THE MOISTURE FROM THE AIR AS WATER RESOURCE IN ARID REGION: HOPES, DOUBTS AND FACTS

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Abstract

The recovery of clean water from dew has remained a fascinating problem in the arid regions of the globe. The stone heaps near the city of Feodosia in the Crimean peninsula were considered for many years to be artificial dew-catching constructions for obtaining drinking water. Several attempts to reconstruct these systems have been made but they have been considered unsuccessful because of low yield. This has caused some doubts and negative estimations regarding the role of the Crimean stone heaps as water collectors. The opinion that there were no dew-catching constructions in Crimea still dominates today.

In this discussion we shall consider the role of the Crimean stone heaps as water condensers and a model of Nikolayev, Beysens et al. (1996) of this process. Some conclusions will be put forward showing why this model does not correspond with the system under consideration, hence concluding that the above mentioned negative opinion, which is based on the model, is a rather hasty conclusion.

The traditional model of the Crimean water collector will be modified by the consideration of the role of the draught in the process of condensation. Qualitative and quantitative analysis of the process and of draught outbreak will be proposed. The efficiency of the collector will be estimated.

Keywords: dew, condensation, water collection, arid region.

Introduction

The demand for fresh water is currently an important political, social and economic issue in many countries of the arid regions of the globe. The main sources of fresh water are rivers, lakes and artesian wells. But river discharge comprises only 7% of the total condensation. The renewable source of fresh water - the moisture of atmosphere is almost not used.

About 200 nights in Highland Negev in Israel are characterized by 100% humidity (Broza, 1979). Annual dewfall in coastal regions, Jerusalem and the North Negev is 60-120 mm (Ashbel, 1935, 1949). The number of foggy nights in the North Negev and Yizreel Valley is about 40 (Levi, 1967).

We consider here the possibility of condensation of the moisture of humid air on some cold surface with certain swiping potential. Condensation of moisture remains in the shadow of other solutions. Nevertheless, the experiments of obtaining water from fog or from moist

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air were conducted in not less than 22 countries (NIkolayev et al., 1996), (Schemenauer et al., 1991). The amount of obtained water depends upon the place, the time of year and the percentage of moisture in the air. Most advanced systems using high elevation fog give 3-7 liters per day per m^2 of working surface (Schemenauer et al., 1989, 1991, 1992). The high quality of the atmospheric water and minimal influence on the environment are important positive factors considered in this approach.

The history of water collection in Crimea is one of more fascinating and intriguing in this area. The purpose of our work is estimation of the ability of the Crimea stone heaps to collect dew and consideration of some negative opinions regarding this ability, development of the traditional model of water collection by stone heap and the role of draught for this model, qualitative and quantitative analysis of the process and of draught outbreak, estimation of the output.

1 The story of the dew collection in Crimea

This section follows mainly to F.I. Zibold, a Crimean forester and engineer (Zibold, 1905). Let us consider some undoubted facts from this work.

The population of the city of Feodosia in the coastal part of Crimea peninsula in the 19th century was about 11,000. The climate was quite dry, the rains were rare and droughts lasting several months were normal. Zibold was unable to find any spring or well around the city, but mentioned a large quantity of dew. The water supply of the city was based on the so-called "fountains", which were big reservoirs of the water. The inscription in the Armenian language found on the 182 m^3 "Karaite fountain" is dated 1586. There were 8 working fountains in 1874 and only 5 working fountains in 1882. There were 26 fountains one hundred years before, in 1784. In the Middle Ages, during the heyday of the city, it is suspected that there were up to 100 "fountains". The reservoirs have obtained the water from a network of tile pipes, 5 to 7 cm in diameter, and channels filled with crushed rock. Nevertheless, there was no trace of springs. The pipes and channels ended in enormous pyramids of crushed calcareous rock of odd shapes and 5 to 10 cm in size.

