



# Geology and Climate Relating to Archaeological Water Management in Jordan



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**Submission:** April 11, 2019; **Published:** April 30, 2019

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## Abstract

All questions concerning water management in Jordan through time must begin with the ways in which water becomes naturally available in the environment, and this depends crucially on the two interlinked factors of geology and climate. Although these are natural factors, they may also be affected by human activity, to produce changes that are both planned and unplanned. It must be said that studies which consider anthropogenic impacts on, for example, soils in Jordan are just at the beginning. To date it is still hard to separate out long-term, short-term and medium-term changes and to ascribe these with certainty to either natural fluctuations or human activities. In many cases the way the landscape has changed at a micro-regional level must be to do with a complex interplay of natural and cultural factors. This paper presents an overview of the geology of Jordan as currently understood, a description of the modern climatic regime, a summary of the limited amount of paleoclimatic data we have and concludes with a discussion of the implications for research on the archaeology of water management.

## Introduction

Much of the principal evidence in this research involves the identification and interpretation of obvious interventions into hard geology, taking the form of excavated wells, cisterns and channels. At a local level, it is also possible to see how walls, by damming up or slowing down rainwater, have influenced slope wash and thus the way soils have been eroded or sedimented up. Geology plays an important role in whether wells can be dug and where; it is also crucial for determining whether a well can be dug relatively shallowly or needs to be extremely deep (the deepest prehistoric well in the overall region being the probably Bronze Age example at Lachish in Palestine at 76m: Withe & Shqiarat [1,2]. In short, geology, therefore, is more likely to account for differences in the number of wells in a locality than any personal preference or technical skill when different settlements and urban centres are compared [3-5].

## Basic Geological Structure

The modern state of Jordan covers an area of approximately 90,000 km<sup>2</sup> and is located at the north-western edge of the Nubo-Arabian plate. It has a predominantly limestone geology, with surface flint pebbles, but this gives way to basalt in the north and granite in the south. The south also includes the distinctive canyoned sandstone zone in which the famous archaeological remains of the Nabataean city of Petra are found. Topographically, the western border with Palestine is

formed by the rift valley of the river Jordan, the Wadi Araba and the Dead Sea. This rift is bounded to the east by the long line of the Jabal As-Sarah Mountains. Beyond this is a broad plateau which eventually gives way to the desert bordering Iraq in the northeast and slopes gently down toward the synclinal depression of Saudi Arabia in the east and south. Rivers in this region are seasonal wadi systems, which contain water only in winter. The central limestone region is karstic and displays a typical changeability in relation to the locations of active springs and streams as the underlying geology is actively remodelled. The climate is predominantly East Mediterranean in nature. The north of the country receives adequate rainfall, while the south has a more arid regime. Soils are varied and Jordan can be divided into four main vegetation zones. It is impossible to understand water management issues in Jordan in the past or present without a detailed understanding of geology, soils and climate, and how aspects of these may have changed over time, in response to long-term natural environmental fluctuations, the constant volatility of the karst zone, and medium and short term anthropogenic impacts [6].

Many geologists have worked on the geology of Jordan, such as Blankenhorn, Quennell, Burden, Wetzels & Morton, Bender & [7-10]. The Natural Resources Authority (NRA) is currently carrying out a detailed map of Jordan on a scale of 1:50000 and tables shows the stratigraphical sub divisions of Jordan, which

covers the age from Precambrian to recent times. The geological structure of Jordan is well known as a result of work by Bender, Quennel, Burden & Parker [7,9,11,12] and others. Although more recent investigation and drilling has assisted in defining and revealed significant new structural trends which were not

identified by the earlier studies, such mapping in not generally available. It has thus not been possible to map the major case-study sites discussed in this thesis against a detailed geological background. Figure 1 reproduces Bender's general scheme with the major case study sites superimposed.

