4th International Conference on Water Resources and Arid Environments (ICWRAE 4): 694-703
5-8 December 2010, Riyadh, Saudi Arabia

Reconstruction of Mid-Holocene Climate Conditions for North-Western Arabian Oasis Tayma

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Abstract: The existence of water ever played a very prevailing role for the development and continuity of settlements in arid environments. Due to climate change since the last 6000 to 8000 years these conditions have varied significantly. The investigations carried out dealt with the north-western Arabian oasis Tayma (Tabuk Province, Kingdom of Saudi-Arabia). The study figured out changes in the water resources balance for the *Sabkha* of Tayma which has a closed drainage basin without any outlet. Since the level of mid-Holocene shoreline was determined by radiometric dating of vermetids and barnacles, it is quite proper to estimate the specific influences of surface runoff, infiltration and evapotranspiration. It is very likely to gain valuable information about climate conditions from the Holocene era till now by determination of these hydrologic factors. For example, the annual precipitation rates during mid-Holocene have been determined to app. 150±25mm/a for several runoff concentrations and rainfall patterns. Thus, the annual fluctuation of sea level, the impact of singular storm rain events and the effect of dry summer periods have been modelled. Also, the investigations provided indication for a monsoon-affected climate during late Holocene era. The general living conditions for human and biota depending on climatic conditions could be deduced by means of hydrologic modelling for this period.

Key words: Holocene climate • North-western Arabia • Oasis • Water resources • Monsoon

INTRODUCTION

Tayma is situated in the north-western part of the Arabian peninsula in a nowadays arid climate (mean annual precipitation: 40 to 90mma^{-1}; average annual temperature: app. 22°C; annual reference evapotranspiration: >2200mma^{-1})[1]. This required since a very long time a very careful handling of limited water resources.

The studied areas include in general the oasis of Tayma, which was investigated intensively during three field campaigns in springs of 2007 to 2009 (location cf. Fig. 1)[2].

Tayma itself is situated in a flat plain surrounded by several ranges of hills. The deepest point is placed north of the settlement with an elevation of about 801.5maSL[3]. Within settled area the highest point is some 845maSL. Archaeological investigations revealed a big number of ancient remains. Parts of them date back to app. 5kaBP[4].

The presumed centre of the prehistoric settlement has been the nowadays called *Qraya,* which is situated between palm-garden and modern city. The *Qraya* has an area of barely 1km² and is the main focus of present archaeological research activities. North of the present-day palm-garden the *Sabkha* is to be found.

[1] Precipitation and temperature date are interpolated values of measurements of the weather stations situated in Tabuk, al-Jouf and Arar during the time period 1980-2007. Based on data provided by the Ministry of Defence and Aviation, Presidency of Meteorology and Environment Protection of the Kingdom of Saudi Arabia (cf.: www.pme.gov.sa). Source for annual reference evapotranspiration data is (FAO 2000).

[2] The studies have been carried out as a sub-project of the archaeological research activities at Tayma which bases on a written cooperative agreement between the General Commission for Tourism and Antiquities, Riyadh (Prof. Dr. Ali al-Ghabban) and the German Archaeological Institute, Oriental Department, Berlin (Prof. Dr. Ricardo Eichmann). The project is promoted by Prof. Said al-Said, King Saud University, Riyadh.

[4] m aSL = meters above sea level

[4] ka BP = 1000 years before present

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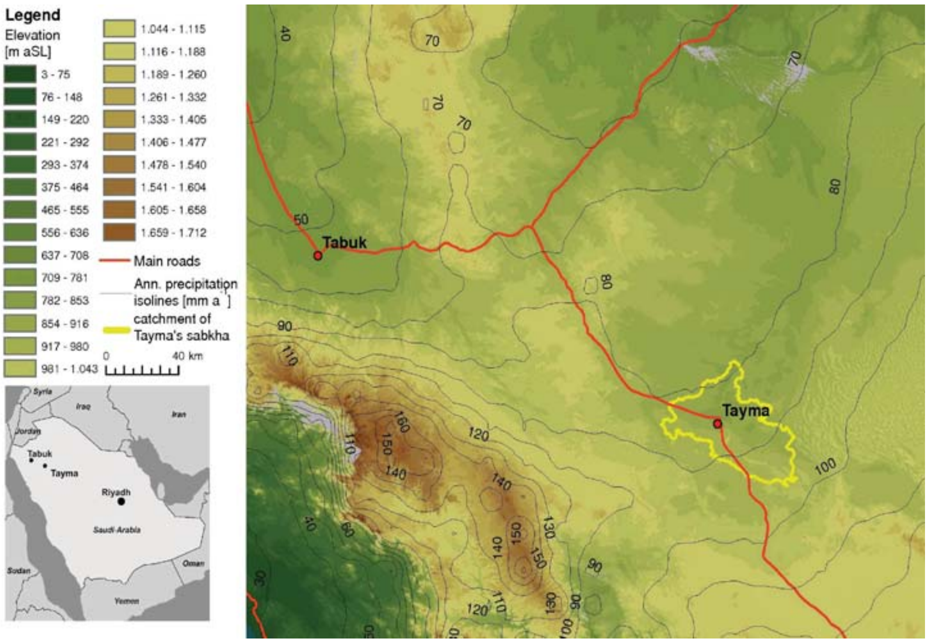

Fig. 1: Map of the study area. In the north-western part of the Arabian Peninsula the investigated oasis of Tayma is situated. (Digital Elevation Model [DEM] based on SRTM remote sensing data provided by the US Geological Survey with a grid of 3 arc seconds; Precipitation data based on [1].

