prediction Project) model (2012 version) was integrated into the QGIS platform (QGIS 3.28.15) prior to running the simulations for improved data processing and analysis. After the archaeological excavation in September 2019, the DEM data obtained through UAV operations was processed to adjust its resolution from 1 meter to 3 meters for the model requirements. The processed DEM was imported into the QGeoWEPP model using the WGS84/UTM coordinate system for spatial accuracy.

QGIS environment is where QGeoWEPP utilized the Topographic Parameterization Program (TOPAZ) to channelize the channel network and determine drainage density. This parameterization is very much necessary for accurate modeling of hydrological processes and sediment transport. The QGeoWEPP interface also allowed us to adjust model parameters such as critical source area (CSA) and minimum source channel length (MSCL), which directly affect the definition of the hillslope and channel features.

For the Resuloğlu Mound study area, the optimal representation of hillslopes was achieved using a CSA value of 0.08 hectares and an MSCL of 20 meters (Figure 5). These parameter settings were crucial in identifying the geomorphological characteristics of the site and were used to simulate erosion and sediment dynamics with high precision.

Hillslopes are groups of grid cells in a DEM that drain to the left, right, or top of individual channels (Cochrane and Flanagan, 2003). For this study, we selected hillslopes by considering key environmental variables influencing soil erosion, such as excavation activities, disturbance types, geomorphology, aspect, and existing soil conservation practices. A total of eight hillslopes were modelled, with four located in the cemetery and four in the settlement (Figure 8.6). Two slopes were left undisturbed and were designated as reference hillslopes to provide a baseline unaffected by archaeological excavation activities.

For the analysis, codes had to be assigned to the hillslopes based on their locations: those from the cemetery area were labeled “Cem” and those from the settlement area were labeled “Sett” Morphological characteristics of each hillslope were subsequently extracted using spatial analysis tools in QGIS (Table 8.2). This process ensured accurate parameterization of the hillslopes for modeling purposes and enabled us to effectively simulate erosion patterns under different conditions.

Table 8.2: Morphometric characteristics of each hillslope based on post-excavation topography.

Hillslopes ID	Situation	Disturbance type	Slope shape	Field length (m)	Field width (m)	Area (ha)	Avr. Steepness (%)
Cem-1	Disturbed	Excavated/Deposited	Uniform	43.8	39.2	0.1716	18.7
Cem-2	Disturbed	Deposited	Complex	50.1	30.1	0.1508	14.7
Cem-3	Disturbed	Deposited	Complex	65.2	25.1	0.1636	11.8
Cem-4	Undisturbed	-	Convex	84.2	18.9	0.1591	12.0
Sett-1	Disturbed	Excavated/Deposited	Convex	65.0	23.4	0.1521	42.9
Sett-2	Disturbed	Excavated/Deposited	Concave	103.3	14.8	0.1528	28.9
Sett-3	Disturbed	Excavated/Deposited	Concave	78.6	26.3	0.2067	39.3
Sett-4	Undisturbed	-	Concave	75.7	26.5	0.2006	50.2

Following this step, scenarios were defined. Based on modeling erosion rates and environmental dynamics that trigger erosion at Resuloğlu Mound, both before and after excavation. Therefore, in Table 8.3, scenarios were designed from known to less well-known parameter settings. In this context, Scenarios 1 and 4 were primary simulations, while Scenarios 2 and 3 were applied additionally to gain a better understanding of the model capabilities to include pre-excavation scenarios and to verify results for different excavation stages from planning to execution of various planning steps.

Table 8.3: Multiple scenario design based on the combination of data sets from pre- and post-excavation.

Scenarios	Slope	Climate	Soil	Management
Scenario-1	Post-excavation-slp.	Observed-clim.	Post-excavation-soil.	Post-excavation-man.
Scenario-2	Post-excavation-slp.	Observed-clim.	Post-excavation-soil.	Pre-excavation-man.
Scenario-3	Post-excavation-slp.	Observed-clim.	Pre-excavation-soil.	Pre-excavation-man.
Scenario-4	Pre-excavation-slp.	Observed-clim.	Pre-excavation-soil.	Pre-excavation-man.

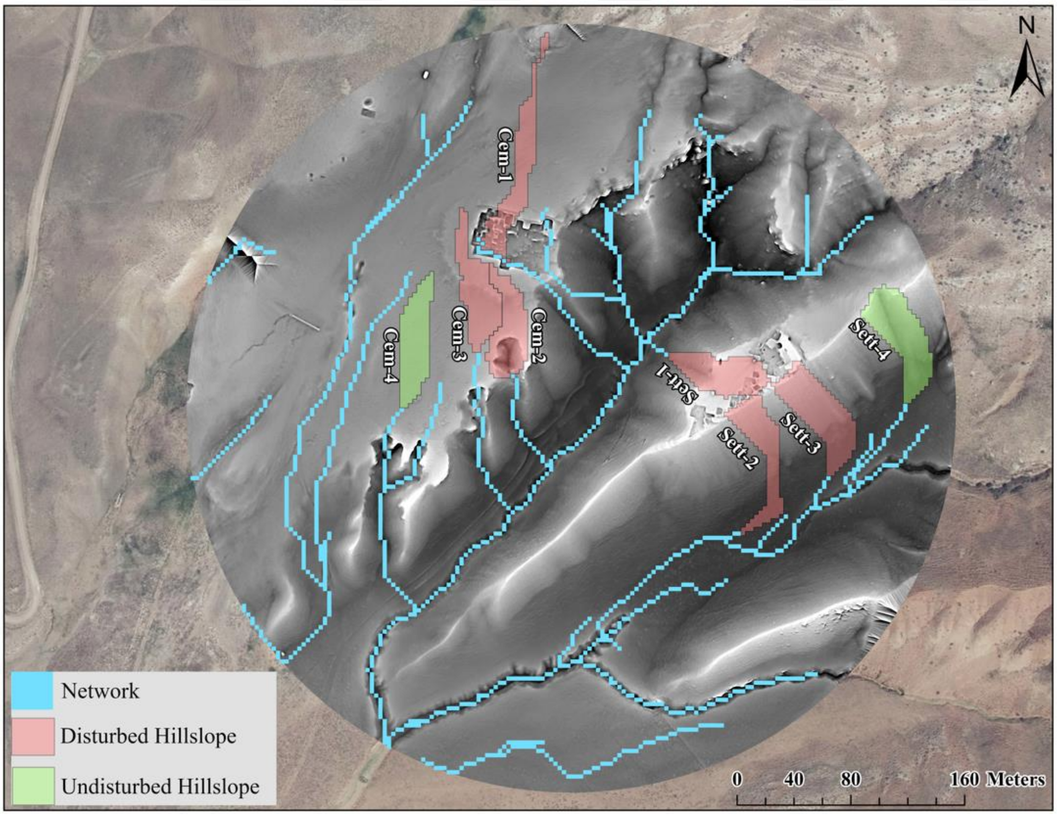

Figure 8.6: Hillslopes where the QGeoWEPP model was applied: Red areas represent disturbed hillslopes, while green areas represent undisturbed reference hillslopes.

8.3.3 Soil properties parameters for post-excavation modeling

The Ministry of Agriculture and Forestry supplied us with a dataset containing soil characteristics before excavation started which included soil texture and depth and rock ratio information. The excavation process led to major changes in the mound structure because rooms deeper than 3 meters were dug out. The removal of materials created rocky surfaces which exposed architectural walls and structures while the deposition of excavated material in flat areas and slopes resulted in increased soil thickness with former surface material deposited first followed by deeper excavated soil deposited last. The excavated soil consisted of fine-grained material. The WEPP model combined with field observations from the Resuloğlu Mound excavation archives and expert analysis from the USDA Agricultural Research Service National Soil Erosion Research Laboratory enabled us to simulate the soil characteristics following excavation. The evaluation assessed the excavated and depositional areas against their original pre-excavation state (Table 8.4).

Table 8.4: Estimated conditions of soil variables in areas where material was excavated and deposited.

Variable	**Simulated values for pre-excavation**	**Expected value for excavated area (Material removed)**	**Expected value for deposition area (Material deposited)**
Albedo	0.23	Low	Low
Initial Sat. Level (%)	30	High	Low
Interrill Erodibility (kg s m^{-4})	1.0e+07	Low	High
Rill Erodibility (s m^{-1})	0.01	Low	High
Critical Shear (Pa)	2	Low	High
Eff. Hydr. Conductivity (mm h^{1})	7	Low	High
Depth (mm)	60	Low	High
Sand (%)	35	High	Low
Clay (%)	35	Low	Low
Organic (%)	0.800	Low	High
CEC (meq/100g)	10.5	Low	High
Rock (%)	25.3	High	Low

8.4 Application of the QGeoWEPP Model

Eight hillslopes at Resuloğlu Mound were modelled using QGeoWEPP. Out of these, six were damaged during archaeological excavation, while two were left undisturbed and used as reference hillslopes (Figure 8.6). The QGeoWEPP model was run continuously over 24 years (2000 to 2024) to analyze the three outputs of Average

Annual Runoff (mm), Average Annual Soil Loss (kg/m²), and Average Annual Sediment Yield (t/ha/yr) under pre- and post-excavation scenarios (Table 8.4).

I have conducted simulations for over 24 years (2000–2024) as meteorological data for this timeframe is available. Additionally, excavations took place between 2003 and 2019, allowing us to analyze the landscape both in the years leading up to the excavations and those following their completion. This timeframe is particularly well-suited for making geomorphological inferences and evaluating the temporal dynamics of landscape changes. For the hillslopes that were disturbed during excavations, clear differences were found between pre-excavation and post-excavation conditions as a function of the geomorphological structure of the hillslopes and the type, intensity and spatial location of the disturbances.

8.5 Validation of model outputs using hydrologic components

The research assesses WEPP model hydrological performance at a 600-meter south location where winter wheat cultivation occurs in a gently sloped area. The model predicts 402 mm of annual rainfall which closely matches the 415 mm average observed at our meteorological station. The model predicts that winter wheat will produce an average yield of 259 kg per hectare. The Turkish Statistical Institute reports that wheat crop yields in this area average at 230 kg per hectare. The model performance evaluation shows these values to be within an acceptable range.

8.6 Chapter Summary

Chapter 8 presents a detailed case study of Resuloğlu Höyük, demonstrating how GIS, remote sensing, and geomorphological approaches can be integrated to protect archaeological sites that are vulnerable to erosion and landscape degradation. The chapter focuses on measuring the physical impacts of archaeological excavations and understanding how such activities can intensify natural processes like erosion. Using the GeoWEPP erosion model, soil loss was simulated under pre- and post-excavation scenarios.

This modeling was based on a combination of high-resolution datasets, including SPOT 7 satellite imagery, digitized 1990 analog aerial photographs, drone surveys, and excavation reports. The comparison of digital elevation models from before and after the excavations revealed that archaeological activities have significantly accelerated erosion in certain parts of the mound—especially in the cemetery area, which lies on softer, more erosion-prone geological formations. The analysis yielded three key findings: first, excavation activities have directly contributed to erosion in geomorphologically sensitive zones; second, the topography of the mound changed substantially between 1990 and 2019, especially in slope areas; and third, the removal of protective surface layers during excavation—not climate alone—is the primary driver of erosion in the current context.

This chapter's contribution to the overall dissertation lies in its demonstration that human-environment interactions are not just a thing of the past—archaeological research itself continues to shape landscapes in the present. Resuloğlu Mound serves as a striking example of how even scientific excavation can unintentionally accelerate degradation if geomorphological risks are not managed. Based on these findings, the chapter proposes practical conservation strategies, including sustainable excavation practices, site-specific management plans, and the use of GIS and remote sensing as monitoring and early warning tools. Overall, the chapter strengthens the dissertation's broader aim by showing how integrated spatial approaches can be used not only to study past landscapes, but also to protect cultural heritage in the face of ongoing environmental challenges.

9 RESULTS AND DISCUSSION

9.1 Chapter Introduction

This chapter examines the socio-ecological changes of the Delice Valley during the Holocene period through an interdisciplinary methodology. The chapter unites paleoclimate models with archaeological settlement data and remote sensing analyses and geomorphological assessments to provide a complete understanding of human environmental interactions across time. The analysis investigates human-caused landscape changes and resource utilization patterns while examining environmental threats in their historical framework. This chapter investigates environmental changes that affected local communities and their development of adaptive strategies to respond to these changes. Four key themes are addressed:

1. The Delice Valley experienced Holocene climate changes which modified its local landscape systems.

2. The spatial and temporal patterns of settlement locations together with their socio-political importance, underwent changes throughout the region.

