Dew and Rain Water Collection in South Croatia

Daniel Beysens, Imad Lekouch, Marina Mileta, Iryna Milimouk and Marc Muselli

Abstract—Dew harvesting needs only weak investment and exploits a free, clean and inexhaustible energy. This study aims to measure the relative contributions of dew and rain water in the Mediterranean Dalmatian coast and islands of Croatia and determine whether dew water is potable. Two sites were chosen, an open site on the coast favourable to dew formation (Zadar) and a less favourable site in a circus of mountains in Komiza (Vis Island). Between July 1st, 2003 and October 31st, 2006, dew has been daily collected on a 1 m² tilted (30°) test dew condenser together with ordinary meteorological data (air temperature and relative humidity, cloud coverage, wind speed and direction). The mean yearly cumulative dew yields were found to be 20 mm (Zadar) and 9.3 mm (Komiza). During the dry season (May to October), monthly cumulative dew water yield can represent up to 38% of water collected by rain fall. In July 2003 and 2006, dew water represented about 120% of the monthly cumulative rain water. Dew and rain water were analyzed in Zadar. The corresponding parameters were measured: pH, electrical conductivity, major anions (\( \text{HCO}_3^- \), \( \text{Cl}^- \), \( \text{SO}_4^{2-} \), \( \text{NO}_3^- \)) and major cations (\( \text{NH}_4^+ \), \( \text{Na}^+ \), \( \text{K}^+ \), \( \text{Ca}^{2+} \), \( \text{Mg}^{2+} \)). Both dew and rain water are in conformity with the WHO directives for potability except Mg\(^{2+}\). Using existing roofs and refurbishing the abandoned impluviums to conformity with the WHO directives for potability except Mg\(^{2+}\). The maximum dew yield that was measured was in the order of 0.6 L m\(^{-2}\) [10], close to the expected maximum when accounting for the available maximum cooling radiative energy (\(~ 150 \text{ Wm}^{-2}\)).

The interest in such water collection devices becomes evident as the necessary cooling energy (radiative deficit) is free and inexhaustible. In addition, the financial investment for the collectors is small and the functioning of such condensers is preserved even if partially damaged. Special dew water condensing devices (inclined planes: see [2]; roofs: see [9], [11]) have then been built with success in Mediterranean islands (Corsica, France; Biševo, Croatia) and in India (Kothara, Gujarat). Large dew harvesting systems have been fabricated on the ground [3], [4], [12]) at moderate cost. Some existing buildings – especially home roofs or rain-catching construction common in the Mediterranean basin, the so-called impluviums – present opportunities to produce dew water with only a modest financial investment for purchasing thermally insulated condensing foil (or paint) and collection gear. Such construction can capture both dew and rain (and to some extent, fog and mist).

Here we evaluate the relative contribution of both dew and rain water collection in the Adriatic area of the Mediterranean basin and their chemical quality. Dew measurements were performed from years 2003 to 2006 at two locations, in Komiza (Vis Island) and in Zadar (Dalmatian coast). This region is characterized by the presence of many very small islands that are deprived of local natural drinking water. The summer season is generally very dry and the inhabitants have built impluviums since ancient times to collect rain. Note that an early attempt to collect dew by massive condensers was carried out in the city of Vis (Vis island) during the last century [13].

The composition of dew water is determined by the dissolution of the surrounding gases and the small particles (aerosols) which settle on the surface of the condenser [14]. The quality of dew water was the object of a few studies [14]-[22]. Chemical analyses were carried out in Chile [20], in the USA [15], in Japan [17], [21], in Jordan [22], in India [23]-[24], in France [2], [4], [14], the characteristics of which can be quite different. Dew water was very corrosive in Chile with a high ionic concentration, very acidic in Japan with a high concentration of sulphates and nitrates, and only slightly alkaline and slightly mineral-bearing in Jordan and France. Biological measurements have been performed in France (Ajaccio [4] and Bordeaux [14]).