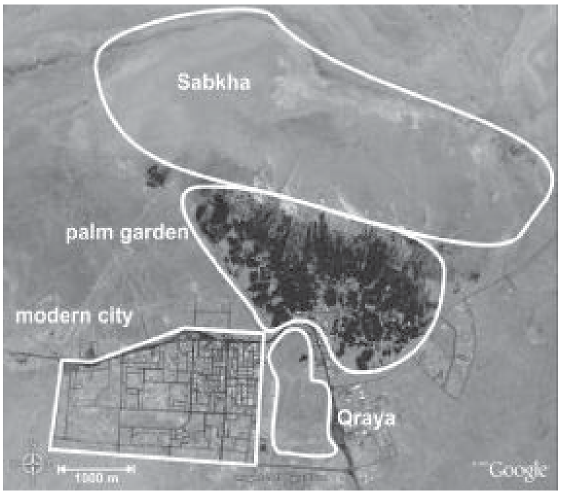

Fig. 2: Spatial units of Tayma. In the north the *Sabkha* is located. Bordering to the south the nowadays palm-garden could be found. *Qraya* is the presumed centre of the prehistoric settlement (source: Quickbird 2, Digital Globe, [2].

This is an depression without outflow, representing one of the main hydrologic aspects of the whole investigation area. Fig. 2 shows these spatial units of Tayma.

Environmental Setting: Sedimentary rocks of Tayma region are a part of an extensive, monotonous laying unit which is gently dipping in north-north-eastern direction with an incline of barely 1°. This uniform structure is interrupted by several graben systems taking course from southeast to northwest parallel to the coast of the Red Sea. The investigated spot is affected by a tectonic depression, the so-called Tayma graben. This hollow with a width of some 2km is morphologic hardly formed. Only shallow hills at the edges of this graben system with a height of less than 50m can be observed.

The area of Tayma is underlain by Phanerozoic sedimentary and volcanic rock. This horizon consists of Ordovician sandstone varying with fine grained siltstone. The grain size distribution of this sandstone is variable and spans from fine to gross grained.

Mesozoic and Cenozoic (Tertiary[5] and Quaternary) sedimentary and volcanic rocks are overlaying in a discordant manner. The Quaternary top layer consists of rubble, stones, gravel and sand. The youngest depositions are of fluvial or aeolian origin and issue from Pleistocene till Holocene [3]. Vegetation is very sparse due to arid climate.

The *Sabkha* is a depression without outflow north of the nowadays palm-oasis of Tayma with an extension of nearly 20km². The deepest point of the *Sabkha* is about

[5]Tertiary includes the eras of Paleogene and Neogene.

801.5maSL. The northern shores are bordering to a steep escarpment which is nearly vertical. The top edge of this shoreline is higher than 840maSL. At the southern side of the *Sabkha* a very gentle slope at the transition to the palm-garden at a level of about 804 to 820maSL can be observed.

The hydrologic system of the *Sabkha* represents the precondition of the former water-management and cultivation at Tayma. Surface water of the catchment could accumulate in this topographic depression and formed a paleo-lake during Holocene. However, due to climate change and less rainfall the evaporating water quantities exceeded the discharge, the water level decreased and finally caused a slow salinisation of the *Sabkha*. The decreasing water level probably enabled the agricultural use of farmland at the transition zone to the palm-garden and subsequently caused an especial development of the oasis. Most likely, an earthworks dam which demarcated the *Sabkha* in west-eastern direction was used for the protection of farmland against episodic (or periodic) flooding during late Holocene (cf. Schneider, in press).

At present time the depression is a kind of salt desert, which is only flooded after episodic occurring rainfall events during wintertime. The bottom of the *Sabkha* consists of thin layers of silt and clay. Intermediate layers are consisting of evaporates, e.g. gypsum, mineral salt or anhydrite.

Today as well as in recent years salinisation takes place due to very high reference evapotranspiration rates of more than $2200mma^{-1}$ [4]. The drainage water of the palm-oasis causes a continuous supply of water and therewith salt minerals. Although this drainage water has a little volume compared to runoff from the catchment, salinisation continues permanently especially at local depressions north of the palm-garden due to evaporation.