3. The MedLanD model simulates different subsistence strategies to evaluate their environmental sustainability through agent-based simulations.

4. The chapter examines Resuloğlu Mound's vulnerability to geomorphological risks and discusses potential preservation methods for this cultural heritage site.

This chapter provides both historical analysis of past environmental and cultural processes and generates model-based insights which guide current conservation practices and rural land-use planning.

9.2 Climate Changes During the Holocene at Delice Valley

The research combines various paleoclimate models with proxy data to study Bond cycles that occurred in the Early to Middle Holocene period, as described in previous units. The research combines model outputs with empirical data while following internationally accepted definitions of these climatic events (Table 9.1).

Table 9.1. Climate events (Bond Events; Bond et al., 1997, 2001) along with their dates and definitions. The last columns show how these specific climatic events are represented in the MCM and CHELSA-TraCE21k Models' outputs for the Delice Valley.

Event	**Age (ka)**	**Global Definition**	**MCM Pattern in Delice Valley**	**CHELSA Pattern in Delice Valley**
B8	11.1	Marked by significant cooling phases, especially around the North Atlantic region (Bond et al., 1997, 2001; Wang et al., 2013)	Decreasing temp. Increasing prec.	Increasing temp. Decreasing prec.
B7	10.3	Characterized by pronounced cold episodes primarily affecting areas surrounding the North Atlantic(Bond et al., 1997, 2001; Wang et al., 2013)	Increasing temp. Decreasing prec.	Increasing temp. Stable prec.
B6	9.4	Associated with widespread cold conditions in the North Atlantic zone (Bond et al., 1997, 2001; Wang et al., 2013; Young et al., 2013)	Increasing temp. Decreasing prec.	Decreasing temp Increasing Prec.
B5	8.2	Cooler and drier climates likely resulted from the collapse of the Laurentide Ice Sheet (Barber et al., 1999).	Stable temp. Stable prec.	Decreasing temp Decreasing prec.
B4	5.9	This period saw notable cold events concentrated around the North Atlantic (Bond et al., 1997, 2001; Wang et al., 2013).	Stable temp. Stable prec.	Decreasing temp Increasing prec.
B3	4.2	Identified by arid and cool climatic patterns, this event is well-documented for its widespread ecological and societal impacts (Bini et al., 2019; Ran and Chen, 2019)	Increasing temp. Decreasing prec.	Increasing temp. Decreasing prec.

The MCM and CHELSA results in Delice Valley revealed some significant paleoclimatic variations over the Early Holocene (hereafter EH, ca. 11700–8300 cal. BP). According to MCM, the EH was a cold and wet period (Figure 9.1). The temperature dropped to 8 °C while the precipitation increased to 650 mm around 11000 cal. BP (i.e., 11.1 ka event). Precipitation decreased (500 mm) and the temperature rose sharply (10 °C) shortly after the 11.1 ka event. Between 10,800 and

9500 cal. BP, there were fluctuations in the precipitation and temperature. The 10.3 ka event was cold but wet compared to today. Around 9400 cal. BP, the temperature increased to 12 °C and the precipitation dropped to 420 mm. This indicates that the 9.4 ka event was dry and warm. By the end of the EH, the paleoclimatic trends became stable with slight fluctuations.

According to the CHELSA model, temperatures show a gradual and slow increase from the beginning of the Holocene until around 10,000 cal. yr. BP. During Bond Event 8 (11.1 ka), unlike the MCM model, CHELSA does not display a major climatic shift. In fact, throughout the Early Holocene, the CHELSA model does not indicate any significant climatic fluctuations corresponding to the Bond cycles (Figure 9.1)

According to MCM, the average annual precipitation remained steady from the beginning of the Middle Holocene (hereafter MH) until 6200 cal. BP. Between 6200 and 5500 cal. BP, precipitation dropped to 400 mm. Even though there were slight changes throughout this phase, average annual precipitation remained around 440 mm until the end of the MH. The annual average temperature increased from 11 °C by 6300 BP, after slight changes during the MH it became stable at 10.7 °C by 4700 BP. During the Middle Holocene the CHELSA model shows major climate changes especially in precipitation. The period that corresponds to Bond Event 4 (5.9 ka) is characterized by lower temperatures and higher precipitation (Figure 9.1)

During the Late Holocene (hereafter LH) temperature and precipitation followed the same pattern as the previous period. The period was stable and close to the modern climate pattern, except around 4000 cal. BP, when there was a small change in temperature and precipitation by nearly 0.5 °C and 50 mm, respectively.

The semi-arid Delice Valley provides an optimal location to evaluate human responses to environmental and ecological changes because it contains diverse archaeological evidence. Firstly, the MCM results provide a detailed assessment of how past climate changed in the research area. The MCM patterns show that the EH was a cold and wet period. The CHELSA model represents the Early Holocene as a relatively dry and cold period. The most significant change occurred at the 11.1 ka event (B8 in Fugure 9.1) when cooler and wetter conditions emerged. The 10.3 ka event (B7 in Figure 9.1) was cold and wet however, the 9.4 ka event (B6 in Figure 9.2) reversed these trends. Most of the proxy records in Figure 9.2 (Lake Nar, Lake Akgöl, Lake Gölhisar, Lake Van, Lake Eski Acıgöl, and İncesu Cave) show that EH was a wet and cold period

(Eastwood et al., 2007, Roberts et al., 2008, Roberts et al., 2016, Ön et al., 2018, Erkan et al., 2022).

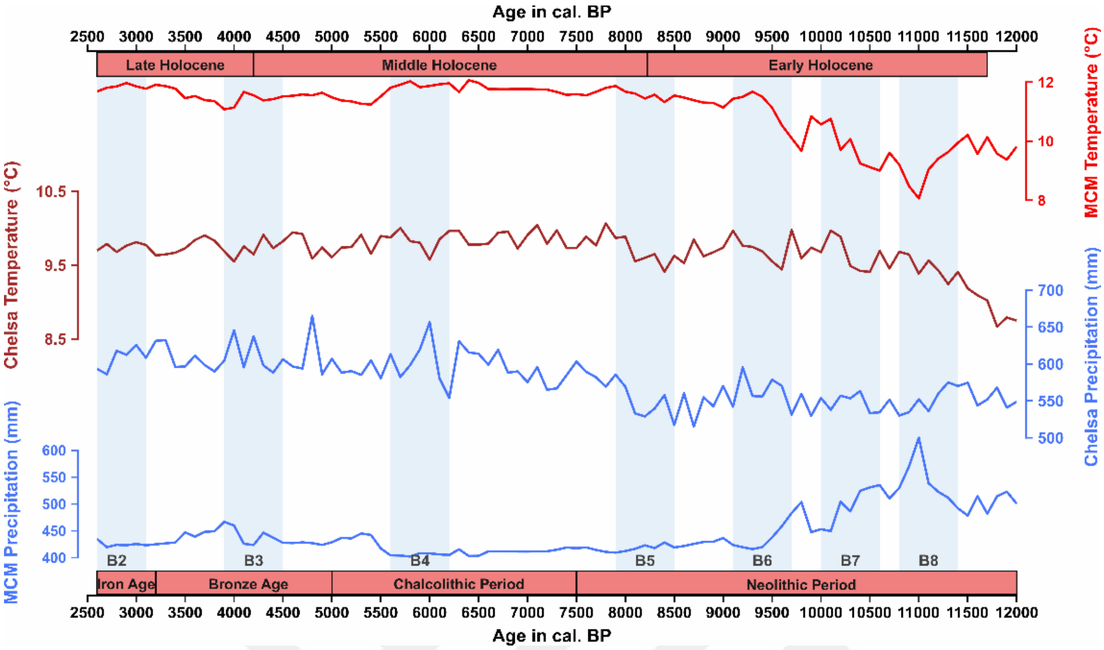

Figure 9.1: The precipitation (blue line) and temperature (red line) results of MCM and CHELSA between 12,000 and 2500 cal. BP (MCM reconstructed from the recent meteorological stations; Figure 1.1c bold black plus represents the source of precipitation and temperature) with the duration of archaeological periods. The light blue bands show the Rapid Climate Changes in the Holocene called the Bond Events; B2 = 2.8 ka, B3 = 4.2 ka, B4 = 5.9 ka B5 = 8.2 ka, B6 = 9.4 ka, B7 = 10.3 ka, B8 = 11.1 ka (Bond et al., 1997, Bond et al., 2001).

Erkan et al. (2022) identified short-term increases in $\delta^{13}C$ and $\delta^{18}O$ values at 11.2, 10.3, and 9.4 ka in records from İncesu Cave, indicating episodes of cold and arid conditions. Similarly, enriched $\delta^{18}O$ values from Lake Nar suggest drier climatic phases around 9.3 ka and 8.2 ka. In contrast, $\delta^{18}O$ levels in Lake Gölhisar show distinct declines at 9.4 and 8.2 ka, while Lake Akgöl exhibits a sharp decrease at 11.3 ka (Figure 9.2). During the Early Holocene, solar insolation at 30°N differed significantly from present-day values, being higher in summer and lower in winter (Berger and Loutre, 1991). These insolation shifts likely triggered changes in atmospheric circulation, precipitation-to-evaporation ratios, land-sea temperature gradients, glacial melting, and river discharge patterns (Arz et al., 2003; Huang et al., 2008), ultimately contributing to the formation of the recent sapropel layer (S1) in the Mediterranean (Grant et al., 2016). Arz et al. (2003) further hypothesized that an enhanced land-sea temperature contrast may have driven a regional monsoon-like circulation, intensifying precipitation across the Mediterranean basin.

In the MH, according to MCM, precipitation and temperature remained steady from the beginning (8200 cal. BP) until 5500 cal. BP with slight fluctuations in the Delice Valley; there was no significant change at the 5.9 ka event (B4 in Figure 9.1). After 5500 cal. BP, precipitation increased and temperature declined.

The second RCC event is the 4.2 ka event (B3 in Figure 9.2), arguably the best-known and the most widely discussed paleoclimatic event in the Northern Hemisphere. Some scholars argued that the 4.2 ka event brought drier and warmer conditions to the greater Southwest Asia and the event even being global (Weiss et al., 1993). Ön (2023) claims that the 4.2 ka event has not had an impact on proxy data from Anatolia and the Levant.

In Delice Valley, MCM suggests a sharp decline in precipitation and a minor increase in temperature around the 4.2 ka event. When compared paleoclimate patterns in different areas of Southwest Asia showed different trends at that time (Gogou et al., 2016, Arıkan, 2021). For example, in Lake Van and Lake Eski Acıgöl, δ18O values increased at 5.9 ka and 4.2 ka (Figure 9.2). However, a sharp drop in δ18O values of Gölhisar and Akgöl lakes at the 5.9 ka shows a reverse pattern than the other lakes which might indicate wetter conditions in the lakes. In comparison, at the 4.2 ka, δ18O values of Gölhisar increased sharply indicating dry conditions. At Lake Tecer, wet/dry phases occurred between 6 and 3 ka, which were interrupted by short arid episodes corresponding to the end of the millennium: a 5.25–4.95 ka aridity, a 450-year-long drought started c. 4.3 ka indicating the 4.2 ka event (Kuzucuoğlu et al., 2011).

The LH period was stable and close to the modern climate pattern, except around 4000 cal. BP when the temperature dropped and precipitation showed a slight increase. The 2.9 ka event brought no changes in the Delice Valley (Figure 9.2). In Lake Hazar, cold arid phases occurred around 3.5 ka and 2.8 ka (Ön et al., 2018**).** In Lake Tecer an alternation of humid (c. 3.9–3.8 ka; 3.65–3.55 ka; 3.4–3.4 ka) and dry (3.8–3.65 ka; 3.5–3.4 ka; 3.25– 3.0 ka) episodes is recorded (Kuzucuoğlu et al., 2011).

In the case of Resuloğlu Höyük, two different climate models—CHELSA-TraCE21k and the Macrophysical Climate Model (MCM)—were applied. These models focused specifically on the period between 4300 and 4100 cal. BP, when the settlement was actively occupied. Using the CHELSA-TraCE21k model, spatially detailed precipitation anomaly maps were generated at 100-year intervals (Figure 9.3). For 4300 cal. BP, the model indicates slightly negative precipitation anomalies in the Resuloğlu region, pointing to a modest decline in rainfall.

