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

Kai Wellbrock, Peter Voss and Matthias Grottker

Laboratory of Urban Water Management and Waste Management,
University of Applied Sciences Luebeck, Germany

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 6,000 to 8,000 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 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±25 mm/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 enduring droughts have been modelled. Also, the investigations provided indication for a possible 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 90 mm a^{-1}; average annual temperature: app. 22°C; annual reference evapotranspiration: > 1,700 mm a^{-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 801.5 m aSL[3] within the *Sabkha* (cf. fig. 2). Within settled area the highest point is some 845 m aSL. Archaeological investigations revealed a big number of ancient remains. Parts of them probably date back to app. 5 ka BP[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 1 km^2 and is the main focus of present archaeological research activities. North of the present-day palm-garden the *Sabkha* is to be found. This is a depression without outflow, representing one of the main hydrologic aspects of the whole study area. Fig. 2 shows these spatial units of Tayma.

[1] Precipitation and temperature data 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).
Annual reference evapotranspiration data base on Trabucco/ Zomer [2].

[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. The grant for this project was provided by the German Research foundation (DFG).

[3] m aSL = meters above sea level

[4] ka BP = 1000 years before present

Corresponding Author: Moenkhofer Weg 239, D-23562 Luebeck, Germany, E-mail: grottker@fh-luebeck.de.

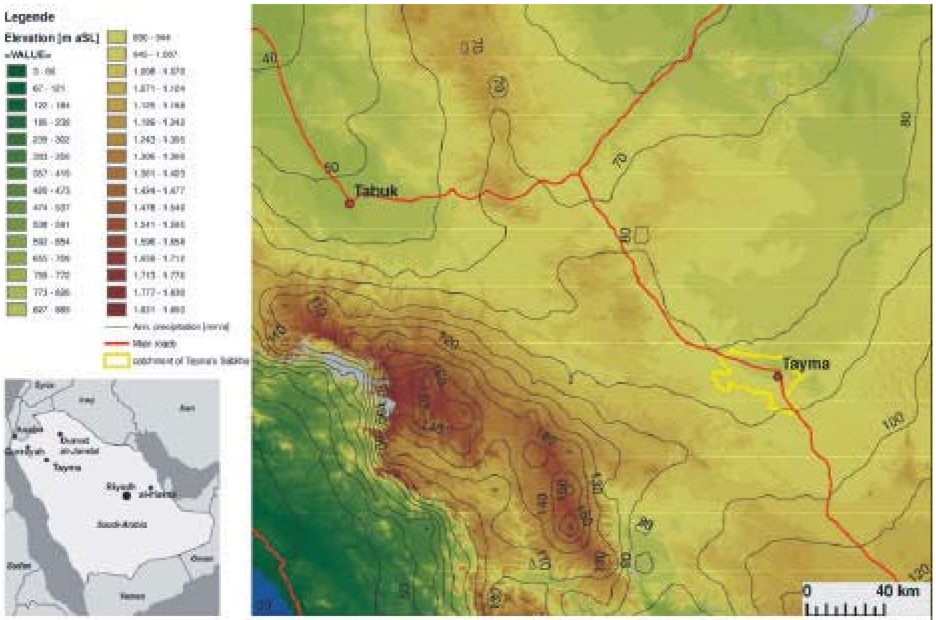

Fig. 1: Map of the study area. In the north-western part of the Arabian Peninsula the investigated oasis of Tayma is situated. (Digital Elevation Model [DEM] based on SRTM remote sensing data provided by the US Geological Survey with a grid of 3 arc seconds; Precipitation data based on FAO[1]).

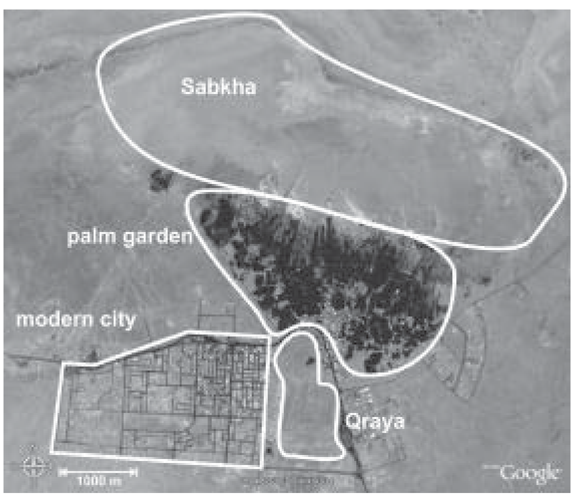

Fig. 2: Spatial units of Tayma. In the north the *Sabkha* is located. Bordering to the south the nowadays palm-garden could be found. *Qraya* is the presumed centre of the prehistoric settlement (source: Quickbird 2, Digital Globe, Google Earth 2007).