In total, seven episodic wadis are supposed to enter the *Sabkha* issuing from different directions [5]. The catchment area adds up to barely $1950km^2$ due to topographic conditions[6]. It is shown in Fig. 1.

Climatic History: For the understanding of the environmental situation in the investigated area the knowledge of climate conditions during Holocene is a precondition. [6] determined two significant climatic optima due to higher mean temperatures app. 8to 6kaBP and 5.0to 3.8kaBP. These temperature variations are linked by [7] to a northwards shifting of the inertropical convergence zone (ITCZ) and therefore allowing the south-western monsoon to affect the (southern) Arabian Peninsula. It is not proved whether this monsoon ever had an impact to the region around Tayma or not. Nevertheless, the thesis of a northwards shifting monsoon is supported by [8]. [9] also suggested that the North African monsoon was stronger than today and therefore may have reached farther northwards and possible also affected the western part of the Arabian Peninsula. As proposed by [10] the ITCZ and therewith the monsoon rainfall belt did not reach farther north than app. 23 to 24°N due to a lack of identified Holocene stalagmites in this region. But this thesis is highly speculative because only a randomized, non-representative sampling of stalagmites was performed in caves of central and northern Saudi Arabia. According to this thesis, Tayma would not have been affected by monsoons due to its location app. 27°35’N.

[11] determined two significant lake periods by dating lacustrine sediments taken in the an-Nafud desert some 80km east of Tayma. The first lake period during the upper Pleistocene is supposed to be app. between 34to 24kaBP. The second minor and even less humid lake period was determined into mid-Holocene (app. 8.4to 5.4kaBP). Interestingly, [11] found that during the minor lake period lacustrine sediments are altering with aeolian deposits. This suggests the interpretation of non-permanent lakes during mid-Holocene.

Higher annual precipitation rates in mountainous regions are often linked to convective phenomena. Rainwater of the mountainous ranges southwest of Tayma partly infiltrates into the soil. This infiltration water then is flowing in north-eastern direction following the gentle surface slope (cf. Fig. 1). At Tayma itself artesian groundwater is rising to the surface due to tectonic disturbances.

Geoarchaeological investigations of sediment cores taken within the *Sabkha* of Tayma support this thesis. During the last persistent lake period significant seasonal climatic fluctuations could be assumed due to submillimetre laminae of evaporates in the stratigraphic transect (Engel *et al.*, in press). Also the stratigraphic sequence of sediments, containing at the lower part a high content of organic material to more grain-like and sandy fractions (i.e. higher aeolian morphodynamics due to drier climate) in the upper parts, indicate the transition from persistent to periodic and finally episodic lake-periods. These analyses also provided evidence for a water level of the former persistent lake of 811.5maSL due to vermetids and barnacles attached to the exposed bedrock

[6]The area of the catchment is evaluated by means of a DEM generated out of SRTM-data.

(cf. [12]). This water level was taken as a basis for the oncoming hydrologic model. By means of radiocarbon dating of bioclastic sediments linked to this shoreline, this water level is carefully connected to the second minor lake period during early mid-Holocene (app. 8.4to 5.4kaBP)[7]. The reconstruction of a stratigraphic transect revealed the existence of a saline environment within the *Sabkha* already during early Holocene [13].

Probably simultaneous with a climate change during mid-Holocene and a changed water resources pattern, the settlement conditions had changed as well [14] Therefore, the climate shifting has to be set in relationship to the water management system and to the timeline of settlement for the investigated areas.

MATERIALS AND METHODS

The focus of the investigations was a hydrological survey. Thus, the natural landscapes (e.g. geographical classification) have been observed, documented and finally evaluated.

In this context topographical surveying with high spatial resolution is essential. The survey was performed using a Differential Global Positioning System (DGPS) of Trimble Comp.[8] with accuracy better than app. 20mm in elevation as well as in location (depending on number of available satellites). The used system runs in combination with a reference station at a fixed position. For surveying at first a sufficient number of available satellites, for both the fixed reference station and the mobile survey unit, is essential. Further, a radio communication between both units is necessary.

At the location of Tayma the reference station was stationed on the elevated roof of the Museum for Archaeology and Ethnography of Tayma. Thus, nearly the whole study area of Tayma was covered by needed terrestrial radio reception. For surveying of the *Sabkha* the reference station was placed at its northern banks in a very elevated position for transmitting radio signals was very well.

At some minor areas the terrestrial radio signal was possibly disturbed by mobile phone signals issuing from transmitter masts situated in Tayma centre (*Qraya*, cf. Fig. 2). In cases DGPS-survey could not be performed due to such disturbing signals (or in the case of the palm-garden, due to a lack of sufficient satellite signals [covering palm fronds or houses and street canyons, respectively]) another survey method using a tachymeter was carried out. As both survey methods are based on different geographic projections the data has to be transformed by a seven-parameter-transformation (Helmert-transformation) to fit to each other. This transformation based on an initial survey campaign, where coordinates of certain fixed points have been determined in both geographic projections[9].