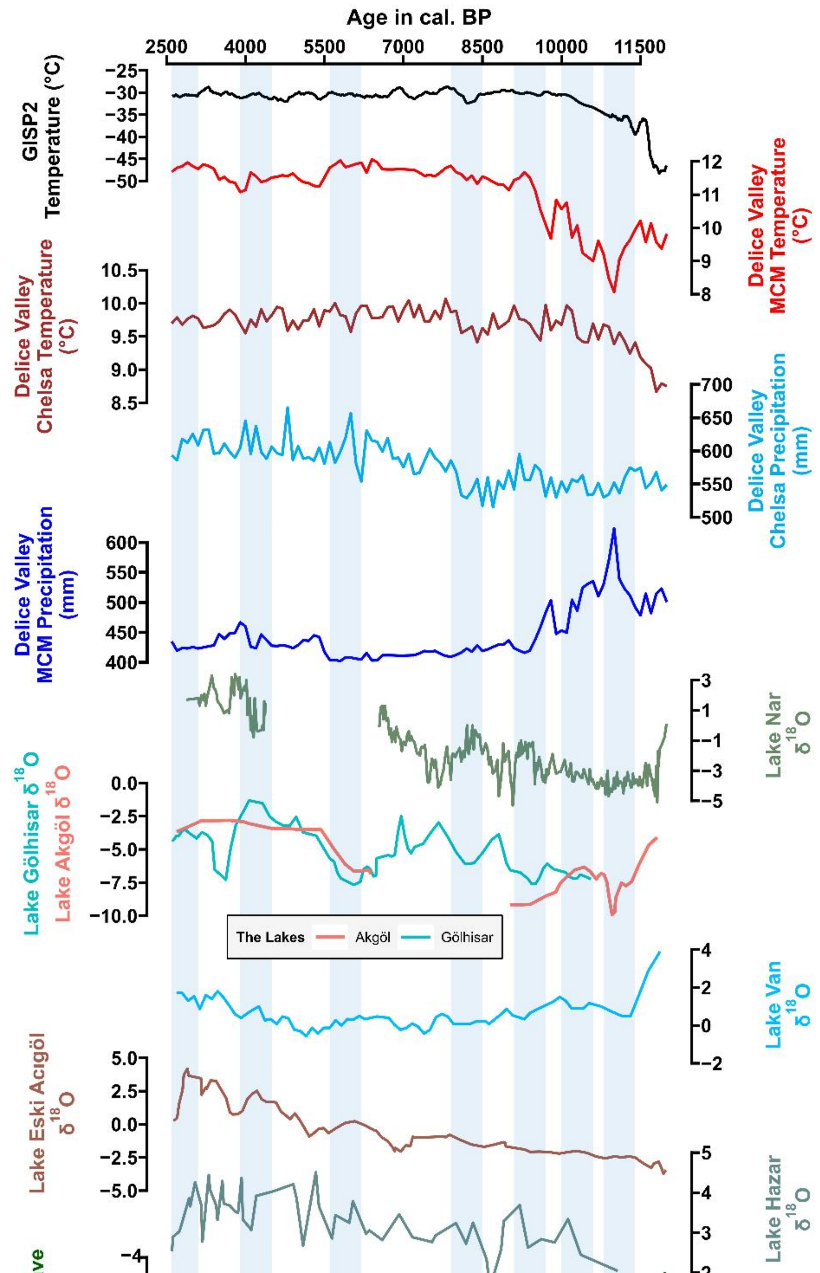

Figure 9.2: Comparison of various proxy records to the MCM and CHELSA results: Temperature records from the GISP2, Greenland (Alley, 2000). The MCM and CHELSA temperature output of the Delice Valley. The MCM and CHELSA precipitation output of the Dicle Valley. δ18O records from Nar Lake, central Türkiye (Dean et al., 2015). δ18O records from Lake Gölhisar and Lake, Akgöl southwest Türkiye (Leng et al., 1999; Eastwood et al., 2007; Roberts et al., 2008). δ18O records from Lake Van, east Türkiye (Wick et al., 2003; Roberts et al., 2008). δ18O records from Lake Eski Acıgöl, central Türkiye (Roberts et al., 2001, Roberts et al., 2008). δ18O records from Lake Hazar, east Türkiye (Ön et al., 2018). δ18O records from İncesu Cave, northwest Türkiye (Erkan et al., 2022).

By 4200 cal. BP, a marked and widespread reduction in precipitation is observed; strong negative values dominate the map, clearly indicating a severe drought episode. At 4100 cal. BP, there is a significant increase in rainfall compared to the previous century, suggesting a partial climatic recovery. Overall, the CHELSA data indicate that the Resuloğlu settlement experienced a phase of pronounced hydrological instability, particularly around the 4200 BP event.

On the other hand, the "normal climate" scenario shown in Figure 7.1 of Chapter 7 for the MML simulations represents precipitation values reconstructed for Resuloğlu Höyük based on the MCM model. A similar pattern is visible here, as in the CHELSA model. Around the 4.2 ka event, there is an approximate 25 mm decrease in precipitation, a change that would have posed a significant risk for agropastoral communities whose subsistence relied heavily on agriculture. Both the MCM and CHELSA models, alongside multi-proxy data, successfully reconstruct the paleoenvironment of the Delice Valley and, more specifically, Resuloğlu Höyük. Although the magnitude of precipitation change differs between models, both capture comparable climatic patterns for the region. The fact that both models indicate a substantial drop in precipitation around the 4.2 ka event strongly supports the interpretation that the grain silos at Resuloğlu were possibly built and used as an adaptive strategy to cope with drought. This reinforces the likelihood that these silos functioned as buffers against periods of climatic stress.

The consistency between the models strengthens the interpretation that the inhabitants of Resuloğlu had to adapt to increasingly arid and variable environmental conditions during the Early Bronze Age. These findings offer critical insights into the site's agricultural capacity, resource management strategies, and long-term socio-ecological resilience.

This stage allows for a return to the initial research question to be reconsidered in light of the overall findings.The question asked whether there was a significant climatic change in the Delice Valley during the Early to Middle Holocene. Based on the paleoclimatic reconstruction derived from multiple models (MCM and CHELSA) and multi-proxy datasets, it is evident that the region experienced substantial climatic variability. In particular, the 4.2 ka climate event stands out clearly in both the model outputs and the proxy records. This climatic shift is also reflected in the subsistence strategies of contemporary communities and in the adaptive measures they adopted to cope with the challenges posed by this environmental stressor.

Although the CHELSA-TraCE21k paleoclimate model offers high-resolution, globally downscaled datasets derived from transient climate simulations, it remains primarily suited for capturing broad-scale climatic trends and variability. However, the unique topographic complexity and microclimatic heterogeneity of the Delice Valley require a more tailored and region-specific reconstruction of past climate conditions. For this reason, the Macrophysical Climate Model (MCM) was preferred in this study. Unlike CHELSA, MCM allows the integration of local topographic parameters, such as elevation, slope, and aspect, with empirical meteorological data from nearby stations. This flexibility makes MCM particularly effective in reconstructing valley-scale hydroclimatic conditions, especially in regions where microclimatic gradients significantly influence settlement dynamics and ecological processes. Furthermore, the MCM framework provides a synoptic understanding of Holocene climate transitions, including seasonal precipitation and temperature trends, which are critical for agent-based modeling experiments and long-term landscape simulations. Therefore, the selection of MCM over CHELSA ensures a more accurate and context-sensitive paleoenvironmental foundation for analyzing human–environment interactions in the Delice Valley.

The first hypothesis aimed to determine whether abrupt Holocene climate events—particularly the 8.2 and 4.2 ka events—had measurable and regionally specific impacts in the Delice Valley. This was tested using high-resolution climate modeling (CHELSA-TraCE21k and Macrophysical Climate Models), proxy datasets, and geomorphological indicators. The findings reveal that these climate shifts led to significant changes in precipitation and temperature regimes within the valley. Notably, following the 4.2 ka aridification event, settlement strategies became more dispersed, storage systems such as silos became more prominent, and a transition toward risk-buffering subsistence practices occurred. These environmental and social shifts are traceable in both archaeological settlement distributions and ecological simulations. Therefore, the hypothesis is supported by the evidence derived from both paleoenvironmental models and archaeological datasets.

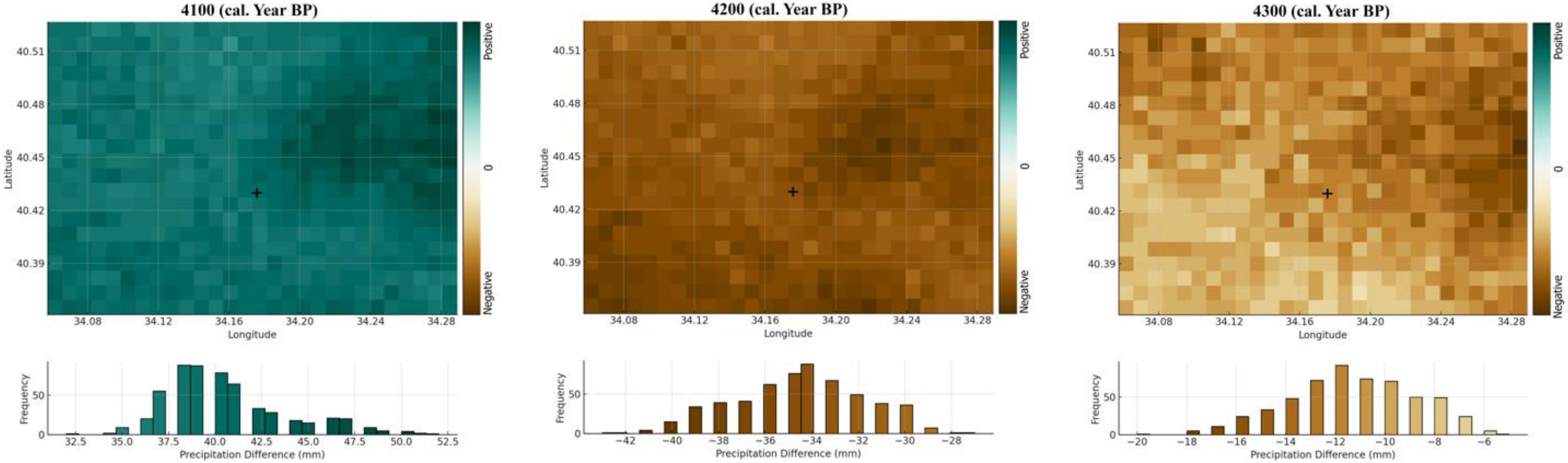

Figure 9.3: Precipitation difference maps and corresponding distribution graphs for Resuloğlu Höyük and its surroundings, generated using the CHELSA-TraCE21k paleoclimate model. Each map illustrates the change in precipitation compared to the preceding time interval. The '+' symbol marks the location of Resuloğlu Höyük.

9.3 The Organization of Settlement Systems Under Changing Paleoenvironmental Conditions

Besides the past environmental conditions, the influence of the socio-political framework must have shaped the settlement patterns throughout the archaeological periods. The scattered nature of settlement patterns throughout the Chalcolithic period (Table 9.1) coincided with the formative nature of this period in terms of the socio-political organization of human societies. One of the possible reasons for the dispersed distribution of settlements during the Chalcolithic period is the relative abundance of resources combined with low population density and a limited number of settlements. These factors may have led to a more widespread use of land and resources, resulting in a more dispersed settlement pattern across the landscape.

During the Early Bronze Age (EBA), the emergence of chiefdoms—representing the region's first middle-range and centralized social formations—contributed to a distinctly clustered pattern of settlement distribution (Table 9.2). This period also marked the onset of intensive and diversified resource exploitation across Anatolia, with the Delice Valley following similar trends (Dardeniz, 2020; Dardeniz, 2023). In contrast, Iron Age settlements exhibited a more dispersed spatial pattern, reflecting the fragmentation of central authority after the collapse of the Hittite Empire. This era signified a transformation wherein the once-complex imperial structure gave way to smaller, locally governed political entities.

The terrain preferences of archaeological settlements were analyzed in detail using modern Geographic Information Systems (GIS) tools. Specifically, the r.geomorphon module within Grass GIS was employed to classify six distinct geomorphological units based on a 5-meter resolution Digital Elevation Model (DEM). These units include flatlands, pits, channels, passes, ridges, and peaks. This classification enabled a detailed temporal analysis of the types of landforms preferred by settlements across different archaeological periods (Figure 9.4).