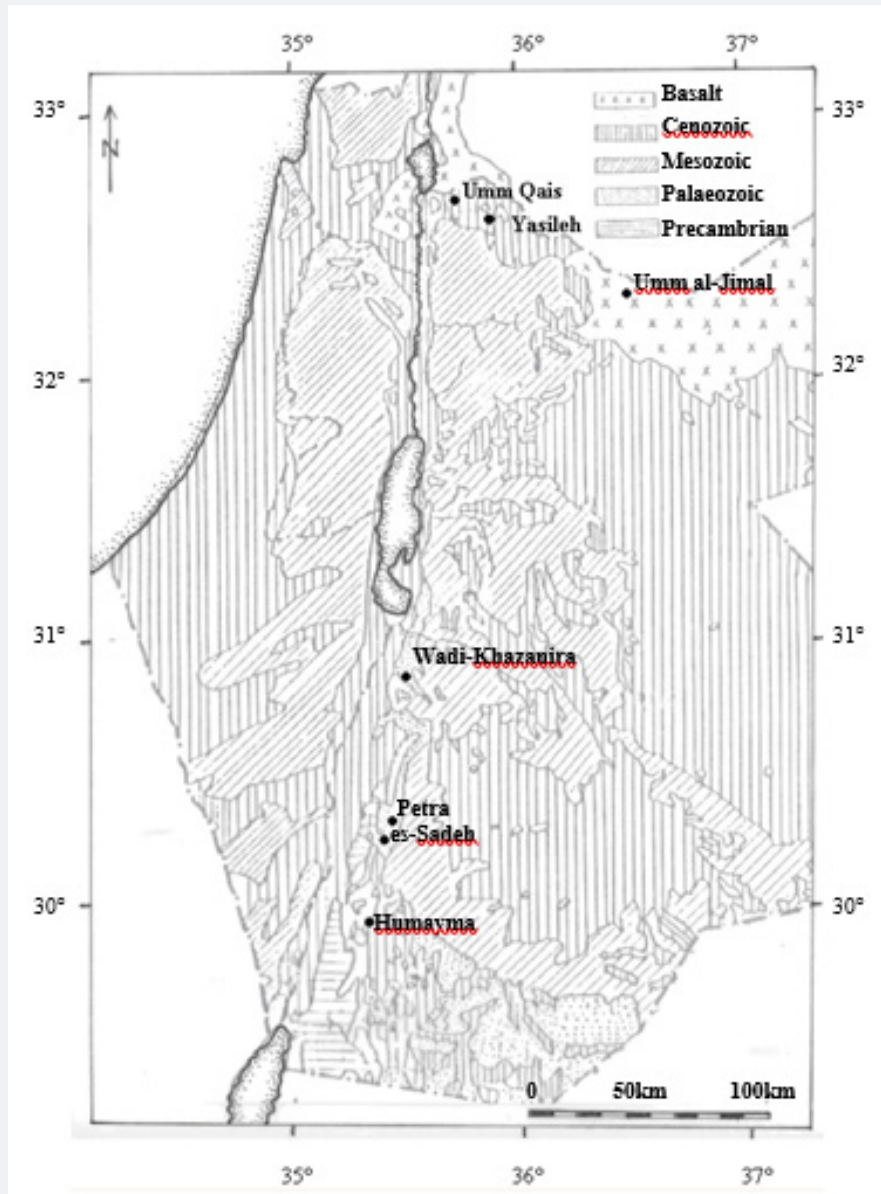


Figure 1: Principal sites in relation to basic geology (redrawn using data from Bender 1974 with minor corrections).

Regionally, the structure of the study area is affected by the presence of the Nubo-Arabian Shield and the formation of the Wadi Araba-Jordan Rift. The southern part of Jordan is the northern rim of the Nubo-Arabian Shield, which is built up of crystalline rocks representing the base to the Precambrian age. The crystalline rocks represent the base of the sedimentary formation of the Arabian Peninsula [9]. The Wadi Araba-Jordan Rift forms a 360km long section of the East Africa-North

Syrian Fault system. A system is recognisable over 6000km. The structural pattern, as seen in exposures on the east side of the rift, and the morphology of the surface of the Precambrian Basement complex suggest that a structural zone of weakness (geosuture) already existed at the end of the Precambrian periods. The occurrences of late Proterozoic Cambrian quartz porphyry volcanism in the southern Wadi Araba, the thickness and facies changes in the sedimentary successions from Araba,

and the thickness and facies changes in the sedimentary successions from the Cambrian to the Lower Tertiary, indicate the continued tectonic activity of the geosuture. However, the Nubo-Arabian Shield in Southern Jordan plunges regionally to the north and north-east. Epi-erogenic movements affected the Palaeozoic strata in southern Jordan, resulting in the gentle regional dip of these strata to the north and northeast. The Palaeozoic formations were, in part, eroded before the deposition of lower cretaceous clastic rocks. Therefore, from west to east in south Jordan, the lower cretaceous rocks overlie, with angular unconformity, progressively younger Palaeozoic rock units that range in age from Cambrian in the west to upper Silurian in the east.

The taphrogenic structural movements that initiated the formation of the present rift apparently occurred along the pre-existing geosuture and started during the late Eocene-Oligocene periods. In the late Oligocene-Miocene periods, the Jordan block was subjected to uplifting movements resulting in continental erosion and locally continental deposition of syntectonic conglomerates in some places in the southern part of the rift. Major Taphrogenic movements restarted in the Pliocene-Pleistocene periods and continued during several intra-Pleistocene phases associated with the wide-spread basalt volcanism of the Middle Pleistocene age. The post Oligocene taphrogenic structural movements were mostly of dip slip type. Only minor local movements of tangential compression and lateral displacement have been observed. Quennell and Freund believed that major strike slip displacement had occurred along the rift of the order of 70km to more than 100km, but this idea was not supported by Bender & Madler [13].