All coordinates given in this paper are in Universal Transverse Mercator (UTM) coordinate system zone 37N. Coordinates are projected using the common World Geodetic System (WGS84) reference ellipsoid.

The topographical data has been implemented in a Digital Elevation Model (DEM) which is the basis for hydrological calculations such as concentration of surface runoff. The handling of data was carried out using common CAD and GIS applications. For the determination of large-sized elevation models (e.g. the catchment of the *Sabkha*) SRTM remote sensing data has been used[10].

By means of DGPS-surveying the topography of the *Sabkha* was recorded for getting a capacity curve of this depression. These data had been merged with SRTM-Data for surveying in the area of the palm-oasis could not be performed satisfactory[11]. Finally a Digital Elevation Model (DEM) of the *Sabkha* could be deduced (Fig. 3).

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7 Oral communication of Prof. Brueckner and his team (Phillips-University of Marburg, Department of Geography) who are performing geoarchaeological investigations of the Sabkha. In this case the dating of bioclastic material by means of radiocarbon dating is difficult, because the samples are recrystallized.

8 Rover: Trimble R8 GNSS-Receiver; Controller: Trimble TSC2 assembled with Survey-Controller software; radio unit: Trimble PDL 450

9 The initial surveying has been conducted by Florian Ziegler and Christian Bost (University of Applied Sciences of Karlsruhe, Germany) during campaigns of autumn 2005 and spring 2006.

10 SRTM-Data (Shuttle Radar Topography Mission) provided by the U.S. Geological Survey (grid of 3-arc-minutes). The dataset provides digital elevation information with a resolution of 90 m in position an 1 m in elevation and is therefore not sufficient for creating a valuable Digital Elevation Model (DEM) of the Sabkha itself.

11 In the palm-garden DGPS-surveying hardly was possible due to shielding palm fronds. SRTM-data representing settled or plant covered areas have to be handled very carefully because the determination of the elevation of earth's surface in such areas is hardly possible by the used radar technology. Therefore SRTM-data has been compared with the little DGPS-data available in these areas. Afterwards a gentle elevation-adaption of SRTM-data to DGPS-data has been conducted before both datasets have been merged.