This shift marks a period of intensified settlement clustering, likely driven by increased reliance on agriculture and more centralized socio-political structures such as chiefdoms. The preference for productive and accessible land indicates a strategic adaptation to both demographic and environmental pressures.

Table 9.2: Average Nearest Neighbor (ANN) analysis results for the archaeological periods discussed.

Periods	Number of Settlements	Dataset Type	ANN Ratio	Z-Score	P-Value	Observed Mean Distance (m)	Results
Chalcolithic	13	Point	1.253571	1.749048	0.080283	6096.7846	Dispersed
EBA	107	Point	0.436936	-11.142436	0.0000	1992.4823	Clustered
Iron Age	60	Point	0.869998	-1.926447	0.054049	5316.1997	Clustered
Unknown	26	Point	0.920603	-0.774499	0.438636	7713.0185	Random

Iron Age settlements, while less clustered than those of the EBA, continued to target *valleys* and *ridges* (Figure 9.3). This indicates a tendency among local, self-governing polities to seek out terrain that offered both agricultural potential and natural defense, in the aftermath of the dissolution of the centralized Hittite Empire. Settlements with unknown chronological association most frequently occupied *flatlands* and *valleys* (Figure 9.4).

The broader geomorphology of the Delice Basin is dominated by *valleys* and *ridges*, characteristic of a geologically young and tectonically active region. Fluvial systems have carved out *hanging valleys* and dissected *peneplain* fragments at higher elevations, while tectonic activity has uplifted the interior of the basin, creating a fragmented and rugged landscape. This complex geomorphological evolution, coupled with the region's long-term arid climate history, led to the formation of extensive *badlands* within the Delice Basin. These highly eroded zones significantly limited the availability of suitable land for permanent settlement. As a result, ancient communities were compelled to carefully select locations based on both agricultural productivity and defensive advantage—favoring flat floodplains and elevated ridges.

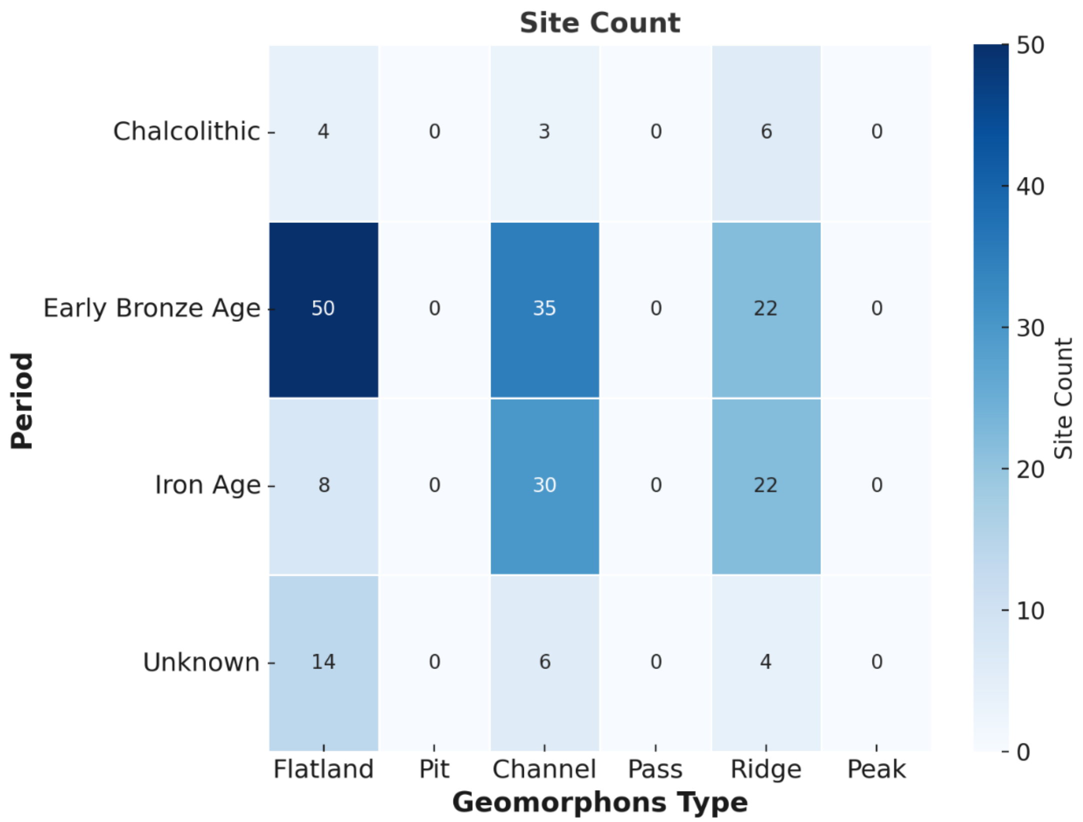

Figure 9.4: Terrain preference analysis of four archaeological periods discussed (n = the number of settlements).

The second hypothesis posits a correlation between climate stability and the type of socio-political organization that emerged. It suggests that hierarchical structures were more likely to form during stable and agriculturally productive periods, while heterarchical or decentralized structures developed under environmentally unstable conditions. This was evaluated using spatial analysis tools such as Average Nearest Neighbor and Kernel Density Estimation to examine clustering and dispersal patterns across archaeological periods. The results indicate that during the Early Bronze Age (ca. 5000–4000 cal. BP), settlements were increasingly concentrated in fertile agricultural zones and near key resources like salt and copper, reflecting more complex, centralized social systems. In contrast, during the Iron Age, following the collapse of the Hittite Empire, settlement patterns became more dispersed, and communities emphasized self-sufficiency. These patterns confirm that climatic variability and resource accessibility directly shaped social and spatial organization. Thus, the hypothesis is well-supported.

9.4 Resource distribution and Settlement Organization around resources

From the natural resource use perspective, the availability of salt and copper puts Delice Valley in a significantly advantageous position during the 6000–2600 cal. BP. Exploitation and distribution patterns of salt and metals were first shaped around the basics like preservation of food or producing simple tools or ornaments. The consumption was later accelerated with diverse socioeconomic and sociopolitical needs that required extensive food processing and guaranteeing herding activities via salt, or securing accumulation of wealth via metals. With the increasing demand for alloys like bronze during the EBA, the need for copper was accelerated. The majority of the EBA sites have a proximity to copper mineralization at Delice Valley (see Figure 2.1b), which exceeded the need for local needs.

Copper and its alloys as well as silver have been the wealth accumulator of the centralized economies of the following periods. Salt on the other hand, rather than being a wealth accumulator, has always been a vital commodity to living populations. Aside from daily consumption and preserving food with various techniques, salt stands as one of the basics of the animal economy. Herding animals and obtaining secondary products including leather requires salt. Given the significance of agro-pastoral lifeways in north-central Anatolia, the presence of settlements from the Early Bronze

Age through the Iron Age in proximity to rock salt deposits and saltpans is hardly unexpected (Dardeniz, 2023). According to Table 3, the EBA and Iron Age sites appear always closer to salt reserves than copper, indicative of the significance of herding activities for economies of clustered systems.

There were several factors responsible for temporal changes in settlement patterns as well as the relatively low-density settlement patterns during certain phases of Delice Valley. Under the progressive aridity that set in after the EH (after ca. 8200 cal. BP), archaeological sites in the region must have employed diverse land use strategies. This coincided with the dispersed Chalcolithic settlements in the research area and across Central Anatolia.

In Delice Valley, these sites targeted ridges for protection and plains, which were the most suitable locations for the agro-pastoral mode of subsistence under generally stable paleoclimatic conditions of this period. Additionally, these sites were not too far from salt resources (see Figure. 2.1a, also in the next paragraph). During the EBA, the impact of paleoclimatic oscillations and the emergence of the first centralized socio-political entities aside from middle-range groups brought heavily clustered settlement patterns where human groups targeted flatlands and valleys in the Delice landscape. This suggests that the inhabitants practiced intensive agriculture, which might have been supplemented with pastoralism.

The westward shift of Early Bronze Age settlements toward the central part of the Delice Valley, along with settlement patterns clustering around salt resources (see Figure 2.1b), reinforces this interpretation. This period also witnessed an apparent intensification in copper ore extraction. In the Iron Age, after the collapse of the Hittite Empire and the rise of local political entities, settlement distribution became moderately clustered, with communities preferentially occupying valleys and ridgelines (see Figure 2c). Although increasing aridity continued to affect the region, the breakdown of centralized authority shifted priorities toward self-sufficiency. As a result, inhabitants concentrated on landscapes best suited for small-scale agro-pastoral livelihoods. Despite these socio-political transformations, overall settlement distribution showed limited deviation from EBA patterns..

Using the distribution of archaeological sites, copper ores, and salt resources in Figure. 2.1a-c, I used GIS tools to calculate the minimum, maximum, and average distances among these points in Table 9.3 According to these calculations, the average distance to salt resources, which are exclusively located in flatlands, diminished from the

Chalcolithic (44.4 km) to EBA (31.5 km). This 29 % reduction in distance was partly due to the increase in the number of EBA sites however, it also supports the agro-pastoral nature of subsistence during this period as salt was a vital resource for these groups. In the Iron Age, the average distance to salt resources was around 36.2 km (18.9 % closer than the Chalcolithic) but this was also due to the number of sites dropping. The preference for Iron Age sites remaining within a day's distance of salt resources suggests the persistence of herding as a main subsistence pattern. As far as the copper ores –all situated on ridges– are concerned, the average distance in the Chalcolithic (51.5 km) dropped to 41.4 km during the EBA (19.6 % change). The distance to copper ores was around 46.3 km in the Iron Age, which was only 9.3 % closer than the Chalcolithic. The increasing distance between Iron Age sites and copper ores might be the result of changes in terrain preferences such as valleys and flatlands.

Table 9.3: GIS-based calculations of the maximum, minimum, and average distances (in kilometers) to copper and salt resources across the four archaeological periods.

Period	**Salt**			**Copper**		
	Max	**Min**	**Avg**	**Max**	**Min**	**Avg**
Chalcolithic	95.8	30.4	44.4	71.2	37.5	51.5
Early Bronze Age	76.5	0.0	31.5	98.1	1.1	41.4
Iron Age	84.2	1.0	36.2	98.1	2.0	46.3
Unknown	83.3	0.4	35.0	104.8	8.6	46.8

The reasons for the relatively low-density settlement pattern during the MBA and LBA in Delice Valley call for an explanation. Delice Valley did not present MBA-LBA sites because under increasing political complexity (i.e., the transition from local kingdoms to the Hittite Empire), intensive agricultural production was the priority.

Delice Valley, with its climatic patterns and highly erosive nature of the topography (badlands in geological terms), was not suitable for establishing large settlements where people farmed extensively. The only large settlement from these periods in the area was Hattusha, which was near Budaközü, a major tributary of Delice. Aside, there must have been numerous villages around the capital that fed its population. Under the Hittite imperial system, it was also possible that the rural population of Delice Valley must have attracted artisanship, crafts production, and long-distance trade. The research area attracted pastoralists because it contained salt deposits and salty water sources (Dardeniz, 2023).

9.5. Landscape Evolution Dynamics in the Delice Valley under Different Land Use Patterns and Climate Change Scenarios

This study aims to understand the effects of settlement activities—carried out under different agropastoral subsistence strategies (land use) and climate scenarios—on landscape evolution at Resuloğlu. results of MedLanD provide an effective tool for investigating surface dynamics and the impact of rural land use on landscapes. Based on extensive archaeological excavations and multidisciplinary research at Resuloğlu Höyük, it is widely accepted that the community primarily engaged in agriculture and maintained a self-sufficient subsistence system centered on farming. The results of ABM experiments align well with these archaeological interpretations, offering the means to test such data-driven assumptions.

9.5.1 Agricultural substitutions strategy

The research evaluated every essential agricultural variable within all three climate conditions. The simulations started with 115 people who evolved throughout time based on environmental feedback from agents and their economic output. The agricultural population managed to endure throughout all climate-driven agricultural situations. Under arid conditions (Scenario 1), the population increased from 115 to approximately 165 individuals. The population levels in Scenario 2 fluctuated between 115 and 130 individuals while following a steady pattern. The population in the wetter climate scenario (Scenario 3) showed extreme changes as numbers dropped between 15 and 90 individuals below the numbers in Scenarios 1 and 2 (Figure 9.5). To evaluate the environmental effects of the agricultural economy researchers computed the average yearly soil erosion values from all climate conditions. The arid climate produced an average erosion rate of -9.55×10^{-4} kg/m²/year. The average erosion rate increased to -1.14×10^{-3} kg/m²/year during normal climate conditions but reached -1.35×10^{-3} kg/m²/year during the wetter climate scenario. The agricultural data reveals that precipitation directly affects soil erosion levels in these environments. The results align with predictions for regions with badlands and high erodibility because heavier rainfall creates more runoff that results in greater soil loss.