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 2 km is morphologic hardly formed. Only shallow hills at the edges of this graben system with a height of less than 50 m 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 app. 20 km^2. The deepest point of the *Sabkha* is about 801.5 m aSL. The northern shores are bordering to a steep, terraced escarpment which partly is nearly vertical. The top edge of this shoreline is higher than 840 m aSL. 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 820 m aSL can be observed.

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

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 [4].

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 deposited 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 app. 1,700 mm a^{-1} [2]. 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 660 km^2 due to topographic conditions. 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. Schoenwiese [6] determined two significant climatic optima due to higher mean temperatures app. 8 to 6 ka BP and 5.0 to 3.8 ka BP. These temperature variations are linked by Burns *et al*. [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 McLaren *et al*. [8] Staubwasser/Weiss [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 Fleitmann *et al* [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.

Schulz/Whitney [11] determined two significant lake periods by dating lacustrine sediments taken in the an-Nafud desert some 80 km east of Tayma. The first lake period during the upper Pleistocene is supposed to be app. between 34 to 24 ka BP. The second minor and even less humid lake period was determined into mid-Holocene (app. 8.4 to 5.4 ka BP). Interestingly, Schulz/Whitney [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 [12]. 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 at least 811.5 m aSL due to barnacles attached to the exposed bedrock (cf. Engel *et al*., in press). This water level was taken as a basis for the oncoming hydrologic model. By means of radiocarbon dating of bioclastic sediments, this minimum water level is carefully connected to the second minor lake period during early mid-Holocene (app. 8.4 to 5.4 ka BP)[6].

[6] 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.