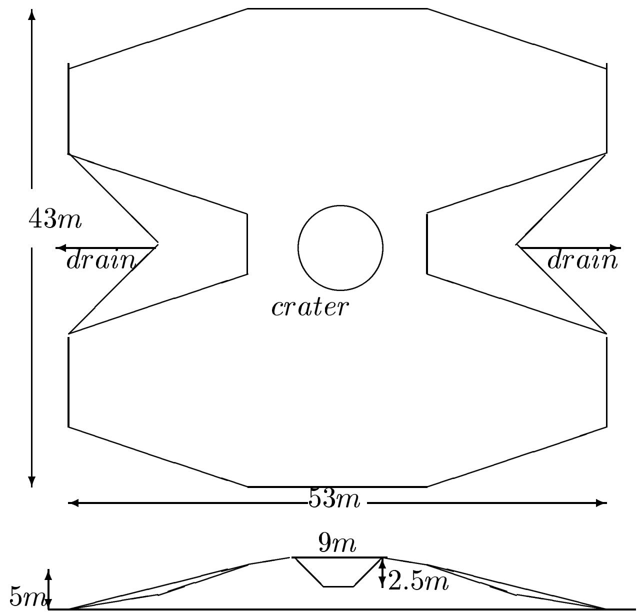
The daily output of the "fountains" was studied twice: in October 1874 (8 "fountains", 66,000 litres), and in May 1882 (5 "fountains", 57,000 litres). Zibold found in 1905 10 stone heaps considered as water condensers and printed the volumes of five of them: 2900, 1970, 1450, 1250, 1250 m^3. So we can consider the average stone heap volume of 1664 m^3.

If we suppose that the number of active condensers was not less than 8 in 1874 or 5 in 1882 and not greater than 13 in 1874 or 10 in 1882, then we can derive that 5,100 - 11,400 litres were the production limits for a single stone heap per day.

A constant deterioration of considered water supply system was mentioned. Only the remains of pipes are noticed now (Nikolayev et al., 1996). The pyramids of crushed rock were destroyed in the beginning of the 20th century (Alexeyev et al., 1998).

Nevertheless, one can find today in Crimean forests some another kind of water condenser also called "fountains" by Crimean inhabitants. The size of the installation is like the size of a little house. The water leaks from the pipe going out from the lower part of the construction. This kind of installation was described in literature (Anonymous, 1925), (Jumikis, 1965).

To verify the possibilities of dew condensation, Zibold built in 1912 in Crimea a stone heap condenser model. He had kept the shape, the size and the structure of old prototypes. Sea-beach pebbles were used as a building material. Unexpectedly, the installation yielded only



300-360 liters per day (Anonymous, 1935), (Nikolayev et al., 1996) and suddenly stopped functioning. A leakage of the bowl was suspected. No information about functioning of the installation can be found in Zibold's publications. The data on daily output we know (Nikolayev et al., 1996) was obtained from an indirect source. One can suppose that Zibold considered his experiment a failure. Hence, this level of diurnal productivity could not be an optimal basis for the estimation of the stone heap average output.

Zibold's attempt inspired some experiments with this type of water condenser in the South of France by L. Chaptal, M. Goddard and A. Knapen. (see (Jumikis, 1965), (Chaptal, 1932), (Knapen, 1925)). These installations called "aerial wells" or (vapor) "captors" were analogous to the Crimean prototypes. The size of the installations was essentially less. Different modifications of the construction were checked. Some of the constructions yielded condensed water, but the amount of the water was less than expected. The rosy hopes of their creators failed.

From the Feodosia weather station data, the average velocity of winds is 7 m/s and winds from the sea are dominant. The average annual rainfall is 366 mm and the average number of days with fog is 25 (Alexeyev et al., 1998), (Nikolayev et al., 1996).

2 The discussion of the role of the Crimean stone heaps condensers

We can conclude that the water supply of Feodosia for many years was on the level of 60,000 litres per day (or greater), and we do not know today of another source of drinking water except the stone heaps on the mountains near this town. We know that the Zibold and Chaptal installations have followed the prototype described by Zibold and have produced water, but the yield was unexpectedly low.

Let us consider other points of view on the Crimea stone heaps. There are doubts of its role as water condensers, and now it is a prevailing point of view. Ashbel (1949) writes: "The exact purpose of the installation in the Crimean peninsula described ... as "dew wells" is not known. If we must speak of "dew wells", we might take as an example those in the desert of Northwest Africa". "No large amount of water is to be expected in such reservoirs: but where no drinking water whatsoever is available, the few liters collected every night is invaluable to thirsty wayfarers".