The agricultural economy framework allowed researchers to examine CV values for vegetation cover assessment across different climate scenarios.

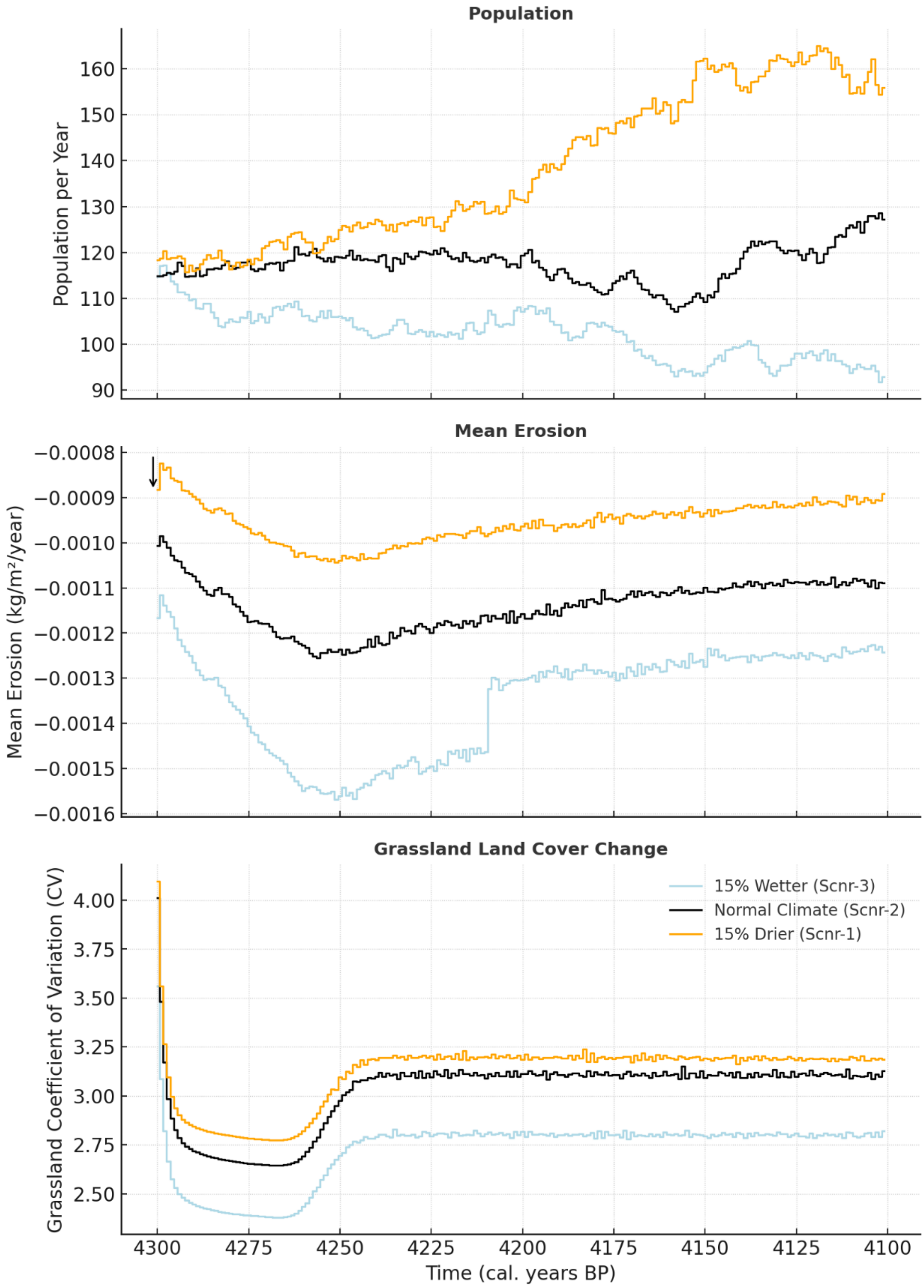

Figure 9.5: Time series representation of population distribution, average erosion (the black arrow indicates the direction of increasing erosion), and the Coefficient of Variation (CV) of grassland land cover change over 200 years (4300–4100 BP) under an agricultural subsistence strategy, modeled across three climate scenarios: 15% drier (Scenario 1), normal (Scenario 2), and 15% wetter (Scenario 3).

The CV serves as a dimensionless value that measures how much land cover changes over time which also reflects biodiversity levels. High CV values show that vegetation structures are diverse while low CV values may suggest ecological degradation or homogenization. At the beginning of the simulations, the three scenarios showed high CV values (~4.1) which indicated that the landscape consisted of mature grasslands and shrubs together with high biodiversity. The initial fifty years brought about rapid decreases in CV values because of human-induced changes to the landscape. The system established a new equilibrium following this period and CV values achieved stability (Figure 9.5). The wetter climate scenario produced CV values that were lower than expected which resulted in decreased biodiversity. The unexpected outcome seems to result from heavy rainfall-induced erosion combined with the fast growth of dominant ecological species which creates habitat simplification. Wetter climatic conditions do not always result in ecological richness because they may cause habitat simplification and destabilization under specific circumstances. (Figure 9.5).

9.5.2 Agropastoral substitutions strategy

In the agropastoral (mixed) scenarios, where the subsistence strategy relies equally on agriculture and animal husbandry (50%–50%), population trends, average erosion rates, and the Coefficient of Variation (CV) values—reflecting vegetation change over grassland areas—have been jointly evaluated, as in the agricultural economy scenarios (Figure 9.6).

Under the mixed economy, all three climate scenarios indicate a significant population collapse over time. The population, which starts at 115 individuals, declines to just 16 individuals by the end of the simulation period in all three scenarios (Figure 9.6). This suggests that the inhabitants of Resuloğlu were unable to sustain themselves over the long term through a mixed economic strategy. Although the population remains slightly higher under the wet climate scenario, the difference is marginal.

In the agropastoral subsistence model, erosion increases in parallel with precipitation. This is an expected outcome, as higher rainfall enhances surface runoff and consequently intensifies soil transport. According to 200-year agent-based simulations run with the MedLanD model (Figure 9.6), the average soil loss under arid conditions (Scenario 4) is -9.75×10^{-4} kg/m²/year; under normal climate conditions (Scenario 5), it is -1.14×10^{-3} kg/m²/year; and under wet conditions (Scenario 6), it rises to -1.29×10^{-3} kg/m²/year (Figure 3).

The CV values, which reflect temporal variation in vegetation cover, are nearly identical across all three climate scenarios (~3.046–3.048). This indicates that, despite climatic differences, the agropastoral system maintains a comparable level of vegetation heterogeneity and biodiversity. In other words, the agropastoral economy appears to offer a degree of ecological resilience, sustaining a stable level of biodiversity even under varying climatic stressors (Figure 9.6).

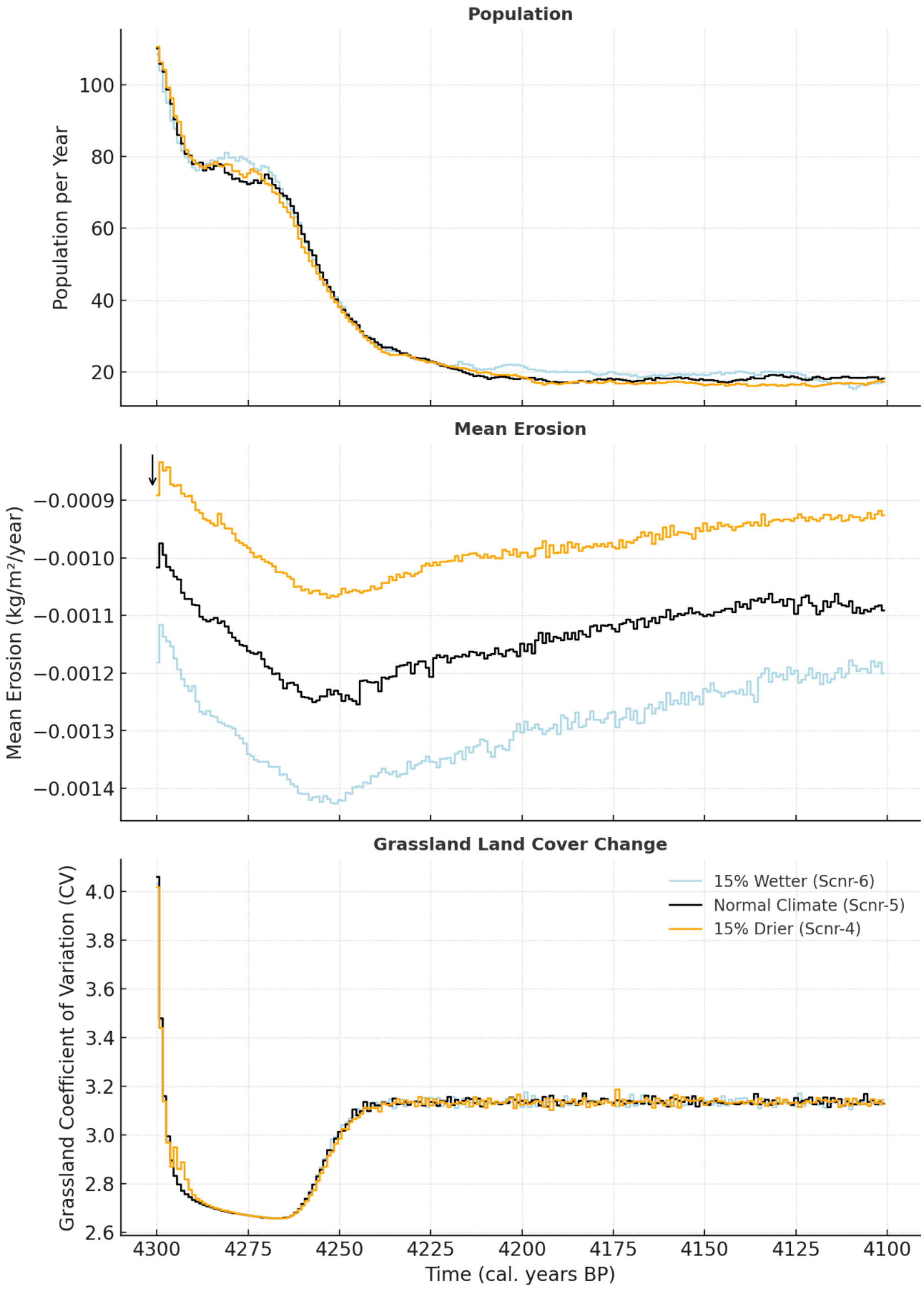

Figure 9.6: Time series representation of population distribution, average erosion (the black arrow indicates the direction of increasing erosion), and the Coefficient of Variation (CV) of grassland land cover change over 200 years (4300–4100 BP) under an agropastoral (mixed) subsistence strategy, modeled across three climate scenarios: 15% drier (Scenario 4), normal (Scenario 5), and 15% wetter (Scenario 6).

9.5.3 Pastoral substitutions strategy

The livestock-dominant pastoral subsistence strategy (80% animal husbandry, 20% agriculture) was evaluated in terms of population dynamics, soil erosion, and land cover change over a 200-year simulation period, similar to the other subsistence models (Figure 9.7).

In all three climate scenarios, population collapse is evident, mirroring the trends observed in the agropastoral scenarios (Figure 9.7). The population, which initially begins with 115 individuals, steadily declines to single-digit values over time. Regardless of climatic conditions, the pastoral strategy proves to be unsustainable in the long term. When compared to agropastoral scenarios, both subsistence types exhibit long-term vulnerability, ultimately failing to maintain a stable population. As with the agropastoral strategy, erosion increases with precipitation under the pastoral model. In arid conditions (Scenario 7), the pastoral system experiences relatively lower soil loss (-9.74×10^{-4} kg/m²/year). In contrast, under wet climatic conditions (Scenario 9), elevated surface runoff and soil saturation result in significantly higher erosion rates (-1.28×10^{-3} kg/m²/year). (Figure 7.5).