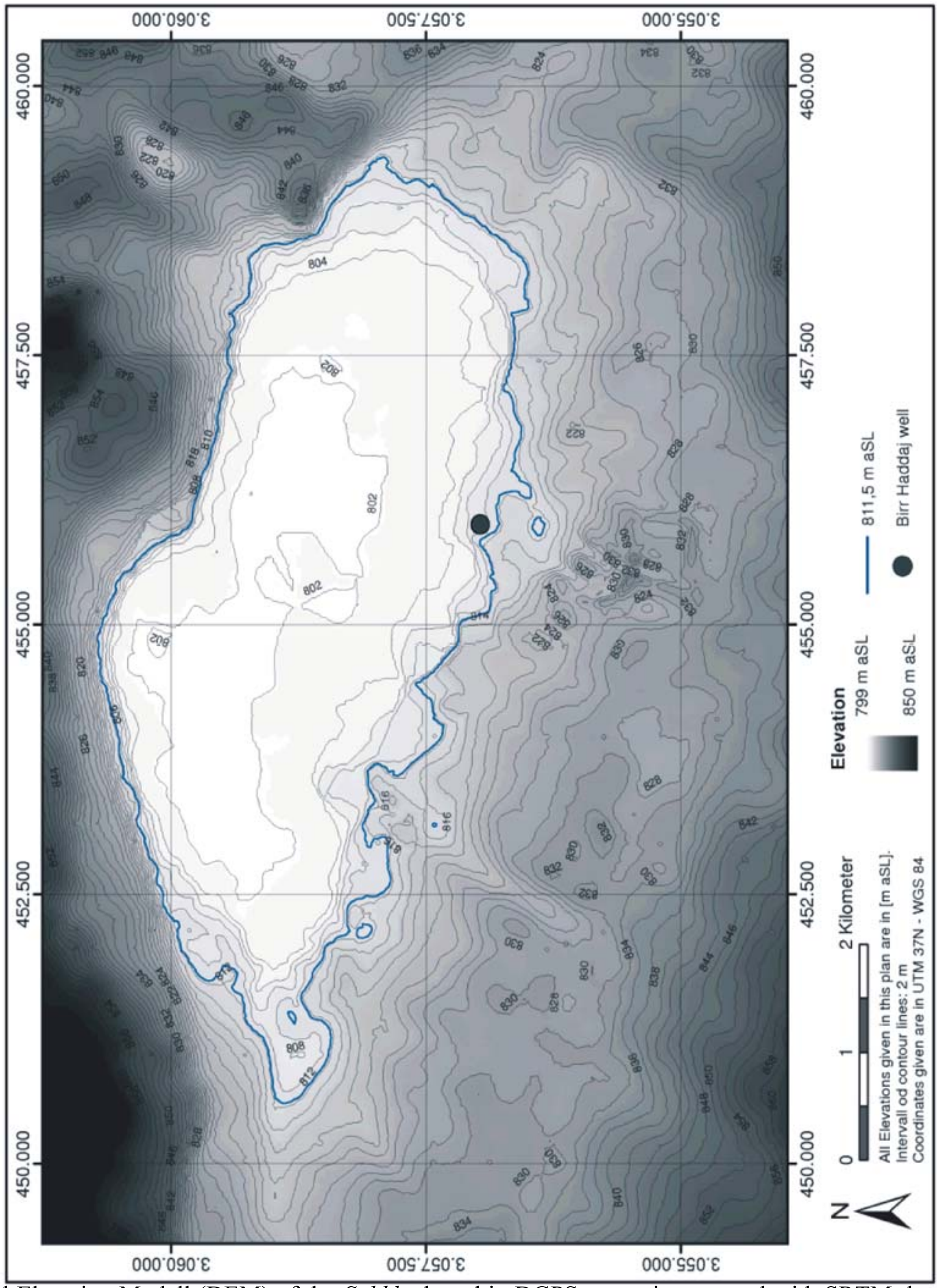

Fig. 3: Digital Elevation Modell (DEM) of the *Sabkha* based in DGPS-surveying merged with SRTM-data. Marked in light blue colour is the assumed minimum water level of former lake at 811.5 m aSL. Additional the well-known *Bir-Haddaj* well is marked in green.

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.

Methodology: 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.[7] with allows to gain an accuracy better than app. 20 mm 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[8].

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 (WGS 84) 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[9].

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[10]. Finally a Digital Elevation Model (DEM) of the *Sabkha* could be deduced (fig. 3).

RESULTS

Alleging that a constant water level throughout the year existed 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[11].

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. 802 to 804 m aSL due to a very gentle slope (the deepest point of the *Sabkha* was determined to 801.5 m aSL). Also the surface and the stored water volume for the assumed water level of former Holocene lake-period of 811.5 m aSL could be estimated to 1,845 ha and 116 mio m^3, respectively.

Morphodynamic changes in terrain's surface within the *Sabkha* which definitely took place between the moment this model was set up for (app. 8.4 to 5.4 ka BP, see above) and the date of surveying (2007 to 2009) could be neglected. This morphodynamic changing mainly

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

[8] 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.

[9] 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 and 1 m in elevation and is therefore not sufficient for creating a valuable Digital Elevation Model (DEM) of the Sabkha itself.

[10] 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.

[11] The potential influence of groundwater which possibly emerged in the area of today's palm garden into the Sabkha or rather unlikely infiltrated into fissures or cracks of the subsurface, which could perhaps be linked to the tectonically disturbances known as the Tayma-graben, have been neglected, since they were found to have probably an minor impact to the water balance. Further research on this topic is necessary in future.