Nikolayev, Beysens at al. (1996) have investigated the history of moisture condensers and have refused to accept the hypothesis concerning the Crimean installations: "The Tepe-Oba mountain is fissured by the remains of a sophisticated system of ancient water supply and tubes can be found within hundreds of meters of every mound. Excavations of more than 80 mounds, however, did not reveal any signs of a hydraulic system. On the contrary, tombs were in each of them. Where water still comes out of the broken water supply, it contains dissolved minerals and thus does not come out of condensers, because condensed water is almost distilled. Moreover, the dry remains of the ancient water tubes are covered (inside) by a thick layer of mineral deposits. Hence it is thought that there were no ancient dew condensers in the surroundings of Feodosia". "A model for calculating condensation rates on real dew condensers" was proposed. This model of water condenser is considered by authors as a model of Zibold type condenser and a scientific base for the conclusions of the paper.

We may give a reason that contradicts this assertion. First of all, the numerical simulation of the diurnal cycle of this model implies condensation of the water in the nighttime. "The condensation starts 4 h after the sunset" and "stops at about 09.00" (Nikolayev et al., 1996, p. 27). The real situation for Zibold type condensers is quite another. The sources concerning this kind of condenser discuss about a day condensation (Jumikis, 1965). The large stone hills are now destroyed but one can find even now in Crimean forests these types of such "fountains" (Anonymous, 1925) (see the illustration of the installation in Jumikis (1965) as well). One of the authors had observed such a system some years ago. The water had leaked from the pipe going out from the lower part of the construction. It was the daytime between 10.00 and 12.00 and some litres of the water were used for dinner. There were no doubts of the role of the pipe and of the installation.

Some installations analogous to the Crimean stone hills were constructed in southern France, in 1928-1931 by Chaptal. Let us note a Chaptal observation that "...it was quite exceptional to find dew formed in the well during the night") (Jumikis, 1965).

Let us go to the tubes having "tracks of mineral deposits". As for the purity of water from the dew condenser, note that the quality of condensed water was studied by Schemenauer and Cereceda (1992) and they establish that it could be used for drinking, but not "almost distilled". Real condensed water contains minerals. A stream of condensed water will produce over centuries "a thick layer of mineral deposits". Therefore, the existence of a layer of mineral deposits does not contradict but supports the existence of a dew collector.

The "excavations of more than 80 mounds did not reveal any signs of a hydraulic system". Truly, tile pipes and channels were situated outside the mounds.

As for tombs found in stone heaps, we find no contradiction in this situation. Crimea had a large population for many centuries. It is difficult to imagine any place in the coastal part of Crimea without tombs.

The model of Nikolayev et al. (1996) corresponds more to the type of water condenser studied by Nilsson (1996) (see also (Vargas et al., 1998)) where the night condensation and cooling of the condensation surface by help of irradiation were considered and some real results were obtained.

The non-trivial part of each study is the estimation of the losses of the real process. For instance, the losses of unknown nature in the Schemenauer (1991) experiment were in the range 70%. Therefore, let us evaluate the results obtained in the numerical experiment (NIkolayev et al., 1996) on the base of real data (Nilsson, 1996). The values 221, 155, 61 litres per night were obtained in the numerical experiment for Zibold condenser with $S = 854m^2$. Thus we have 0.25, 0.18, 0.07 l/m^2, correspondingly. The maximum single night collection of Nilsson installation was 0.24 l/m^2. So there exists a good correspondence between two maximal values, but the average night dew collection of Nilsson installation in the dry months was only in the range 0.04 - 0.03 l/m^2. Therefore we can take into account the possible losses and estimate the night output of Zibold condenser in the range of some dozens of litres. It does not correspond the reported data 300-360 l (NIkolayev et al., 1996) of the diurnal output of Zibold condenser. We can suppose that the Zibold type condensers produced the water mainly in the daytime and the model of Nikolayev, Beysens et al. (1996) explains only the night output of the condenser, but does not explain the whole output.

The negative conclusion of the role of the Crimea stone heaps as water collectors seems therefore too hasty and unfounded.

3 Traditional condensation model

The traditional model of a functioning Zibold type condenser was proposed by Chaptal (1932) and Knapen (1928) (see Jumikis (1965) too). The model is based on the results of the Zibold and Chaptal experiments.