The CV values are consistently high and show minimal variation across the three scenarios. This indicates that the pastoral strategy—based primarily on animal husbandry—generates a comparable degree of vegetation diversity and temporal variability across different climatic conditions. In other words, while these systems are ecologically dynamic, as shown by the population analyses, they are not demographically sustainable (Figure 9.7).

Modeling population within a complex systems perspective is essential. While a meaningful pattern was observed between subsistence strategy and the population's ability to sustain itself, no significant correlation was found between climate change and population sustainability. Specifically, under all three climate types, the agricultural economy was able to support a population size consistent with the archaeological evidence. However, both agropastoral and pastoral strategies proved unsustainable for Resuloğlu, as neither could maintain a stable population over time. Considering the substantial grain storage facilities and the load-bearing capacity of architectural structures at the site, it is evident that the population likely ranged between 110 and 120 individuals, and that the storage systems point toward an agricultural mode of subsistence. In this context, the MedLanD proves successful in modeling both population dynamics and subsistence strategies in alignment with archaeological realities.

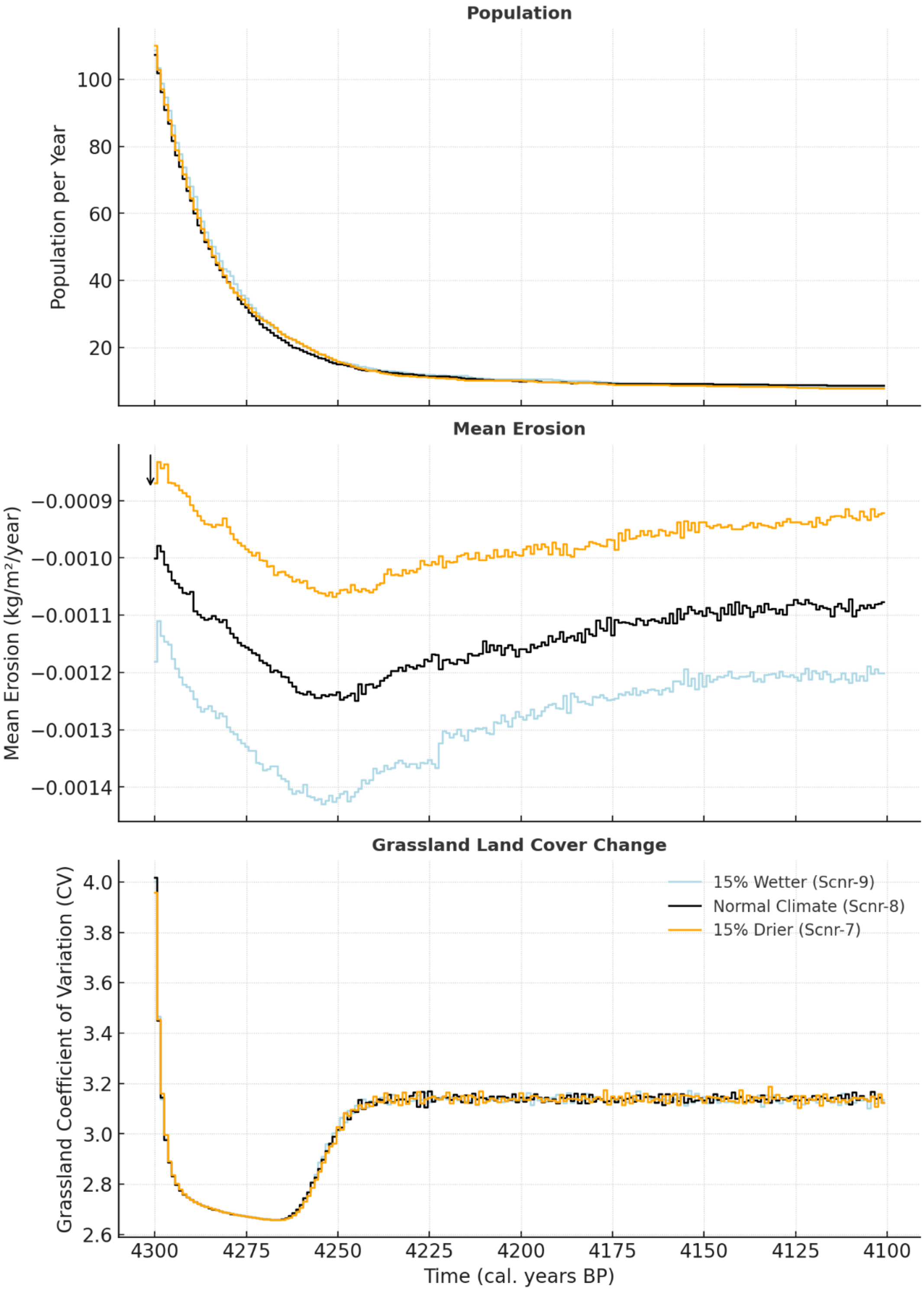

Figure 9.7: Time series representation of population distribution, average erosion (the black arrow indicates the direction of increasing erosion), and the Coefficient of Variation (CV) of grassland land cover change over 200 years (4300–4100 BP) under an pastoral subsistence strategy, modeled across three climate scenarios: 15% drier (Scenario 7), normal (Scenario 8), and 15% wetter (Scenario 9).

Each subsistence strategy was simulated under three distinct climate scenarios (Figure 9.8). The results reveal clear differences in the effects of various subsistence modes on landscape erosion under the three climate scenarios. Under the 15% drier climate scenario, the agricultural subsistence strategy (Scenario 1) resulted in the lowest erosion rate at -9.55×10^{-4} kg/m²/year. This can be attributed to the limited surface runoff caused by low rainfall, which prevents significant soil displacement on cultivated fields left exposed due to vegetation removal. In contrast, the pastoral subsistence strategy (Scenario 7) exhibited a higher erosion rate of -9.74×10^{-4} kg/m²/year (Figure 9.5). This increase is primarily due to the biotic pressure from intensive livestock activity, which accelerates the degradation of pastureland. Under the 15% drier climate scenario, the environmental impact of the agropastoral subsistence strategy (Scenario 4) is relatively higher than that of the agrarian strategy (Scenario 1), and it produces erosion levels similar to those observed in the pastoral strategy (Scenario 7). Especially in badlands—topographies highly susceptible to erosion—the impact of this biotic pressure is amplified. As a result, the region is highly vulnerable to livestock-induced degradation under dry conditions, leading to significantly elevated erosion values.

Under normal climate conditions, all three land use strategies displayed relatively similar environmental impacts. However, erosion rates under normal rainfall were significantly higher than those in the drier scenario, primarily due to increased surface runoff driven by 15% more precipitation.

The subsistence strategies simulated under the 15% wetter climate scenario exhibited varying degrees of anthropogenic impact. The agricultural strategy (Scenario 3), under these conditions, produced the highest erosion rate not only for this climate type but across all modeled scenarios, with a value of -1.35×10^{-3} kg/m²/year (Figure 9.8). This elevated impact results from the combined effect of intensive land disturbance from agricultural activities and increased rainfall, which together heighten soil erodibility. Conversely, the pastoral strategy (Scenario 9) under wet conditions had a lower erosion impact. Under the 15% wetter climate scenario, the erosional impact of the agropastoral subsistence strategy (Scenario 6) is lower than that of the agrarian strategy (Scenario 3), but higher than that of the pastoral strategy (Scenario 9). This is mainly because increased precipitation supports year-round green pastures, promoting ecological continuity. Additionally, in badlands topography, long grasses can effectively cover the soil, reducing stress from surface runoff and thereby limiting erosion.

In all scenarios—regardless of climate type or subsistence strategy—the average erosion rate increases rapidly within the first 50 years, reaching peak levels (Figure 9.8). One of the primary reasons for this early surge is the initial disturbance caused by the introduction of human activity into a previously undisturbed landscape. The system requires a certain recovery period to adapt to this intervention. Furthermore, relatively high levels of precipitation during the first 100 years, combined with the inherently low resistance of badlands topography to surface runoff—especially during heavy rainfall events—further contribute to the sharp rise in erosion observed in the early phase.

In summary, no direct correlation was observed between erosion levels and population size. However, the combination of the applied subsistence strategy and the prevailing climatic conditions proved to have a decisive influence on landscape evolution. It is evident that precipitation is the dominant force shaping the region's landscape dynamics. Nevertheless, whether precipitation is high or low plays a key role in determining the environmental impact of pastoral communities. Under dry climate conditions, biotic pressure on pastureland exacerbates erosion. In contrast, under wetter conditions, pastures are more resilient to intensive grazing. The sustained presence of green, tall grasses helps protect the soil surface, mitigating erosion over time.

The third hypothesis asserts that different land-use strategies introduced during the Early Holocene—ranging from extensive pastoralism to intensive agriculture—led to distinct landscape transformations and erosion dynamics. To evaluate this, agent-based modeling experiments were conducted using the MedLanD framework under three climate scenarios (dry, normal, and wet) and three subsistence strategies (agricultural, agropastoral, and pastoral). The results show that intensive agricultural practices led to rapid and localized soil degradation, while extensive pastoral systems induced more gradual but spatially widespread changes. Agropastoral strategies produced more balanced outcomes and were generally more sustainable depending on climatic context. These findings demonstrate that subsistence strategies not only influenced demographic resilience but also significantly shaped geomorphological processes.

Consequently, the hypothesis is confirmed through both simulation data and ecological interpretation.

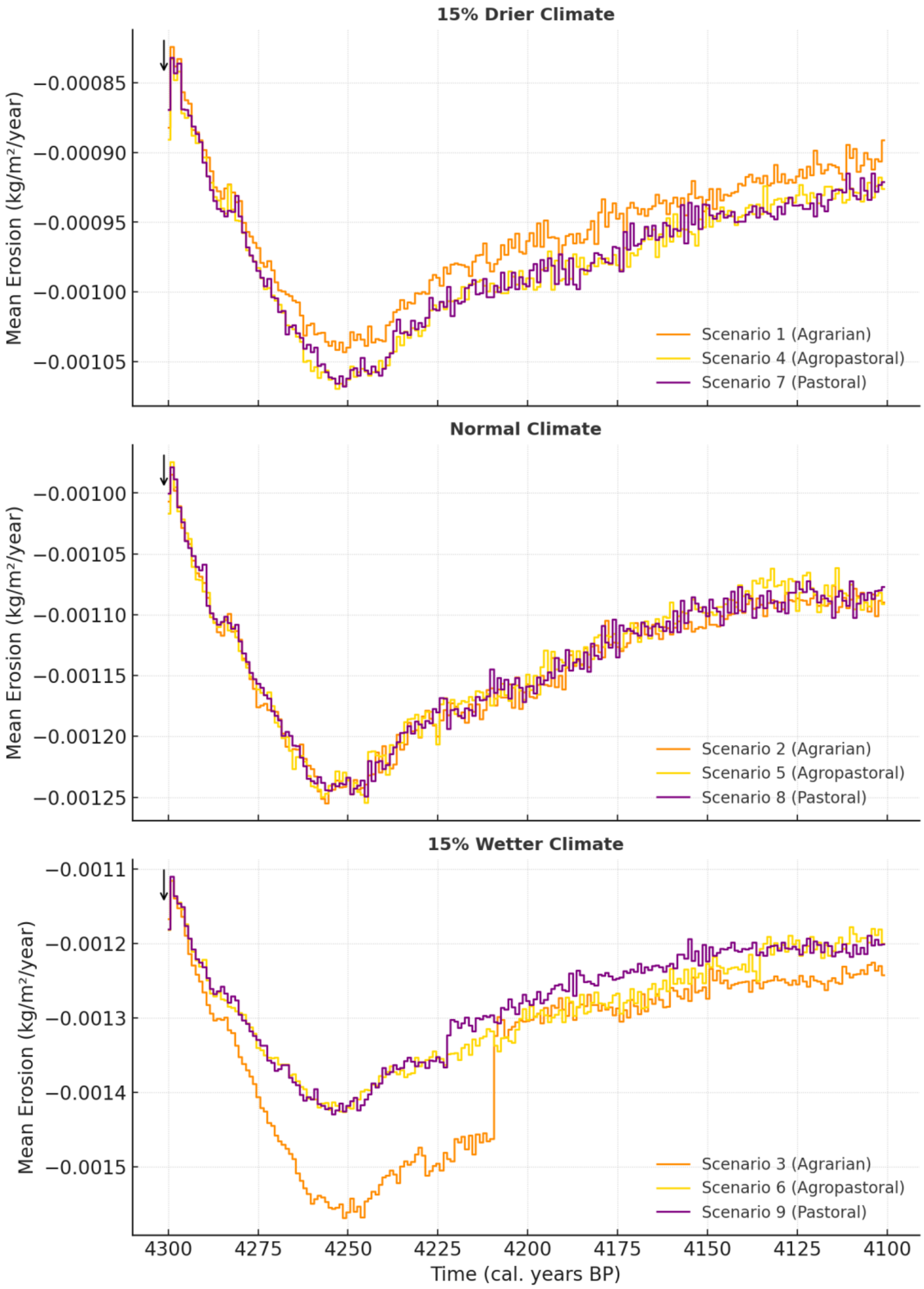

Figure 9.8: Annual erosion rates for all subsistence strategies (agrarian, agropastoral, and pastoral) simulated under each climate scenario. Black arrows indicate the direction of increasing erosion (Note; The differences in y-axis scales).