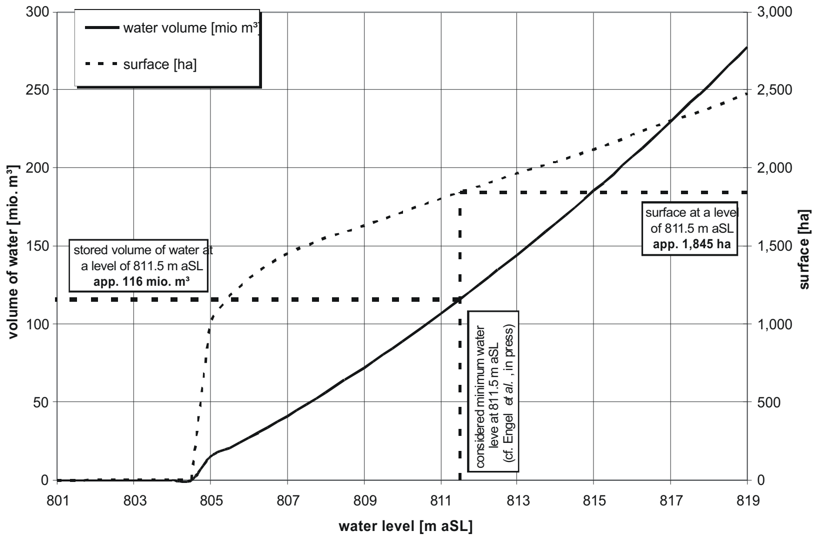

Fig. 4: Capacity curve and function for surface of water body depending on the water level of the *Sabkha*. Determined on the basis of the DEM (fig. 3), which was derived from DGPS-surveying merged with SRTM-data. Also the considered level of the former shoreline as well as its assigned surface and stored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

Table 1: Runoff exponent values and runoff coefficients for different soil types of arid and semi-arid environment [15]

Soil type	A	B	C	D
Surface	Gravel, cobbels boulders, aeolian sand, sand dunes	Quarternary deposits, sand, fracture	Sedimentary rocks, weatherd rocks, metamorphic rocks	Clay, silt, intact rock
k_s	0.15	0.30	0.50	0.75
r	0.14	0.26	0.39	0.53

would have resulted in a lifting of the *Sabkha*'s bottom due to blown sand and bed loads transported by the wadis, respectively and thus influencing the storage capacity. The lake's surface is not depending very much on the stored water volume if more than app. 120 mio. m³ already are retained (cf. fig. 4). Since infiltration as well as evaporation depend on the lake's surface, the influence is not that relevant.

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^{-9} m s^{-1} have been considered according to empirical values. Since the annual infiltration volume has been found to be app. 2% of the annual runoff volume for this assumption, further evaluation is not necessary.

Further, runoff-coefficients r which represent the runoff concentration pattern in the catchment have been evaluated. Mean runoff-coefficients characterise the percentage of annual rainfall becoming surface runoff and therefore are essential for solving the water balance equation. The most important hydrological components during rainfall events in arid or semi-arid environments are the intensity and duration of precipitation, runoff and infiltration rates, hence evaporation and interception could be neglected because of less or absent vegetation. Runoff-coefficients 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. Further the catchment area has a certain impact on the runoff coefficient. As bigger the catchment, as bigger the transmission losses of surface runoff in wadis are considered to be.

To evaluate all these influences is hardly possible, in particular if a model represents a prehistoric scenario. But, because the antecedent hydrologic conditions of rainfall events in arid and semi-arid are extremely dry, only the soil type has a major impact on the runoff-coefficent. The empirical formula (1) to estimate a runoff coefficient, which was derived by Şen [15], was found to fit very well to a long-term water balance in arid and semi-arid environments.

Formula (1) $$r = 1 - e^{-k_s}$$

The runoff exponent value k_s represents the soil conditions. For typical rock outcrops and surfaces in arid or semi-arid environments Şen [15] gives empirical values to calculate the runoff-coefficients (cf. Table 1).

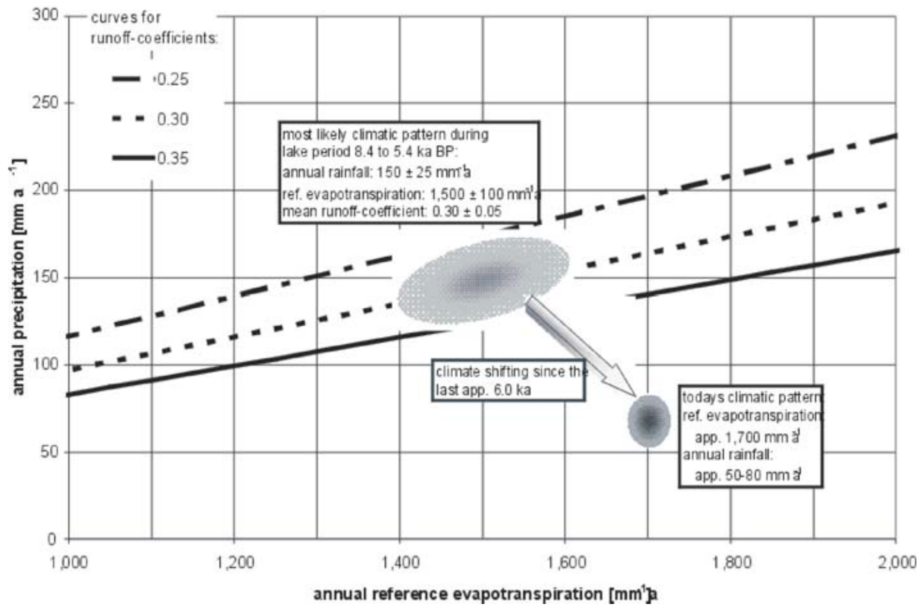

Fig. 5: Reconstructed annual precipitation and reference evapotranspiration rates for different mean runoff-coefficients and an equal water balance at a water level of 811.5 m aSL of the *Sabkha*. As shown in this figure, a climate shifting from cooler and wetter conditions during second lake period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