Taphrogenic movement in the rift strongly affected the area bordering the rift, chiefly along north-west, north-northeast striking normal faults, antithetic and flexures of minor displacements occur in the area. A few small anticlines in Central and Southern Jordan, such as at Thunah, northwest of Ma'an can be explained by tangential compression. The pattern of dominant block faults in central and southern Jordan gradually changes northwards into another structural pattern in north Jordan, where up warping and tilting becomes a common feature with faulting. However, the relatively thin and dominantly competent beds in the south, reacted to structural stresses by fracturing and faulting, whereas the thicker and more incompetent beds in the north reacted to the same stresses by arching, tilting and flexuring, for example, the northwest striking anticlinal trend of Jabal Safra, southeast of Amman, the uplift of Suweileh northwest of Amman, and the up warp of Ajlun.

### Structural Features in Jordan

The main structural features in Jordan are the Jordan valley, the Wadi Araba Rift Valley, and the folds and synsedimentary structures in the Sirhan and Azraq basins. The faults in Jordan are normal and extend northwest (e.g. the El-Hasa and El Karak faults). The main structure is the Wadi Shueib structure which

extends north east folds and converts to flexure in the Baq'a area [14]. The Amman Hallabat fold structure appears north of Na'ur and extends eastwards passing, the southern part of Amman [15]. The southern part of Jordan is considered part of the Gulf of Aqaba-Dead Sea transform fault system, and as a complex structural feature, which comprises the Gulf of Aqaba, the Wadi Araba, the Dead Sea and the Jordan valley [16]. The Gulf of Aqaba-Dead Sea structure, however, is described in terms of plate tectonic theory as a transform type of fault where sinistral movement took place between the Arabian Plate and the Sinai-Palestine Plate [17]. A sinistral movement along the Gulf of Aqaba-Dead Sea transform took place during several phases of movement in the Neogene age [18].

The total thickness of all post-Proterozoic sedimentary rock is generally 2000-3000m. The Nubo-Arabian shield, which is of Precambrian date is exposed in south-western Jordan and extends under most of Africa and the Arabian Peninsula. It is characterised by Precambrian plutonic and metamorphic rocks and some minor occurrences of Upper Proterozoic sedimentary rocks, which is known as the Precambrian basement complex. The Precambrian basement complex has repeatedly moved up and down during epillarsogenic activities ranging in age from Cambrian to early Tertiary. These movements resulted in several marine transgressions and regressions of the Tethys Sea, which lay to the west and northwest, over part, or all of Jordan. The basement complex produced the material from which, during certain periods, continental sediments were deposited in the Tethys Sea. During the transgressions, marine sediments of considerable thickness were laid down. Inland of the transgression coastlines, and during intervals of regression, terrestrial deposits accumulated: these consist mainly of sandstone of the Nubian facies with no or few fossils. This pattern of regressions and transgressions explains the pattern of the different lithofacies-marine calcareous, marine sandy and continental sandy- of Cambrian, Ordovician and Silurian sandstone and shale of continental and marine origin, which, unconformably overlie the rocks of the Precambrian basement complex. The rock units, gently dipping towards the north and northeast become overlain by a succession of younger marine sediments, which are mostly made of carbonate of Upper Cretaceous to Eocene in age.

Regionally, the marine influences on the deposition increase toward the north and west during the transgressive intervals of the Middle Cambrian, Early Ordovician, Early and Middle Triassic, Middle Jurassic and Middle Cretaceous to Oligocene times. Different shorelines have been formed due to these successive transgressions. The sedimentary belt in Jordan, results from the sepillarsogenetic movement that was repeated several times from Cambrian to tertiary times and resulted in a series of marine transgressions and regressions of shallow, Sepicontinental Sea (Tethys Sea). The sedimentary rocks cover wide areas of Jordan.

## Soil and Vegetation Cover

### Soils

Investigations of Jordanian soils, carried out by many workers, have been summarised by Bender & Aresvik [19], but it has unfortunately not been possible to locate a map showing the spatial distribution of Jordanian soils from any published sources known to the present author. gives a description of soil types as summarised by them. Red Mediterranean soil covers extensive areas along the high lands east of the rift from Ajlun, via Madaba, Karak and Tafliah, as far as Shawbak. It has been noticed in the eastern part of Tafliah sheet and is used for agriculture. The soil is red to brown in colour as a result of the iron oxide content. The thickness of the soil ranges from 0.7m to 1.5m and is Holocene (recent) in age [2].