With the decrease in air temperature at night the chilled air (now heavier than the warm air in the inner part of the stone heap) drives out the warm air that was accumulated in the system during the day. The cool temperature is transmitted by conduction and heat exchange throughout the stone heap. The wind accelerates the chilling of the stones. As a result, the temperature of the interior of the system reaches the temperature of the night air. The surface of the stones becomes chilled and is thus in a condition to condense the warm, damp air for a certain period of time. During the day the warm air, more or less saturated with water vapor, enters the condensation surface and contracts. The air is gradually chilled until the vapor reaches the dew point. Part of the vapor condenses on the surfaces of the stones. After some time, the temperature between the inside and outside will reach equilibrium and condensation stops. The following night, the process starts all over again.

The amount of condensation evidently depends upon the temperature difference between the exterior and interior of the system, upon the degree of saturation of the air and upon the properties of the condenser surface. The warmest day gave the largest quantity of captured water. There should be sufficiently effective renewal of the air in the interior in the night and in the day, but in the day the ventilation should not be too high and turbulent (or else evaporation would consume the aqueous deposit immediately as it forms). The condensation is the most sensitive part of the process. The permeability of the stone heap is satisfactory due to the size of stones.

The traditional model of a functioning Zibold type condenser and the model of Nikolayev et al. (1996) differ in consideration of the working layer of the condenser. The yield of the condenser depends linearly on the surface area of condensation (Nilsson, 1996), and the surface area depends on the depth of the working layer as a quadratic function.

A narrow working layer of Zibold installation of depth 0.3 m is considered in the last model. The working layer in the traditional model is essentially greater. If we suppose that effective ventilation can be expected up to 3 m, then it gives us 100 times greater upper bound on the yield of the Zibold type condenser. Hence, the surface of condensation does not influence the upper bound for the yield of the Zibold system in the traditional model. We must consider more essential restrictions on the productivity such as heat capacity of the active layer. The diurnal output of the Zibold type condenser in the traditional model therefore is measured as l/(grade m^3) (or kg/(grade m^3)).

Let us use the following notation: specific heat capacity of the stones $c_s = 1090\ Jkg^{-!}K$, latent heat of condensation $L = 2\ 260\ 000\ Jkg^{-1}$ (Nikolayev et al., 1996), density of the stones d_s is 2500 kg m^{-3} - 2700 kg m^{-3} (Nikolayev et al., 1996), (Alexeyev et al., 1998)l.

For specific volume m_w of the condensed water during one day per one grade we have

$$m_w = \frac{K_s c_s d_s}{L} \tag{1}$$

where K_s denotes the ratio of volumes of the stones of the heap and the heap. The heating of the air is not considered here for the sake of simplicity. $K_s = 0.5$ (Nikolayev et al., 1996) or 0.7 (Alexeyev et al. 1998). Because the difference is essential, let us carry the necessary calculations.

We begin from the case of low density for to find a lower bound on the parameter. Let us consider every stone as ellipsoid with axes a, b, c that is inscribed in regular parallelepiped of size 2a X 2b X 2c. Suppose that the hill consists of such parallelepipeds and distinct parallelepipeds have no intersection.

The volume of ellipsoid is equal to $\frac{4}{3}\pi abc$ (Beyer, 1991), the volume of the parallelepiped is $8abc$. So for the desired ratio in the case of low density we have

$$K_s = \frac{4}{3}\frac{\pi abc}{8abc} \simeq 0.5236$$

For the case of high density and for the upper bound on K_s let us consider the stones as spheres with radius R. Suppose that the centers of three neighbor spheres form a regular triangle with side $2R$ and the centers of four neighbor spheres form a regular triangular pyramid with the same edge $2R$. The attitude of the regular triangle is $R\sqrt{3}$, The attitude of the regular triangular pyramid is

$$\sqrt{(}(R\sqrt{3})^2 - (\frac{R\sqrt{3}}{3})^2) = 2R\sqrt{\frac{2}{3}}$$

So for the desired ratio in the case of high density we have

$$K_s = \frac{4}{3}\frac{\pi R^3}{8R^3}\frac{2R}{R\sqrt{3}}\frac{2R}{2R\sqrt{\frac{2}{3}}} \simeq 0.7405$$

The real experiment with beach pebbles gives us some values from 0.56 to 0.62. So let us accept the average value of these theoretical and practical results: $K_s = 0.6$.