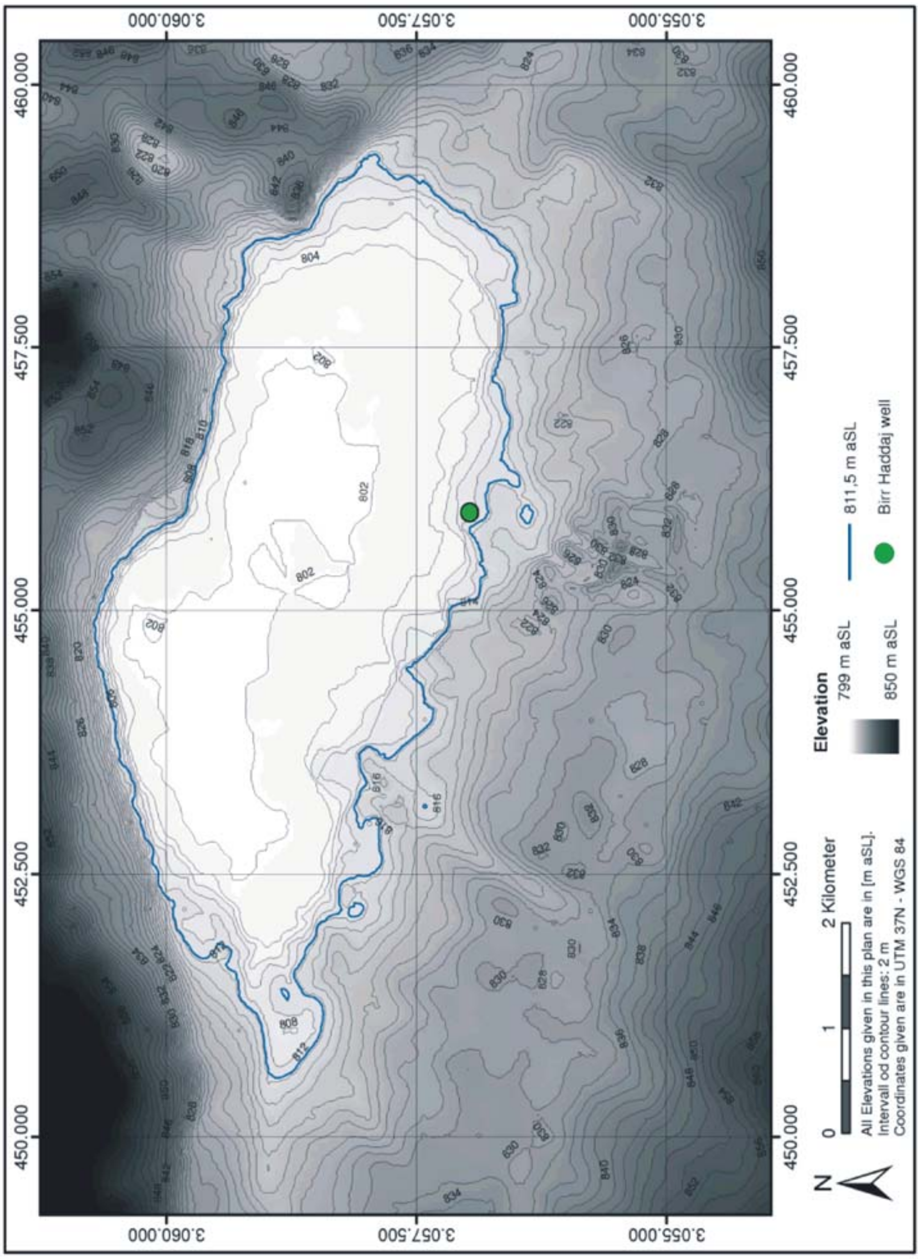

Fig. 3: Digital Elevation Modell (DEM) of the *Sabkha* based in DGPS-surveying merged with SRTM-data. Marked in light blue colour is the assumed shoreline of former lake at a water level of 811.5maSL. Additional the well-known *Bir-Haddaj* well is marked in green.

RESULTS

Alleging that a constant water level throughout the year was existing the hydrologic water balance equation has to be solved. This means that annual runoff volume to the outlet-less *Sabkha* has to be equal to the annual infiltration and evaporation rates.

Based on the surveying of the *Sabkha* and the resulting DEM (cf. Fig. 3) the capacity curve could be determined using common GIS-applications. Fig. 4 shows the function of the lake's surface and stored water volume relying on the water level. As one can see the surface is increasing very fast at low water levels of app. 802to 804maSL due to a very gentle slope (the deepest point of the *Sabkha* was determined to

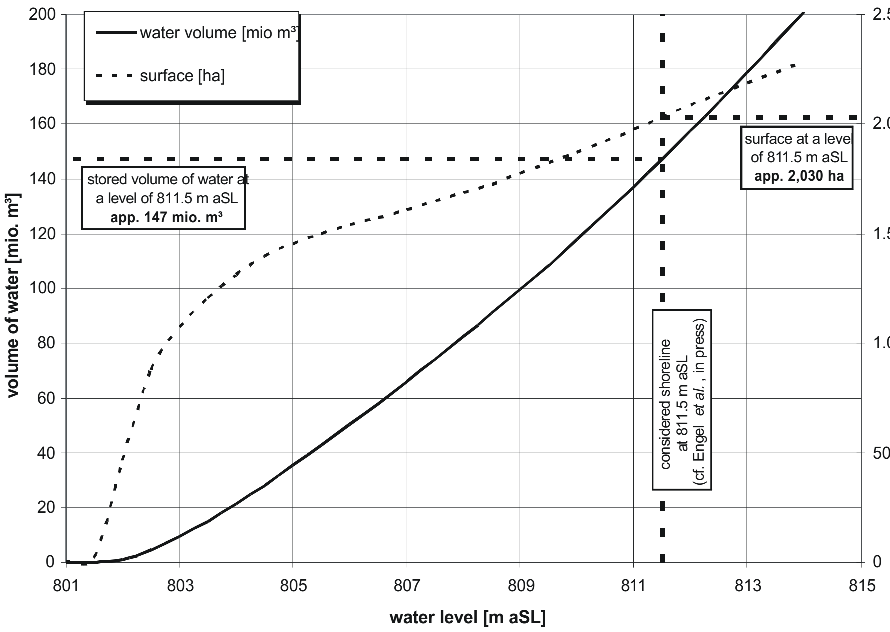

Fig. 4: Capacity curve and function for surface of water body depending on the water level of the *Sabkha*. Determined on the basis of the DEM (fig.3) which was derived from DGPS-surveying merged with SRTM-data. Also the considered level of the former shoreline as well as its assigned surface and stored volume are aligned

801.5maSL). Also the surface and the stored water volume for the assumed water level of former Holocene lake-period of 811.5maSL could be estimated to 2,030haand 147miom^3, respectively.

To estimate annual infiltration volume certain coefficients of permeability for the silty soil respectively sand- or limestone at the bottom of the *Sabkha* in the range of $10^{\bullet 10}$ ms$^{\bullet 1}$ have been considered. Further, runoff-coefficients representing the runoff concentration pattern in the catchment have been evaluated. Runoff-coefficients characterise the percentage of annual rainfall becoming surface runoff and therefore are essential for solving the water balance equation. They take the soil type, the mean surface slope as well as vegetation patterns and seasonal as well as temporal distributions of singular rainfall events into account. In particular, both last mentioned parameters are very hard to evaluate for pre-historic runoff patterns because they are linked to the climate.