Soil and vegetation cover are indicators of the quantity of precipitation, temperature and altitude. They change from grey lowland desertic soil, with perennial shrubs developed in areas with less than 150mm mean annual rainfall, to brown soils with a complete cover of perennial shrubs and grasses in areas having a mean annual rainfall of 150-300mm. Further to the west and along the Western Highlands, as the altitude and precipitation increases and temperatures decrease, red and yellow Mediterranean soils with mountain forest are developed in areas where the mean annual rainfall exceeds 300mm. Other smaller biotic communities grow where hydrologic conditions are favourable. The most prevalent is the dense growth of phreaphytes commonly found along perennial and intermittent stream courses. In some areas, azonal soils are developed, such as the weathered basalt in the northeast, the saline soils in the topographic depressions (in Azraq, Hasa and Jafer), alluvial soils and regosols formed from recently deposited detrital materials, and lithosols - thinly covered consolidated rocks such as basalt flows.

### Vegetation

The distribution of vegetation in Jordan follows the variations in the amount of precipitation. Where there are enough precipitation forests exist. Where there is little rain there is steppe and where there is no rain there is desert. The rain is not the only factor controlling the distribution of the vegetation cover: soil, geology, underground water and differences in temperature play an important role. In the higher parts of the upland regions, where the rainfall is more than 300mm, the vegetation is of distinctly Mediterranean type, with forests of pines and other varieties, for instance oak and bushes. Due to overgrazing, agriculture and firewood cutting, the forest areas have shrunk to a narrow discontinuous strip along the eastern escarpment of the Rift Valley and, occasionally, to patches on top of the highlands. This forest has been destroyed over the centuries, for fuel, agriculture and grazing [20].

In the steppe region the climate is more continental than Mediterranean. Rainfall varies between 150mm and 300mm

and, generally, the plant cover is grass and Artemisia, especially where soils are relatively stable. In the desert region rainfall is generally below 100mm. The vegetation is extremely poor in both variety and density, except in wadi bottoms, channels and depressions. In the sandy desert, such extensive bare surfaces are not common but, in between the individual shrubs, the grounds are quite bare of vegetation: occasionally a few short annual grasses are found. Between the steppe and desert regions there is a broad transitional zone, linked to steadily decreasing precipitation levels [19].

### Climatic Overview

Most writers agree that the general climatic conditions prevalent in all parts of the Levant today emerged during the Early Bronze Age II and III 3000-2400BC [21]. The climate in Jordan can be divided into two major types: the Mediterranean type on the Western Highlands and the semi-arid to arid type on most of the Central Plateau and Eastern Desert. The climate is characterised by cold winters and hot dry summers. January is the coldest month and August is the hottest. Average annual temperatures range from about 13 °C in some high mountainous areas to about 18.7 °C in the lowlands and the extreme south-eastern area. Temperatures are subject to large daily and seasonal fluctuations. Monthly temperatures vary between 5 and 25 °C. Large variations in temperature also occur within short distances due to topography.

Rainfall is primarily controlled by the Eastern Europe and Western Mediterranean cold fronts, which are drawn by the Eastern Mediterranean low-pressure system. Rainfall in the study area is seasonal, occurring in the period October to May with the highest fall in December and January. Rainfall outside this period would be an extremely rare event. Precipitation generally decreases from west to east and from north to south. However, this pattern changes locally in some areas owing to orographic effects over the high elevations of the Western Highlands. The mean annual precipitation decreases from about 600mm/a in the northern Western Highlands to less than 50mm/a in the south-eastern desert. However, in the eastern and south-eastern deserts, extended periods of no rain and periods of flooding are not unusual (Figure 2).

Latitude is the main determining factor of climatic zones. The latitude of a place, together with its elevation and relation to surrounding relief, determines the light and heat received from the sun. In the tropics, the intensity of insolation is greater than at other latitudes because the sun's rays fall vertically on the surface of the earth, so that a bundle of rays of a given wide is spread over the minimum possible area and has the shortest possible passage through the atmosphere. The inclination angle of radiation, absorption and the long of night and day also vary in relation to latitude, whereas inclination angle of radiation decreases with latitude. Therefore, light and heat decrease pole wards. In summer, the duration of sunlight increases with

increasing latitude and decreases in winter. Thus, in summer, the low intensity of insolation in high latitudes is partly offset by the greater long of day up to 43° 30' N, where maximum insolation is reached.