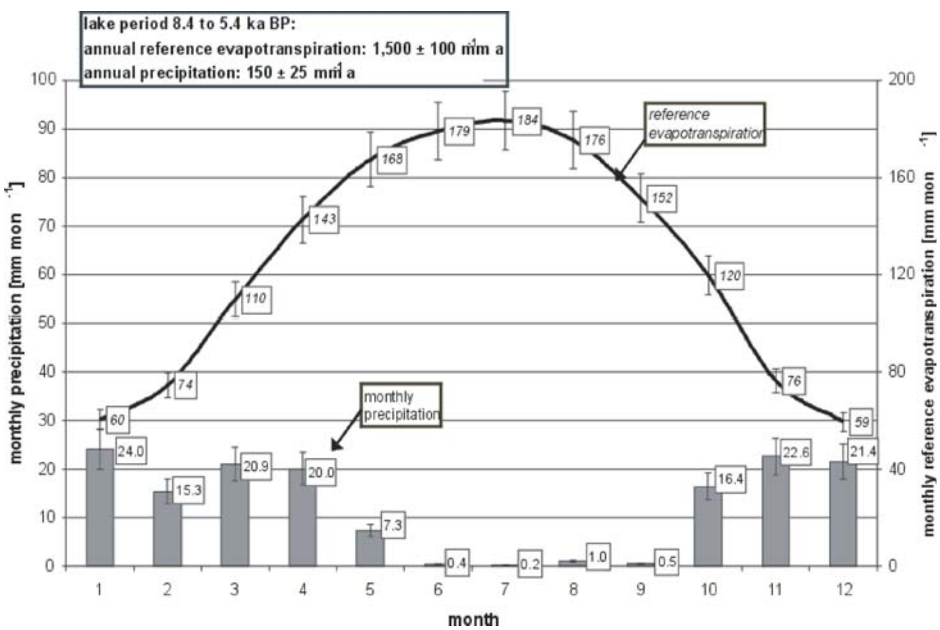

Fig. 6: Reconstructed seasonal distribution of precipitation and reference evapotranspiration for second lake period 8.4 to 5.4 ka BP according two today's climate pattern.

The catchment of Tayma exhibits mainly soil types B and C of Table 1 (see above). But, since quaternary deposits are predominant runoff-coefficients in a range from $r = 0.25$ to 0.35 have been taken as a basis for the oncoming calculations, whilst $r = 0.30$ is the most likely.

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 today's climate pattern has been assumed (rainfalls in wintertime, high evaporation rates in summertime).

It should be noticed, that orbital parameters which are influencing the solar insolation and therewith the potential evapotranspiration among others, varied since Holocene very smooth [16]. Therefore, an annual reference evapotranspiration of 1500±100 mm a^{-1} seems to be plausible. Denser cloudiness during wetter periods would have decreased the reference evapotranspiration in comparison to today's 1700 mm a^{-1}. The assumed monthly values for precipitation height and reference evapotranspiration are presented in fig. 6.

Monthly rainfall was expected to occur as singular rainfall events in order to neglect transmission losses of very small 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 811.5 m aSL depending on these three parameters are shown in fig. 5.

Therefore, the annual precipitation rate for the less humid and younger lake-period (8.4 to 5.4 ka BP) which was linked to a persistent water level of app. 811.5 m aSL was estimated to 150±25 mm a^{-1} considering an annual reference evapotranspiration rate of 1500±100 mm a^{-1}. These calculations base on the assumed today's climate pattern with certain annual distributions of rainfall and evapotranspiration (cf. fig. 6).

Interestingly, no major influence of a monsoon-affected climate (rain periods during summertime) could be identified. Even if a lower reference evapotranspiration of app. 1,400 mm/a for such conditions could be assumed, the annual precipitation rate would have been at 136±23 mm a^{-1}, which also seems to be conceivable.