9.6 Mitigation measures

It is possible to identify mitigating strategies (i.e., adaptive behaviors) of archaeological societies under changing environmental conditions from the perspective of settlement distribution across the landscape. In terms of mitigating strategies, well-irrigated arable fields were always regarded highly and settlements were located near such plains throughout the periods. The inhabitants of Delice Valley also employed strategies other than targeting specific landforms or locales in the landscape. The scattered nature of settlement patterns throughout the Chalcolithic period makes it difficult to make conclusive statements about mitigating strategies or adaptive behaviors. The EBA (c. 4300–4100 cal. BP) site of Resuloğlu was inhabited during the 4.2 kyr event, which reflects all of the characteristics mentioned above. This hilltop settlement spanned an area of 0.3 hectares and was accompanied by a contemporaneous cemetery situated on the adjacent hill (Arıkan and Yıldırım, 2018). The steep side of the triangular hill was lined with a fortification wall, where houses abutted this structure. These houses were small, two-story structures with hearths, bins, ovens, weaving stands, and other domestic installations that were typical of the EBA. A large, chiefly residence of 15 rooms was located at the short end of the triangle. This unit had its enclosure as well as domestic installations. The central courtyard was reserved for communal activities. A distinctive feature of Resuloğlu is the discovery of up to 70 silos, each capable of storing nearly one ton of grain (Dardeniz and Yıldırım, 2022). Both the chief's residence and ordinary houses had these silos. It is highly probable that the inhabitants of Resuloğlu farmed the floodplain of Delice Valley and transported the harvest up to the hilltop settlement to store in large silos around the 4.2 kyr event. The settlement infrastructure together with its installations demonstrate no signs of socio-economic or political crisis because of drought in the region which indicates the effectiveness of drought mitigation strategies at the site.

9.7 Preserving and Passing Down Cultural Memory and Heritage in the Context of Resuloğlu Mound

Resuloğlu has been shaped by significant erosion processes from past to present and currently remains under erosion risk. One of the main research questions in this study investigates whether the archaeological excavations conducted at the site have triggered further erosion. Between 2003 and 2019, archaeological excavations significantly disrupted the geomorphic systems surrounding Resuloğlu (Figure 9.9). Excavators opened structures reaching depths of up to 3 meters, and large soil covers were removed, leaving the terrain uneven. In Chapter 8, the study addresses this research question by applying QGeoWEPP, an innovative and user-friendly soil erosion model.

Figure 9.9: Disturbance to the topography during archaeological excavations at Resuloğlu Mound. Soil removed from excavation rooms was dumped downslope, disrupting the geomorphological structure and accelerating erosion. Photograph from the Resuloğlu Excavation Archive (2023)

The QGeoWEPP model served as an erosion prediction tool to simulate eight hillslope erosion rates under pre-excavation and post-excavation scenarios through GIS and remote sensing and geomorphological analysis. The simulation results demonstrate that unregulated fine-grained excavated soil disposal on steep slopes (Figure 9.9) caused significant erosion.

The Cem-1 ID hillslope had pre-excavation values almost identical to its reference hillslope, Cem-4 ID. However, post-excavation, the average annual runoff for the Cem-1 ID hillslope increased from 12.6 mm/yr to 20.1 mm/yr. This is because the soil cover was completely removed, exposing burial chambers and architectural features with a pavement-like surface that significantly reduced infiltration and increased surface runoff. Pavement surfaces typically accelerate runoff as water moves rapidly over them and the average annual soil loss for this hillslope increased from 1.1 kg/m² to 2.1 kg/m², while the Average annual sediment yield increased from 11 t/ha/yr to 21 t/ha/yr. These results highlight the substantial impacts of excavation-related disturbances on hillslope dynamics and their hydrological and geomorphological processes.

Soil material removed from areas outside the boundaries of the hillslopes was deposited in the upper sections of Cem-2 and Cem-3. The excess soil deposited on their upper sections resulted in a decrease in runoff in the post-excavation period. In the slopes with the 'Sett' ID in the settlement area, erosion values have been recorded higher compared to the slopes with the 'Cem' ID in the cemetery area due to the extent and scale of the destruction (Table 8.4). The primary reasons for this include the excavation of deeper chambers and the dispersion of excavated material over steep slope areas. Additionally, the significantly high average slopes of Sett-1, Sett-2 and Sett-3 (Table 8.4) make it considerably more difficult to protect the displaced soil from erosion in these areas. Particularly on the slopes of Sett-2 and Sett-3, surface runoff after excavation has significantly decreased compared to pre-excavation conditions (Table 8.4). The main reason for this is that the second segments of these slopes (the area where the material was deposited) constitute a large portion of the slope profile. Furthermore, the thickening of the deposited soil along this segment and its ability to facilitate good infiltration support the reduction in surface runoff.

The GeoWEPP model generates its results through text and GeoTIFF outputs which present spatial distributions of runoff and sediment yield and soil redistribution. Users can use these outputs to analyze patterns effectively and design targeted erosion mitigation strategies. The post-excavation scenario of Sett-3 hillslope shows erosion and sedimentation patterns in Figure 9.7 which reveals the spatial distribution of these

Excavations at Resuloğlu affected more than just archaeological remains—they disrupted the surrounding environment as well. Erosion became a major threat, not only to the cultural layers but also to nearby farmlands, grazing areas, and ecological stability. Factors such as livestock pressure further contributed to the landscape's degradation. For example, rapidly deepening gullies and shifting streambeds now pose serious risks to both the architectural features and the preservation of archaeological data.

Figure 9.10 offers a clear example: a post-excavation GeoTIFF map of the Sett-3 slope shows that soil removed from chambers deeper than 2 meters (Segment 1) was deposited on Segment 2. The steepness of the slope, the high erodibility of the deposited soil, and the lack of vegetation led to significantly increased erosion rates in that area.

Table 9.4: QGeoWEPP model results for all eight hillslopes under *pre-* (Scenario 4) and *post*-excavation scenario (Scenario 1) compared to two neighboring undisturbed reference hillslopes.

Hillslope ID	24 Years of Simulations	Average Annual Runoff (mm)	Average Annual Soil Loss (kg/m²)	Average Annual Sediment Yield (t/ha/yr)
Cem-1	Pre-Excavation	12.6	1.1	11.4
	Post-excavation	20.1	2.1	21.4
Cem-2	Pre-Excavation	12.6	1.0	10.3
	Post-excavation	9.5	1.5	11.3
Cem-3	Pre-Excavation	11.9	0.8	8.7
	Post-excavation	10.5	1.1	11.4
Cem-4	Reference	12.2	1.1	11.3
Sett-1	Pre-Excavation	8.9	1.9	19.1
	Post-excavation	10.8	3.0	30.1
Sett-2	Pre-Excavation	8.2	0.8	8.7
	Post-excavation	6.2	3.8	7.8
Sett-3	Pre-Excavation	8.1	1.1	11.6
	Post-excavation	6.4	4.9	13.7
Sett-4	Reference	8.6	1.5	15.4

The GeoWEPP model provides outputs in both text and GeoTIFF formats, visualizing how runoff, sediment transport, and soil redistribution vary across space. These outputs allow researchers to identify erosion-prone areas and develop targeted strategies to reduce erosion. The erosion and sedimentation patterns visible in Figure 9.10 help illustrate how excavation can drastically reshape landscape dynamics.

Importantly, this modeling work does more than explain past damage—it helps predict future risks. Based on these findings, the study proposes both immediate and long-term conservation strategies, including slope stabilization, vegetation restoration, post-excavation site management, and restrictions on livestock access.

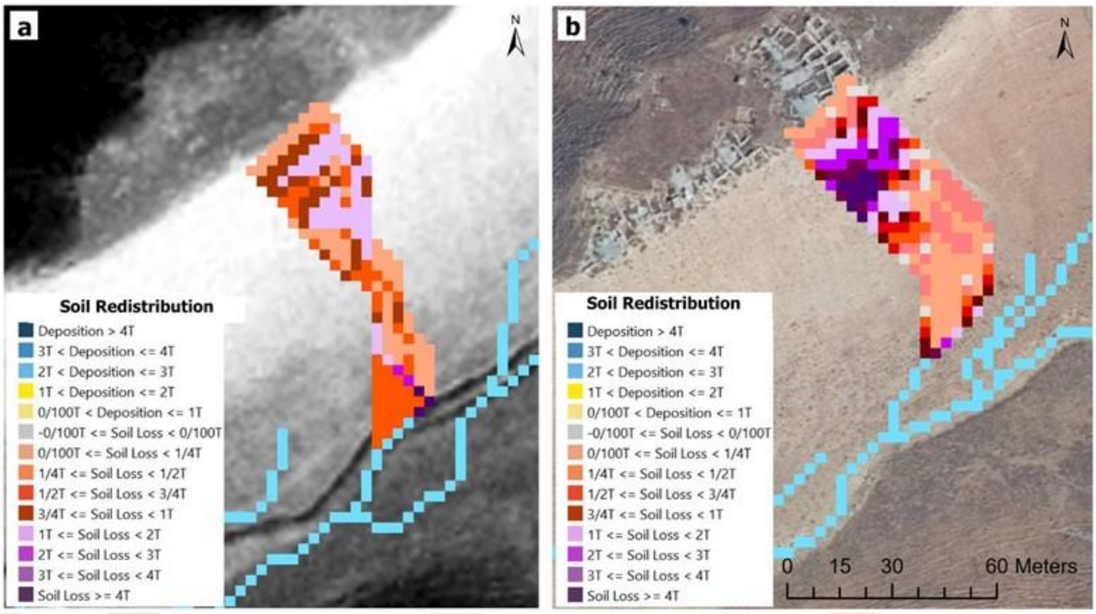

Figure 9.10: Results of the GeoWEPP model applied to the hillslope identified as Sett-3. The figure presents a soil redistribution map illustrating 24 years of modeled erosion and deposition (T = tons per pixel) under the pre- and post-excavation scenarios. The output was generated in GeoTIFF format. a) Base map for the pre-excavation scenario derived from an analog aerial photograph dated to 1990. b) Base map for the post-excavation scenario based on a high-resolution orthophoto from 2024.

The current conservation strategies and land use practices at Resuloğlu Höyük are inadequate and require significant improvement. At present, protection efforts are limited to fences surrounding the excavation trenches (see Figure 9.11). However, given the high risk of soil erosion in the area, it is essential to develop more extensive and integrated policies that consider the site’s broader hydro-geomorphological context.

Moreover, a nearby natural water source draws livestock from the surrounding region to the vicinity of Resuloğlu. This results in additional pressure on the site due to overgrazing and trampling by animals. To reduce this impact, the water should be transported to more distant locations or delivered to animals through more sustainable means.

In summary, this research shows that preserving cultural heritage at Resuloğlu requires more than archaeological excavation. It also demands careful environmental planning. Tools like QGeoWEPP provide a valuable foundation for developing policies and practices that ensure long-term site protection. Such integrated approaches are essential to safeguarding cultural memory and passing it on to future generations.