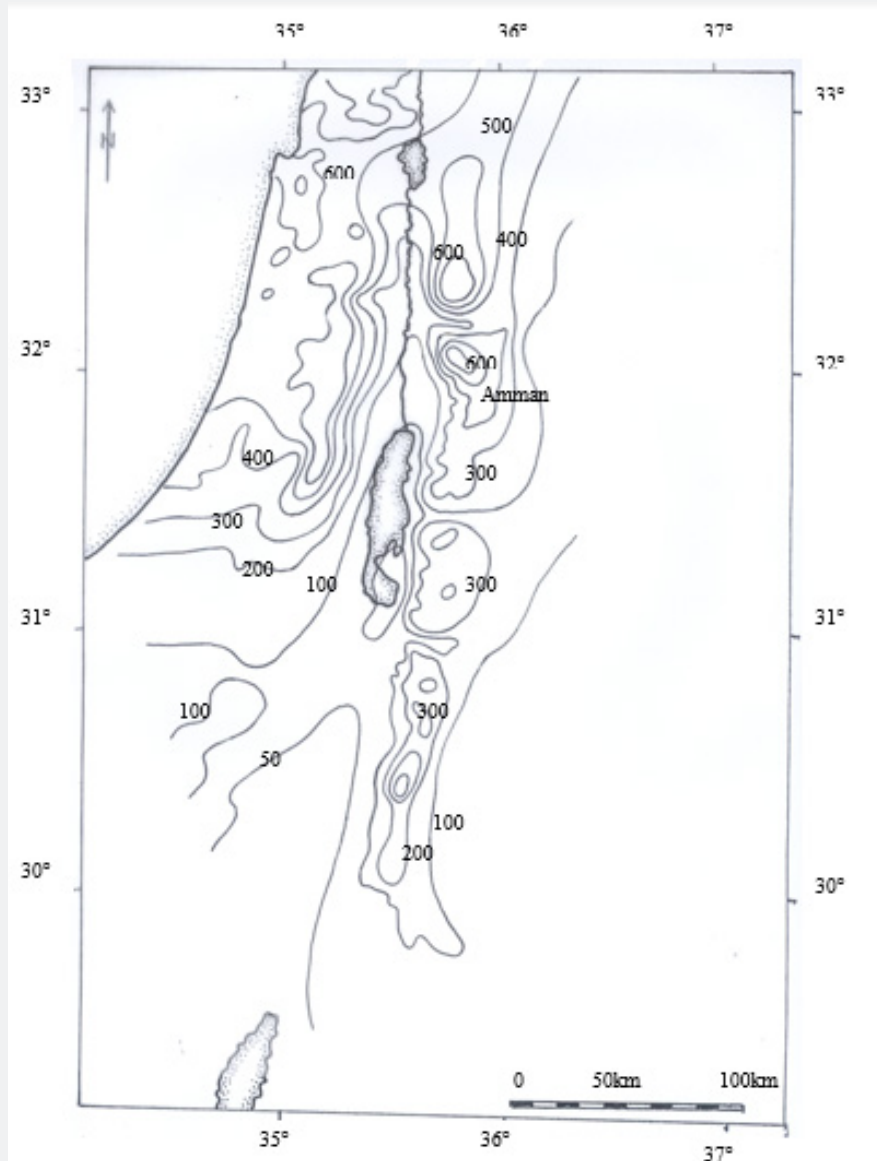


Figure 2: Current average rainfall in Jordan (redrawn using data from MacDonald 2001, with minor corrections).

Because of the low angle of the sun between the latitudes of 43° 30' and 62° N, the amount of insolation decreases to a minimum at the latitude (62° N), the length of day increases rapidly until, at the Arctic Circle, it is 24 hours long. Beyond the Arctic Circle to 23° 30' at the pole. Also, annual ranges of temperature, radiation and the long of night and day increase with increasing latitude. At the Equator the day is 12 hours long throughout the year. Day long increases with increasing latitude until, at the poles, there is six months of day followed by six months of night. At the equator, the amount of insolation received varies little throughout the year, for the range of the long of day is close to zero. At midsummer, north and south of the equator,

insolation is greater both at the Tropics of Cancer and Capricorn than it ever is at the equator, for the duration is longer and the intensity is just as great, the sun being directly overhead [22]. Furthermore, in the Tropics there are fewer clouds than over the equator on most days of the year. Therefore, zones at about 20° north and south in summer receive the greatest insolation on the earth [23]. As a result; the extremely hot and dry deserts of the world are within the tropical and sub-tropical zone. Cyclones of mostly Mediterranean origin usually start affecting Jordan in mid- October or early November and dominate the weather until late April [24].

Jordan lies within the Mediterranean bioclimatic region of semi-arid to arid type [25,26]. The essential features of this climate are dry, hot summers and cool winters. The climate regime is determined by the interaction of two major atmospheric circulation patterns. During the winter, the temperate latitude climatic belt prevails, and moist cool air moves eastward from the Mediterranean. In the summer, the subtropical high-pressure belt of dry air causes relatively high temperatures and no rainfall. Weather parameters such as atmospheric temperature variations, air pressure and relative humidity. Jordan is part of the eastern Mediterranean weather system and has a climate with distinct seasons in different areas of the country, including wet and cool-to-cold, with occasional snowstorms. In the highlands there are often temperatures several degrees centigrade high than in the range of hills overlooking the valley to the north. There are marked seasonal contrasts, however: summers are dry and warm-to-hot and winters are wet and cool-to-cold, with occasional snowstorms. In the highlands, there are often strong, cool breezes on summer nights and low-lying areas enjoy pleasant, moderately cool winters.