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 has 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. 80 cm 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.

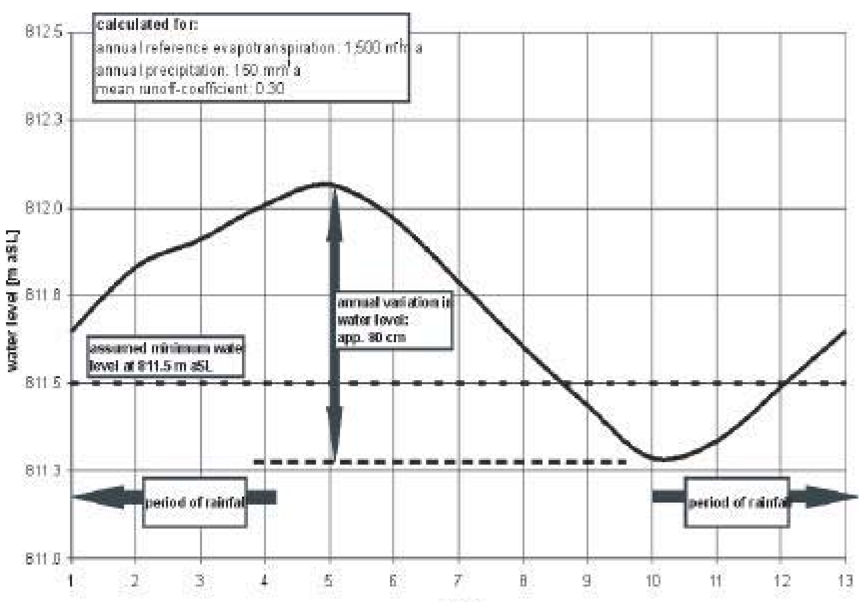

Fig. 7: Annual water level hydrograph for the *Sabkha* representing considered conditions during second minor lake period 8.4 to 5.4 ka BP.

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. 20 to 30 cm. Still today after singular rainfall events during wintertime the water level rises significantly.

DISCUSSION

For the older and probably more humid lake-period (app. 34-24 ka BP) an annual precipitation of 200±50 mm a^{-1} was assumed by Wood/Imes [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 (150±25 mm a^{-1}) because the younger lake period (8.4 to 5.4 ka BP) is supposed to be less humid than the older one. Furthermore, these results fit quite well to the results of the pollen analysis for the time period in question[12]. 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 barnacle species (*balanus sp*.) like they were found at the northern shoreline of the paleo-lake (sample Tay 7, cf. [12] in press). 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 could not be proofed whether Tayma actually was affected by the Indian monsoon or not. Since the model is very sensitive to an adjustment of runoff-coefficients, a monsoon-affected climate (rainfall during winter and high evapotranspiration rates during summer) leeds to annual precipitation rates in the range of 136±23 mm a^{-1}. This range seems to be plausible at its upper boundary.

These statements are referred to the assumed shoreline of the *Sabkha* paleo-lake at a level of 811.5 m aSL, which is based on geoarchaelogical investigations. But also a former shoreline at a level of perhaps 818 m aSL is conceivable under a hydrologic point of view. The lake's surface would have been bigger by app. 22% then. Due to a higher evapotranspiration and infiltration volume the annual precipitation rates would be in the range of 180±30 mm a^{-1}, which still seems to be plausible at its lower range. A persistent lake at a level of 818 m aSL would have had its shoreline in close vicinity to the prehistoric as well as to the ancient settlement which earliest findings were dated to app. 5 ka BP. For the development of the community this would have had a major impact even if the water of the *Sabkha* was already saline. Further investigations regarding this topic are in progress.

CONCLUSION

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 perhaps monsoon affected climate during Holocene era, though the environment also has been arid then. The most likely value for the annual precipitation rate was determined to 150± 25 mm a^{-1} for the second minor lake period in mid-Holocene (app. 8.4 to 5.4 ka BP).

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

The applied model bases on the water mass balance. It is quite sensitive in changes of runoff-coefficients, which have been evaluated by trend, yet. To determine the water balance more in detail, exact knowledge of the catchment is necessary.

Today the investigated area is found to be hyper-arid with annual precipitation rates of distinctly less than 100 mm a^{-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.

[12]Oral communication: R. Neef (2009).

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