From (1) for specific diurnal output m_w we have

$$m_w = 0.72\frac{kg}{m^3} - 0.78\frac{kg}{m^3} \tag{2}$$

per grade without consideration of losses.

(Let us remember that the real values obtained in Zibold and Chaptal installations lay between 0.31 and 0.05 kg/m^3. In the fog collector installations (Schemenauer et.al,1989), the real deposit was 2.9 times less than the theoretical but here the gap is greater).

Let T_s be temperature of stones in hill, T_a is the temperature of air, T_d denotes the temperature of dew point. Suppose $T_a > T_s$, $T_d > T_s$. Let V be volume of active layer of stone hill. The diurnal mass of condensed water may be presented in the following form:

$$m_d = \frac{K_d V c_s d_s}{L}(min(T_a, T_d) - T_s) = m_w V \Delta T \qquad (3)$$

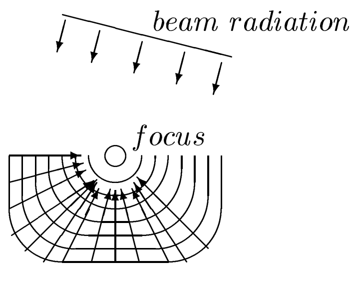
The average volume V of the mound was about 1664 m^3 (Zibold, 1905)). So, the stone heap can yield a maximum of 1200 - 1300 litres per grade every day. The difference between the air temperature and the temperature of stones during the day is not greater than the difference between the day and night temperatures of the air. If we suppose that the last is about 5-10 grades and the air is saturated ($5 < \Delta T < 10$) then we obtain 6,000-13,000 litres as an upper bound of diurnal output for the stone heap. It is possible in an ideal situation when the day air temperature is equal to that of the dew point, the permeability of the stone heap is optimal, the evaporation is minimal and the drain inside the stone heap is satisfactory. The real yield was essentially less because of losses. It corresponds with the real data from Feodosia (Zibold, 1905) and the estimation found above on the base of the data (5,100 - 11,400 litres).

The Zibold hopes were more optimistic - 55,000 liters per day from one stone heap (Jumikis, 1965). Therefore, his real results imply deep disappointment. The value obtained in Zibold installations is about 0.3 l/m^3 and in Chaptal installations - 0.05- 0.2 l/m^3 (Jumikis, 1965). The daily output per grade was essentially less. So, these installations could not be considered as completely perfect.

Some modification of traditional model will be considered below.

4 The role of air draught in day condensation

One of the most important features of the Crimean dew collector is a crater in the central part of the stone heap (Alexeyev et al., 1998), (Nikolayev et al., 1996), (Zibold, 1905). In the day time the sun heats the stones and they heat the air in the crater. For to estimate the nascent temperature gradient let us consider the axial section of the inner surface of the crater as a non-singular curve of a second degree (hyperbola, parabola or ellipse). The horizontal section of the inner surface of the crater will be considered as a circle. Therefore the inner surface of the crater may be considered as a surface of rotation with focus on the vertical axis of symmetry of the surface. Suppose also that the surface is specular and gray.



The distance d between the focus and the vertex of the surface (the bottom point of the crater) can be calculated in the standard way from the equation of the axial section of the surface

$$Ax^2 + 2Bxy + Cy^2 + Dx + Ey + G = 0$$

One of the coefficients is here free and five others can be calculated by considering five distinct points on the section. Moreover, due to symmetry, we need only coordinates of two points regarding to the bottom vertex. The equation may be transformed to the canonical form (Berger, 1987) or some other manual in analytical geometry), then we calculate the desired focal distance d of the curve. From scanty date we have in the case of Zibold installation, the focal distance can be estimated very roughly: 2 - 4 m.