January is the coldest month and, although below-freezing temperatures are not unknown, the average winter temperature is above 7.2 °C. The hottest month is August, when temperatures may reach 48.9 °C in the Jordan valley. In Amman, the average summer temperature is a pleasant 25.6 °C. Rainfall is mostly during the winter months and ranges from 660mm in the northwest to less than 127mm in the east of the region [24,27,28]. The climatic features of the area can be described by considering north-south and west-east trends. The climate in the northern and western mountainous areas is Mediterranean but, moving eastward, there is a rapid change to semi-arid and arid types, as the influence of the Mediterranean Sea is replaced by that of the continental land mass, causing a decrease in rainfall and an increase in the temperature range. Farther to the southeast, in the El Jafr Basin, the climate has been classified as arid or as a Mediterranean Saharian climate of the warm variety [25]. Additionally, there is a marked secondary influence of topography upon the climatic parameters throughout the country.

The relative humidity in the Ghor varies from 70% in winter to less than 50% in summer while, in the eastern plateau, the variation is from 75% to 35%. Dew originates from the cooler winds of the Mediterranean and occurs in summer, gives beneficial moisture supplying to summer crops grown under dry farming conditions [19]. In the Wadi Araba, there is no indication that the climate has ever been other than semi-arid within recent times, but it is reasonable to suppose some variation within the semi-arid range, and that at different times the streams have flowed more strongly, and further than at present. In the Wadi Araba, the present rainfall is estimated at between 50mm in a dry year and 150mm in wet year, a falling mainly between November and April [29].

### Climatic Zones

Jordan can be divided into three physiographic regions, each with a distinct climate

- a. The highlands comprise mountainous and hilly regions that run through Jordan from north to south. Several valleys and riverbeds intersect the highlands, such as Wadi Mujib, Wadi Hassa and Wadi Zarqa, all of which eventually flow into the Jordan River, the Rift valley or the Dead Sea. The highlands are by no means uniform. Their altitude varies from 600 to 1600 metres (1969-5249 feet) above sea level and the climate, although generally wet and cool, also varies from one area to another. It is in the highlands that we find the major remains of ancient civilisation in the cities of Petra, Jerash, Philadelphia (Amman), Madaba, Gadara (Umm Qais) and Karak. For much the same reasons, abundance of water and strategic location, the highlands are the most densely populated areas today.
- b. West of the highlands is the Jordan Rift Valley, which runs along the entire length of Jordan. The Rift Valley plunges to over 400m (1312 feet) below sea level at the Dead Sea, becoming the lowest spot on earth, and reaches a minimum wide of 15 kilometres. The Rift Valley encompasses the Jordan (the Ghor in Arabic), the Dead Sea, Wadi Araba and Aqaba. The Rift Valley is rich in water resources, including thermal mineral water. Therapeutic treatment is available at Zarqa Mai'n, a deep gorge close to the Dead Sea with over 60 mineral springs. The Valley is rich in agricultural land and is warm throughout the year.
- c. The desert region in east Jordan is an extension of the Arabian Desert; it is a semi-arid, steppe-like region in which small plants survive in winter and spring.

There is extreme variation in the climate of the desert between day and night, and between summer and winter. Summer temperatures can exceed 40 degrees Celsius, while winter nights can be bitterly cold, dry and windy [28].

### Effects of Water Bodies

Next to the variation of insulation with latitude, the distribution of land water on the earth is the most important factor affecting climate. Water conserves more heat than land: being slower to warm up and slower to cool down it has a moderating influence on temperature [22]. So, temperature ranges in Jordan increase with increasing distance inland, in parallel with increasing continentality. The nearest large body of water which affects the climate of Jordan is the Mediterranean Sea. Both land masses and water bodies affect the climate of the Jordan, but the landmasses have a much bigger influence than the water bodies. Consequently, the climate of Jordan is characteristically an arid, continental climate: it is dry and hot, with a large temperature range between day and night, and

between summer and winter, especially in the Jordan Valley, the Aqaba Region, and wet and cool-to-cold in the highlands [30,31].

The most stable season in Jordan is summer. The following major changes occur in the pressure fields over the eastern Mediterranean due to the intensive heating of landmasses. First, a centre of high-pressure forms over the Mediterranean. Then a low-pressure region develops during the summer months and extends from North Africa to Pakistan and India through the Arabian Peninsula and Indian Oceans. This huge low-pressure belt brings the eastern Mediterranean within the monsoon belt of southern Asia and invites hot and dry northerly continental tropical air masses from the high-pressure centres over Mesopotamia, Asia Minor and the lowland around the Caspian Sea. Two centres of low-pressure cut-off are formed over the northern Red Sea and Saudi Arabia. The hot winds blow from the Rub-al-Khali (the Empty Quarter, bringing occasional invasions of very hot air masses, which raise the temperature to very high levels and cause heat waves [24].