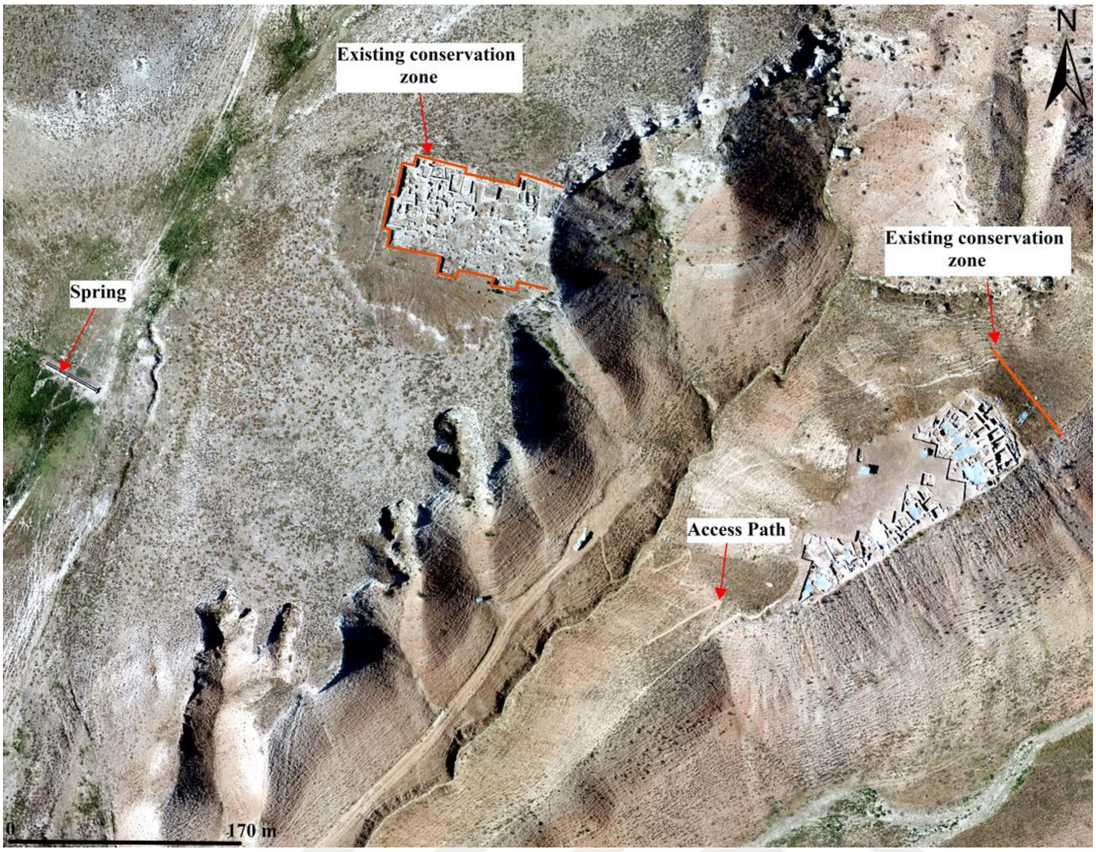

Figure 9.11: Drone imagery of Resuloğlu Mound and its surrounding area, showing infrastructure and current conservation zones. Photograph from the Resuloğlu Excavation Archive (2023)

The final hypothesis explores the geomorphological impacts of modern archaeological excavations, particularly in erosion-prone landscapes such as Resuloğlu Mound. To test this, the GeoWEPP model was employed using SPOT 7 satellite imagery, historical aerial photographs (from 1990), high-resolution drone data, and on-site observations. The model outputs indicate that excavation activities, especially in the cemetery zone situated on steep and geologically sensitive slopes, have accelerated erosion. The removal of protective topsoil layers and the dumping of excavated material downslope have altered the site's natural geomorphology and increased erosion risks. These findings not only shed light on the current degradation processes but also inform future excavation and conservation policies. The hypothesis is thus validated, with practical implications for heritage management and sustainable fieldwork practices.

9.8 Chapter Summary

This chapter presents a detailed analysis of how climate change, settlement patterns, land-use strategies, and geomorphological risks shaped the Delice Valley throughout the Holocene. Drawing on both modeling results and archaeological data, it brings together interdisciplinary methods to address the core research questions of the dissertation. Each section is designed to interpret how human communities interacted with their environment and how these interactions left lasting traces on the landscape.

Climate model outputs (MCM) for the Delice Valley reveal that the Early Holocene (12,000–8200 BCE) was dominated by cold and humid conditions. Rapid climate events—such as those at 11.1 ka, 10.3 ka, and 9.4 ka—caused sharp shifts in temperature and precipitation. Around 6200 years ago, a long-term drying trend began and continued through the Middle and Late Holocene, eventually creating climate patterns similar to today. These environmental changes contributed to the formation of badlands, altered river systems, and—when combined with human activity—led to long-term landscape transformation.

Spatial analysis of 206 archaeological sites using tools such as KDE (Kernel Density Estimation) and ANN (Average Nearest Neighbor) revealed major shifts in how communities settled the valley. During the Chalcolithic period, settlements were sparse and scattered. By the Early Bronze Age, they had become more clustered, especially near key resources like salt and copper, and in fertile lowland areas. This pattern reflects increasing social complexity and the possible emergence of regional political hierarchies. In the Iron Age, with the collapse of centralized powers like the Hittite Empire, settlement became more dispersed again.

The chapter also explores how the distribution and use of natural resources shaped settlement choices. Archaeological data suggest that the location of salt flats (near Lake Tuz and the Delice River) and copper deposits in the southeast part of the valley played a key role in where people chose to live—especially during the Chalcolithic and Early Bronze Age. The concept of the "resourcescape" is used not only to describe the physical location of these resources, but also how they influenced social organization, trade, and systems of access and control. Settlement density and artifact distribution both show strong correlations with proximity to these resources, indicating that communities were economically and politically structured around them.

To test the environmental impacts of different land-use strategies over time, the chapter uses the GRASS-GIS-based MedLanD model. This agent-based model simulates how villages with different population structures interacted with topography, soils, and resources under three climate scenarios: 15% drier, normal, and 15% wetter. The results show that intensive agriculture, while effective for supporting larger populations, significantly increases erosion—especially in wet conditions. Pastoralism performs better in arid climates but struggles to maintain population sustainability in the long run. Agropastoralism offers the most balanced results, supporting both ecological health and demographic stability. These findings provide valuable insight into how ancient communities adapted to environmental change and can also inform rural planning today.

The final part of the chapter focuses on the effects of archaeological excavation at Resuloğlu Höyük. Using the QGeoWEPP erosion model, the study evaluates how digging activities affected slope stability and soil loss. It finds that the uncontrolled dumping of fine soil on slopes during excavation dramatically increases erosion risk. This not only threatens archaeological layers but also nearby farmlands and ecological systems. In response, the chapter recommends slope stabilization, vegetation recovery, and improved excavation management practices.

In conclusion, this chapter emphasizes that human-environment relationships are not just historical—they continue to be shaped by present-day archaeological practices. The models used in this research provide insights not only into the past but also offer tools for the future: for protecting cultural heritage sites, managing land sustainably, and preparing for ecological risks. The long-term impacts of different land-use strategies, especially those tested using the MedLanD model, demonstrate how certain approaches—like over-reliance on pastoralism under dry conditions—may lead to socio-ecological collapse, while others can offer more resilient outcomes

10. CONCLUSION AND RECOMMENDATIONS

This doctoral dissertation examines the long-term evolution of socio-ecological systems in the Delice Valley (North-Central Anatolia) from 6000 to 2600 BCE using the framework of complex adaptive systems theory. It looks at the relationships between climate change, settlement dynamics, resource use, and landscape evolution. The study combines theoretical approaches from landscape archaeology and ecological anthropology with advanced methodologies, including GIS, remote sensing, geomorphological modeling, and agent-based simulations.

In the first part of the thesis, Multiple paleoclimate datasets including MCM and CHELSA-TraCE21k along with proxy records were used to reconstruct the Holocene climate changes in the Delice Valley. The reconstructed environmental changes were employed to evaluate how human populations and their ecosystems were affected. The study confirms that the Delice Valley was affected by major regional climatic events, particularly the 8.2 ka and 4.2 ka events, which left significant traces on river systems, soil erosion, and settlement density. The 4.2 ka event is especially important. The event triggered a rise in storage architecture (e.g., silos), more emphasis on pastoralism, and more scattered settlement patterns — all of which suggest the use of adaptive strategies under climate stress.

Through spatial data from 206 archaeological sites, the study employed GIS-based tools like Average Nearest Neighbor (ANN) and Kernel Density Estimation (KDE) to identify changes in settlement organization. The Chalcolithic period saw settlements that were sparse and scattered. The Early Bronze Age period displayed increased settlement clustering near key resources, which indicated growing social complexity and the emergence of local political systems. In the Iron Age, after the fall of the Hittite Empire, settlement became more decentralized and dispersed again. These findings show that communities were drawn to fertile lowlands and strategic resources such as salt and copper. The idea of a “resourcescape” — a landscape shaped by how societies identify and use natural resources — is explored both theoretically and empirically here.

The GRASS-GIS-based MedLanD model was used to simulate how different climate scenarios and land use strategies (agriculture, pastoralism, agropastoralism) affected the landscape. The results indicate that agricultural strategies offered the most population stability, but also caused severe erosion under intensive use. Pastoralism was more suitable in dry conditions but proved less sustainable in the long term, often contributing to ecological degradation. Simulations focused on Resuloğlu Höyük show how human activities, especially during the Anthropocene, have intensified environmental pressures and disrupted natural landscape evolution through complex feedback loops. The last part of the thesis deals with how archaeological excavations at Resuloğlu Höyük have affected the landscape.

The GeoWEPP erosion model is used to evaluate slope stability and soil loss prior to excavation and post-excavation. The results show that the uncontrolled dumping of fine-grained soil down slopes has significantly increased erosion risks. This highlights the need to revise both excavation methods and site management strategies. The integration of landscape-based conservation policies into archaeological practice must occur since these policies serve both artifact protection and environmental protection purposes. Detailed geomorphological impact assessments must be conducted prior to excavation for sites with badlands-type, highly erodible soils. The dumping of soil down slopes should be avoided since it intensifies erosion. Remote sensing and GIS-based monitoring systems need to be established to track erosion, soil loss, and slope changes over time. The simulation-based findings from the MedLanD model should be used to guide local land use and rural development policies.

The conceptual tools of landscape archaeology and ecological anthropology should be fully integrated into excavation and conservation planning. A multi-stakeholder conservation plan — involving archaeologists, geomorphologists, local officials, and NGOs — should be developed for Resuloğlu. The plan should include controlled excavation methods and public engagement strategies that respect the site's geomorphological vulnerability. This dissertation provides a modern scientific framework for understanding the relationship between humans and the environment. This dissertation presents new approaches for landscape archaeological analysis and future scenario testing as well as practical conservation methodology. This study establishes an innovative interdisciplinary approach to Anatolian archaeology by presenting the Resuloğlu case.

The integrative methodological framework developed in this dissertation—including paleoclimate modeling, geomorphological analysis, remote sensing, GIS-based spatial analysis, and agent-based simulation—offers a transferable and scalable approach for studying long-term human–environment dynamics in other regions. Particularly, regions with sufficient archaeological settlement data, paleoclimate proxies, and high-resolution topographic datasets can benefit from the application of this framework. The simulation models (e.g., MedLanD ABM and GeoWEPP) allow researchers to evaluate how different subsistence strategies and climate regimes shaped landscape evolution, soil erosion patterns, and settlement sustainability. Thus, the methods applied in this study provide a useful template for examining coupled socio-ecological systems beyond the Delice Valley.

For implementation in other areas, key datasets must include georeferenced archaeological settlement records, high-resolution digital elevation models (DEMs), detailed soil and land cover maps, paleoclimate reconstructions (e.g., CHELSA-TraCE21k, MCM), and records of natural resource locations such as salt and copper. Spatial relationships among these datasets should be established using GIS-based analytical tools such as Kernel Density Estimation, terrain preference models, and proximity analysis. This integrative data structure supports the construction of realistic, location-specific simulation environments. When calibrated appropriately, these tools can provide insight into how ancient communities across different regions adapted to environmental variability, making this dissertation's methodological approach applicable to diverse archaeological and geomorphological settings.

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CURRICULUM VITAE

Name Surname : Kemal KOCAKLI

EDUCATION :

- **B.Sc.** : 2015, Ahi Evran University, Faculty of Arts and Sciences, Geography
- **M.Sc**. : 2018, Van Yüzüncü Yil University, Institute of Social Sciences, Geography

PUBLICATIONS, PRESENTATIONS, AND PATENTS ON THE THESIS:

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