The solar radiation received at the inner surface of the crater is partially absorbed by the surface, partially reflected and emitted.

$$e = e_{absorb} + e_{refl}$$

Relationships among absorption capacity, emittance and reflectance depend upon the material of the surface. For our case we have the following estimation (Duffy et al., 1974)

$$0.1e < e_{refl} < 0.5e \tag{4}$$

The energy absorbed by unit of surface is equal to

$$e_{absorb}\cos(\alpha)$$

where the angle α is the angle between the normal vector of the surface and angle of incidence of ray. Therefore the maximum of absorbed energy received at the point where both directions coincide. This point has changed his position during the day in neighborhood of the vertex of the surface.

Let us now consider the distribution of energy in the crater and higher. This distribution depends upon direction of reflection of sun rays and of absorbing capacity of air, dust particles in the air and water vapor. Due to geometrical properties of the inner surface of the crater, the reflected rays are directed to the focus of the surface.

Let us consider a sequence of surfaces S_i, where S_0 is the inner surface of crater, every S_i has the same form, the same vertical axis and the same low focus. Suppose that for focal distance d_i of S_i

$$d_{i+1} = d_i - \Delta d \tag{5}$$

Every layer between two neighboring surfaces absorbs the same amount of energy, whence for every two equal volumes of air V_1 and V_2 with absorbed energy $e(V_1)$, $e(V_2)$ and layer focal distances $d(V_1)$, $d(V_2)$ we have

$$\frac{e(V_1)}{e(V_2)} = \frac{d^2(V_2)}{d^2(V_1)} \tag{6}$$

Therefore the maximum of absorbed energy is concentrated in little lens containing the point of focus and is growing with approaching to this point. According the Stefan-Boltzmann formula (Duffy et al., 1974)

$$e = \sigma T^4 \tag{7}$$

where the Stefan-Boltzmann constant σ is equal to $5.6697 \circ 10^{-8} W/m^2K$, T is the absolute temperature.

Let us consider two equal volumes of air V_1 and V_2 in above-mentioned neighboring layers of air with absolute temperatures T and $T + \Delta T$, absorbed energy e and $e + \Delta e$, layer focal distances d and $d - \Delta d$, correspondingly. (7), (5) and (6) imply in an area where the beam radiation is essentially less than the reflected radiation

$$\frac{(T+\Delta T)^4}{T^4} = \frac{e+\Delta e}{e} = \frac{(d-\Delta d)^2}{d^2}$$

Therefore $(1 + \frac{2\Delta T}{T} + (\frac{\Delta T}{T})^2) = (1 - \frac{\Delta d}{d})$, whence

$$\frac{2\Delta T}{T} \approx \frac{-\Delta d}{d}$$

The integration of corresponding differential equation gives us the connection between the absolute temperature T and focal distance of the layer d

$$T\sqrt{d} = C$$

where $0 << d << d_0$, the constant C depends on absorptive properties of the air. In view of (4) and (6), the equation predominates for d less than $0.3d_0 - 0.7d_0$, scattering implies $0 << d$.

This establishes a temperature gradient in the vertical direction. More precisely, it is the direction from the point of maximal radiation to the point of focus. Let us notice that the wind can dissipate the considered lens of hot air, but only the strong wind can destroy it completely and dispose the temperature gradient.

The temperature gradient creates draught in vertical direction stimulating the heat exchange in the stone hill. Thus we have continuous, moderate and stable draught some hours after sunrise. The air draught involves the surface of the stones in the inner part of the mound in the process of condensation. Two processes - condensation and heat exchange - are working together and the role of each process depends upon the humidity of the air. Every point between the outer surface of the heap and the inner surface of the crater participate in both processes. If the moist air from the sea reaches the stone hill with the beginning of draught (it depends on wind and distance from the sea) then the condensation predominates. In the case of low humidity the heat exchange prevails and the condensation surface remains dry. Therefore, the condensation is the most sensitive and unstable part of the process. Maximal values of the daily output of the process are given by the formula (2): about 0.75 kg m^{-3} per grade.

There is another situation at night. The stone heap may be considered as a hot island in the cold night air because the cooling of the air is more rapid than that of the stones. This creates an uprising stream of air in the heap. The process of ventilation ends when the temperature of the stones achieves that of the air. Both processes of day condensation and night cooling are not independent. The day condensation stimulates heating of the inner part of the stone hill and as a result the night draught. The night cooling of the surface of the stones promotes the day condensation on the surface.

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