In winter, meridional circulation of the upper air over the eastern Mediterranean is related to the differential heating between the warm waters of the Mediterranean and the cold landmasses of southern Europe and the Atlas Mountains. Deep upper air troughs are correlated with the invasion of the region by cold polar air masses. When a zonal circulation prevails, waves form over the Mediterranean and move rapidly toward the east causing light rainfall and near average temperatures. The main features of the pressure distribution during the winter are that, over the Arabian Peninsula, Armenia, Turkey and northern Iraq, high-pressure centres develop. The thermal difference between the Mediterranean waters and the land masses lying to the north and south then causes low pressure centres to develop over the central and eastern Mediterranean, and the Azores high-pressure centre extends to the areas lying south of the Atlas Mountains [24].

The eastern Mediterranean is invaded by different types of air masses including cold arctic air masses and cold polar air masses, which are usually associated with anticyclones or ridges of high pressure. Especially in autumn and spring there are continental tropical air masses, which come from North Africa. In winter, the Mediterranean is occupied by one of the normal frontal zones in which disturbances frequently develop and move eastward. Frontogenesis relates to the sharp contrast in temperature and humidity between continental tropical air masses and the cold polar air masses. Short fluctuations of low temperature which occur in Jordan during the winter are usually associated with cold fronts, but severe outbreaks of cold weather are caused by cold pools and cold lows.

The weather in Jordan and other eastern Mediterranean countries is dominated in winter by a series of depressions, which move along the Mediterranean front from west or southwest to east and northeast. Most Mediterranean depressions form as lee or wave depressions over the Mediterranean [24]. The

general conditions favouring cyclogenesis are the existence of a baroclinic or frontal zone, air convergence on the leeward slopes of the Alps and instability of air masses. The Mediterranean depressions may be grouped according to their areas of formation and include depressions of the western Mediterranean basin, which are usually called 'Genoa depressions' and which do not usually reach the eastern Mediterranean and therefore have no effect upon the climate of Jordan. Khamasin depressions are frequently called Saharan depressions because they form in the area south of the Atlas Mountains and move along the southern shores of the Mediterranean. Most of these depressions, which account for 18 per cent of the Mediterranean depressions, occur during the spring. Depressions of the central and eastern Mediterranean sometimes form in the northern Ionian Sea, the southern Aegean Sea and the region of Cyprus, but the formation of new depressions in this area is rare and what is more common is the rejuvenation of old weak depressions, especially in the neighbourhood of Cyprus.

Most depressions in the eastern Mediterranean move along three main tracks with an annual average of 10.5 depressions moving to the northeast through northern Syria and southern Turkey. Eleven depressions move annually to the east and a few of them reach northern Iraq, with an average of 1.5 depressions moving to the southeast. The decreasing number of cyclones moving in southern tracks explains the decrease of annual rainfall in Jordan from north to south [24]. In winter, the climate of Jordan is influenced more by conditions in the Mediterranean. The main sources of rainfall for the country are the Mediterranean Sea in winter and the monsoon in summer. The influence of the Mediterranean Sea on the climate of Jordan decreases towards the south and north. Cyclones from the Mediterranean may bring winter rains as far south as 20 N°.

### Effects of Mountain Bodies

Mountain ranges are important climatic factors because they interfere with the flow of air. A mountain range restricts the influence of the seas, acting as a barrier to the inland passage of moist air. There are differences in the annual and diurnal variations of temperatures between maritime-influenced regions, and regions on the lee of mountain barriers which are sheltered from maritime influences. Furthermore, it is known that temperature decreases, and rainfall increases with increasing altitude. Therefore, the As-Sarah Mountains (Shawbak, Ajlun and Negeb), which run parallel to the Red Sea, are affected by maritime influences, which bring rain, much more than the low areas located to the east and west of the mountain ranges, or even the coastal plain which runs parallel between the Dead Sea and As-Sarah mountains. At the same time, these mountain ranges restrict marine influences on a short distance from the coastline [32]. As a result, rainfall in the mountains falls mainly on the As-Sarah Mountains, and little falls over the northern plateau and the coastal plain. Also, the daily and yearly temperature ranges, which give an indication of the degree of

continentally of the climate in the northern plateau areas, are larger than those in the mountain ranges and coastal plain. There are no other important mountain ranges in the country that affect the climate. However, because the country is small, some local variations occur, especially between the southern and northern regions.

### The Biogeographical Regions in Jordan

Long [25] divided Jordan into nine bioclimatic regions, based on the analysis of climatic data from twenty-four stations in Eastern Jordan. Al-Eisawi [33] followed the same method as Long. The climatic, rainfall and temperature of data thirty-one stations between 1966 and 1980 was analysed and the distribution of the resulting bioclimatic zones. Among the studied stations are Shawbak (close to Petra). This is considered to lie in a semi-arid Mediterranean bioclimatic zone of cool variety.