[15] investigated mountainous catchments of similar area in the south-western part of the Arabian Peninsula. They pointed out that only 3% of the extensive precipitation becomes surface runoff. The largest amount was found to be lost due to evaporation losses (63%). Finally, app.31% are stored as soil moisture in the unsaturated zone and about 3% are recharging the groundwater. Because of certain differences in topography, geology and land use of the investigated catchment these results are hardly transferable to the conditions of Tayma.

[16] determined for a catchment at the Sinai Peninsula with very little annual precipitation (less than 50mma$^{\bullet 1}$) and comparable soil conditions (limestone, sandstone, alluvial deposits) by means of remote sensing data a runoff-coefficient of app. 0.085 for catchments of similar size. Hence runoff-coefficients are depending on the annual total rainfall as well as on its seasonal distribution they could be assumed to be a little higher than 0.085 due to changed vegetation during wetter periods. Consequently, for the investigated catchment of Tayma's *Sabkha* the mean annual runoff-coefficient had been evaluated in the range of 0.100 for the mid-Holocene.

For solving the hydrologic water balance equation, at first a certain annual precipitation rate was chosen. Afterwards, the monthly distribution of rainfall and reference evapotranspiration fitting to monsoon-affected climate has been assumed. For this a comparison to south Arabian locations, which are affected by the Indian monsoon still today, was drawn. In monsoon-affected climate rainfall occurs during summertime (mainly June to August). During winter there is only very little rainfall. It should be noticed, that in monsoon-affected climate the annual reference evapotranspiration is significantly smaller due to heavier cloudiness in summertime.

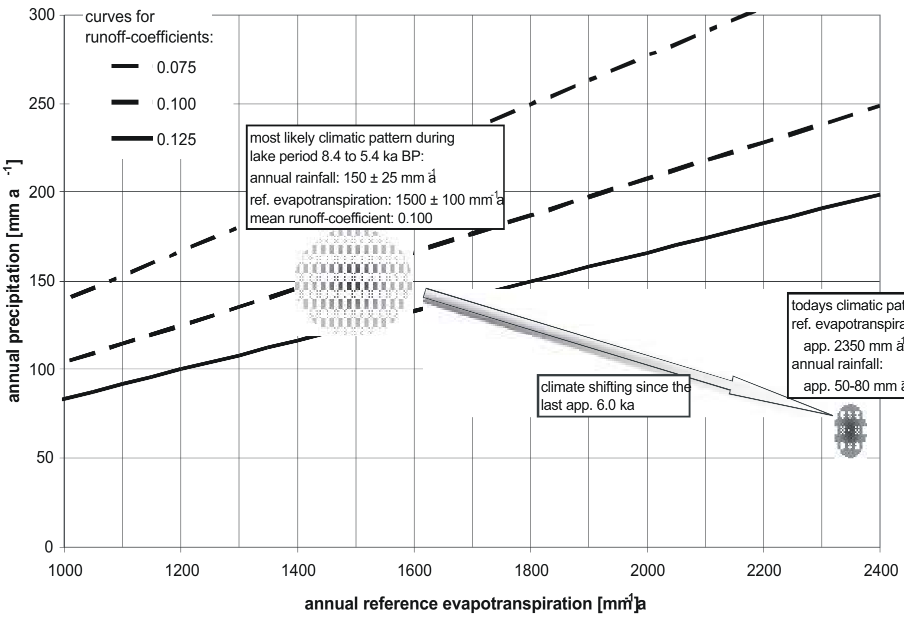

Fig. 5: Reconstructed annual precipitation and reference evapotranspiration rates for different mean runoff-coefficients and an equal water balance at a water level of 811.5maSL of the *Sabkha*. As shown in this figure a climate shifting from nowadays pattern to cooler and wetter conditions during second lake period should be assumed.

Monthly rainfall was expected to occur as singular rainfall events. Finally the monthly runoff volume depending on monthly precipitation rates has been calculated. Using the capacity curve (Fig. 4) the surface relying on stored water volume for each month was determined and hence the monthly infiltration as well as the monthly evaporation volume could be calculated. For the calculation of the following month another initial water volume taking the changes of the previous month into account was applied and so on. Finally, after the calculation of each month of a year one has to secure that the hydrologic water balance equation is fulfilled (the initial stored water volume has to equal the final water volume). Therefore, the annual precipitation rates for certain reference evapotranspiration rates as well as runoff coefficients were varied until this balance was obtained. The results of these calculations for an initial water level of 811.5maSL depending on these three parameters are shown in Fig. 5.

Regarding the before mentioned climate shifting it is also considered that with a more humid climate and colder mean annual temperatures the potential evapotranspiration rates had been smaller than today. Therefore the annual precipitation rate for the less humid and younger lake-period (8.4 to 5.4kaBP) which was linked to a persistent water level of app. 811.5maSL was estimated to 150±25mma^{-1} considering an annual reference evapotranspiration rate of 1500±100mma^{-1}. These calculations base on the assumed monsoon-like climate with certain annual distributions of rainfall and evapotranspiration (cf. Fig. 6).

By means of the seasonal distribution of runoff (calculated due to monthly precipitation) and reference evapotranspiration (Fig. 6) it has been possible to determine the water level hydrograph for the *Sabkha*. For this purpose the monthly evaporation volume as well as the monthly infiltration volume have been calculated out of the surface at certain water levels. Thus, considering the monthly inflow to the *Sabkha*, the seasonal stored water volume was estimated. Using the capacity curve (cf. Fig. 4) the seasonal water level could be determined (Fig. 7). Therefore a mean annual water level difference between winter- and summertime of app. 50cm has to be assumed.

The hydrograph shown in Fig. 7 is related to reconstructed mean annual precipitation rates. Probably there have always been variations in this pattern. It should be pointed out that due to runoff-concentration after intense rainfall events the water level rose within a couple of hours by app. 30 to 40cm. Still today after singular rainfall events during wintertime the water level rises significantly.

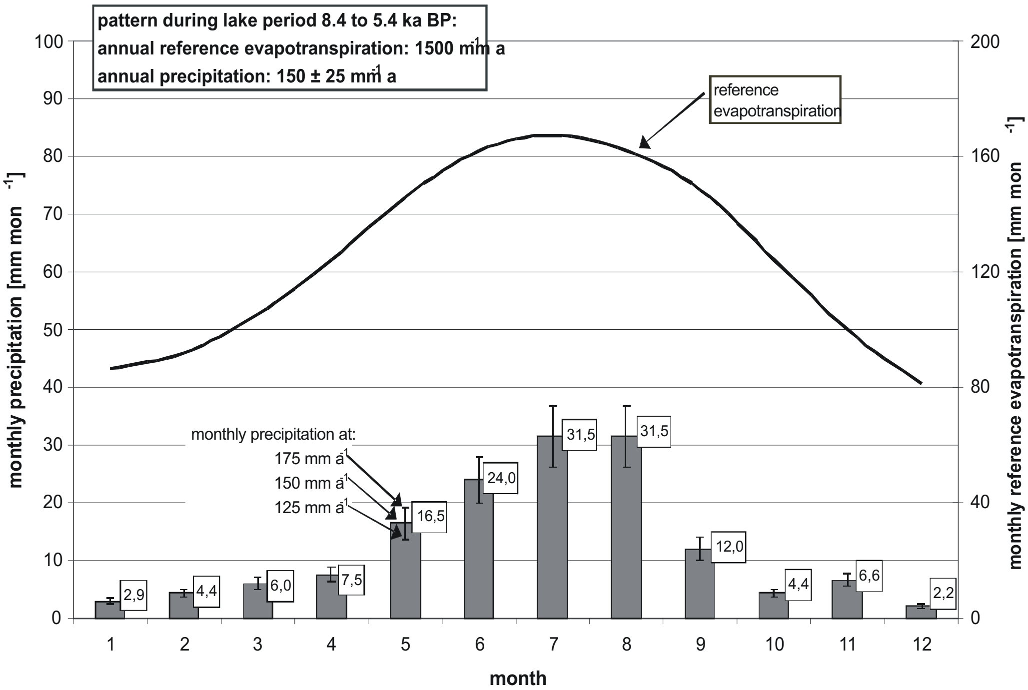

Fig. 6: Reconstructed seasonal distribution of precipitation and reference evapotranspiration for second lake period 8.4 to 5.4kaBP as it was affected by the Indian monsoon