### Conclusion

The distribution of the archaeological sites in Jordan has been affected by climate change throughout the history of the area. The data obtained from the Jordan Antiquity Information System (JADIS) demonstrates that the number of archaeological sites in Jordan increased during wet periods but declined during dry ones. Previous site occupation, soil fertility and proximity to water are the physical characteristics of the reoccupied sites, even during unfavourable climatic episodes. The prehistoric people who inhabited Jordan responded to climate changes through migration to these favourable sites.

In his chapter 'Climatic Changes in Jordan through Time' in the *Archaeology of Jordan* volume (which he co-edited) Burton MacDonald writes that: "A wetter phase is one of the explanations for the occurrences of widespread silts from Qadesh Barnea in the south to the central Shephela region in the north, during the Byzantine and Early Islamic periods, that is, between roughly 1600 and 600 Bp [34,35]. The widespread silts, however, could have been caused by the influence of human activity on the landscape in the form, for example, of deforestation and over-grazing. Archaeology supports the hypothesis of a wetter climate since the area was densely occupied by large Byzantine settlements. It is hard to envisage how such a large population could survive under the regime of today's arid conditions.

There is a circular element to this argument, and it could be argued that MacDonald's assumption is possible based on under appreciation of the sophistication of Nabataean and Roman-Byzantine water management systems. What is clear from this, however, is that lack of good quality data on climate change means that understanding changing water management patterns fully remains difficult. MacDonald & Goldberg [34] recognizes that independent verification of his hypothesis is needed using techniques such as palynology. In general, it must be accepted that the prehistoric people who inhabited Jordan responded to climate changes through migration to more favourable areas

both within and outside what now constitute the borders of modern-day Jordan. The Dead Sea levels, presented by Frumkin [36] as indicators of paleoclimate in the area, match the number and distribution of archaeological sites in Jordan during the same periods. One could argue that site reoccupation in prehistory has a positive relationship to moist climate conditions and could be used as paleoclimatic indicators in the absence of chemical and isotopic analyses. The variations in the local climate of Jordan motivated early settlers to reside in, and occupy, the areas of north and middle Jordan. Access to water resources was a major factor in site distribution in Jordan and encouraged reoccupation even in dry periods.

The study by Frumkin & Carmi [37] did not focus on seasonal climate variations and human adaptation to such variations; further studies in the area are needed in order to have a complete picture of the seasonal climate throughout the prehistory of Jordan. In the North African climate, following a wet phase from 40,000 and 20,000 BC, with the last major pluvial at 6,000 BC and significant climatic change between 4,000-2,000 BC there has not been substantial climatic change since 2,000 BC. In general, we might expect that Jordan follows the North African pattern, with no major climate changes during the period under study here (later prehistoric through to present). It has been postulated that the region experienced a slightly moister environment at one or two points during the classical period [36,38]. However, these scholars are rather unspecific about the data they use to support this suggestion and are not exact in defining precise chronological units. Much more work needs to be undertaken before a clearer assessment can be made and the implications for core and peripheral regions of Jordan deduced.

Gaining higher-quality paleoclimatic data is an important future research objective because, even if there were no major shifts in the last four millennia, even minor shifts can have major effects on what is possible or impossible in subsistence terms. In short, if water management technology is sophisticated, then a lot of extra benefit can be derived from even minor increases in precipitation. One could argue that the pattern of the spatial and temporal distribution of archaeological sites in Jordan might have been determined by climate, but without adequate supporting data this can only be a supposition. One of the most impressive revelations concerning ancient water supply and management has been the important role which geological terrain, particularly karst, played in the ability to access and utilise available water. The volatility or dynamism of the limestone karst landscape has been described above, and the water-created subsurface tunnelling, caverns, sinkholes, and springs, have always been relatively easy to discern. To date, however, relatively little archaeological work has been done in these contexts. In general, similar water-management structures - wells, cisterns, aqueducts, etc - are found on the sandstone as on the limestone regions of Jordan, while absent from the basaltic formations of the north - the earthquake zone.



Karst is the prevailing geology throughout much of the Mediterranean region and played an important role in the water supply of numerous cities in Antiquity. Dora Crouch presents clear evidence that most, if not all, Greek cities were established either on or near karst terrain [39], while Dan Gill's recent article about Hezekiah's Tunnel in Jerusalem clearly demonstrates that naturally-created the tunnels and shafts were enlarged deliberately in order to channel more valley water to city [40]. Thus, it seems that people utilised karst terrain to their advantage throughout the Mediterranean. While nature provided the basics for a well-watered site, it was still up to the humans who inhabited the area to develop and utilise the water in the ways they desired [41-43].

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DOI: [10.19080/GJAA.2019.09.555753](https://doi.org/10.19080/GJAA.2019.09.555753)

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