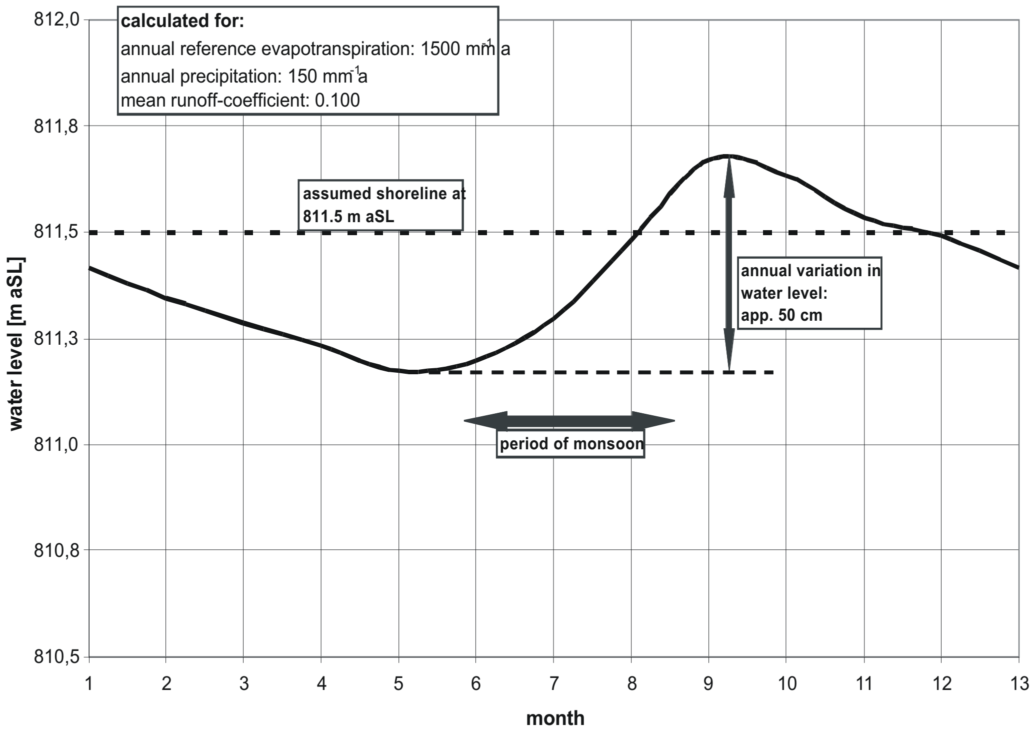

Fig. 7: Annual water level hydrograph for the *Sabkha* representing considered conditions during second minor lake period 8.4 to 5.4kaBP.

DISCUSSION

For the older and probably more humid lake-period (app. 34-24kaBP) an annual precipitation of 200±50mma•^{1} was assumed by [17] by means of groundwater-recharging models for the southern part of the Arabian Peninsula. These results accord to the estimation of annual precipitation in this investigation because the younger lake period is supposed to be less humid than the older one. For the northern part of the Arabian Peninsula no other comparable information of estimated precipitation rates during Holocene is available yet.

Fluctuating water levels within *Sabkha* probably have promoted the development of certain vermetid and barnacle species (*balaneus sp*.) like they were found at the northern shoreline of the paleo-lake (sample Tay7, cf. [12]). These species are supposed to be specialised in such barren aquatic habitat with highly fluctuating salinities and nutrient supply as it would occur due to very high variations in annual water level hydrograph or singular flooding events after intense rainfall. Therefore, the calculated water level hydrographs correlates with the almost exclusively findings of these certain barnacle species.

It is very likely that Tayma was affected by the Indian monsoon. Due to a lack of cloudiness in a non-monsoon climate the annual reference evapotranspiration rates would have been much higher than assumed in this model. Consequently, this would have increased the annual precipitation rates to balance the hydrologic water balance equation. Comparable calculations using the recent climate pattern of Tayma (rainfall during winter and high evapotranspiration rates during summer) led to annual precipitation rates in the range of 250±50mma•^{1}. Such rainfall rates could be excluded by means of the results of the pollen analysis which was performed in Tayma[12].

These statements are referred to the assumed shoreline of the *Sabkha* at a level of 811.5maSL which is based on geoarchaelogical investigations. But also a former shoreline at a level 818maSL is conceivable under a hydrologic point of view. The lake's surface would have been bigger by app. 25% then. Due to a higher evapotranspiration volume the annual precipitation rates would be in the range of less than 190mma•^{1} which still is plausible. A persistent lake at a level of 818maSL would have had its shoreline in close vicinity to the settlement. For the development of the community this would have had a major impact even if the water of the *Sabkha* was saline. Further investigations regarding this topic are in progress.

CONCLUSIONS

For Tayma obviously the development of the *Sabkha* is strongly connected to the one of the settlement. Due to decreasing water levels of the salty lake during mid- to late-Holocene agriculture in the nowadays palm-garden possibly was enabled. It is conceivable that the agriculture was promoted not only because of the fertile area which was released by decreasing water levels but also because of an interaction of groundwater and surface water at the margin of the *Sabkha*.

The solving of the water balance equation for the *Sabkha* of Tayma gave indication for a more humid and probably monsoon affected climate during Holocene era, though the environment also has been arid then. Due to a supraregional climate shifting since the last app. 6000 years, the impact of the monsoon weakened and finally vanished. Therefore, today the investigated area is found to be hyperarid with annual precipitation rates of partly less than 50mma•^{1}. Consequently, the groundwater-table decreased and most wells exsiccated. Additionally, this decline is strengthened by motor driven pumps which convey more water than naturally is recharged.

During Holocene, the monsoon possibly promoted the oasis with annual rainfall and surface runoff reliably. With the weakening or even the absence of this reliable rainfall events in a more arid becoming environment, only the groundwater-based oasis were able to endure. Maybe this is a reason for the decline of other oases (e.g. Qurayyah northwest of Tabuk), whereas Tayma stand the test of time till today.

ACKNOWLEDGEMENT

The authors are grateful for the financial support of the German Research Foundation (DFG) and the logistical support of the German Archaeological Institute (DAI).

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