II. EXPERIMENTAL PROCEDURE

A. Measurements Sites

In Zadar, the measurement site is situated at a meteorological station operated by the Meteorological and Hydrological Institute of Croatia (MHIC), located at 44°08' N, 15°13' E, at 5 m a.s.l. It is situated on a long peninsula, spreading over the Adriatic Sea and within 10 m from the sea. The mean annual rainfall is 917 mm.
In Vis Island, the measurements were also performed at a meteorological station of the MHIC in Komiža (43°03' N, 16°06' E, at 20 m a.s.l). Komiža is a town and harbour situated in the centre of a mountainous cirque open to the sea to the SW. The Vis Island is about 140 km away from Zadar. The annual mean rainfall is 817 mm (mean computed between 2003-2005) and very erratic. Because of the situation, this site is representative of a poor location for implementing dew collection; the dew yields will thus be considered as a minimum in the area.

B. Setup

Dew was collected on a condenser of 1 m x 1 m inclined at a 30° angle from horizontal (Fig. 1). It was coated with a condensing foil, 0.35 mm thick, made of TiO₂ and BaSO₄ micro spheres embedded in low density polyethylene with one % food surfactant (similar to Nilsson [1]; made by OPUR, France, www.opur.u-bordeaux.fr). The foil was thermally insulated from the condenser frame by a 30 mm thick Styrofoam plate. Dew quantities were collected and its volume V measured daily in the morning, corresponding to water collected by gravity flow in a bottle and scraped from the surface. As polyethylene is sensitive to UV radiations, the foils was changed every six months. The following parameters were also recorded: air temperature, relative humidity, wind speed at 10 m elevation, wind direction, cloud cover data. These parameters were recorded at the following times (UTC +1) 08:00, 19:00, 21:00. Frost were excluded from the dataset. In Zadar, a cup anemometer measures the windspeed at 10 m height, with a stalling speed of 0.5 m/s and within 0.1 m/s resolution. In Biševo, windspeed is measured in Beaufort (Bf). Rain was collected and its volume measured in a standard stainless steel 200 cm² surface area pluviometer.

Dew and rain water were stored in Polyethylene bottle of 0.5 L. Water was not filtered. Volumes below 10 cm³ were discarded as this amount is the minimum needed for complete chemical analysis. The dew and rain samples are sent to the chemical laboratory in Zagreb each two weeks; meanwhile, the samples are stored in a refrigerator. The following determinations were performed: (i) physico-chemical properties: pH, conductivity EC, (ii) chemical concentration; cations: NH₄⁺, Na⁺, K⁺, Ca²⁺, Mg²⁺, anions: HCO₃⁻, Cl⁻, SO₄²⁻, NO₃⁻; (iii) Determinations specific to potable water.

III. RESULTS AND DISCUSSIONS

A. Dew Yield

The dew yield data are shown in Figs. 2ab (evolution) and the statistics are summarized in Table I. The mean yearly dew yield is 19.9 mm (Zadar) and 9.3 mm (Komiža). The daily dew yields can exceed 0.4 mm on both locations and sometimes reach 0.6 mm in Komiža. Zadar has more dew days (18%) than Komiža and the cumulative dew yield is about 2.5 times that of Komiža. The reasons are twofold. (i) Due to this coastal setting, the Zadar mean windspeed is lower than in Komiža (Zadar : 2.5 m/s, Komiža: 2.3 Bf). The location of Komiža, with strong infrared scattering from the mountains around, hinders dew formation. However, although the number of dew days is fewer than in Zadar, the dew yields are higher on average. This observation agrees with a comparison between island and coastal (and continental Alpine sites), see Beysens et al. [6].

Fig. 1. The dew condenser (1m x 1m surface area) at the Zadar station (Croatia). Collection is made in a PE bottle (B)

Fig. 2 Evolution of dew yields (in mm/day) for both experimented sites (2 ½ year period). (a) : Zadar, (b) : Komiza
B. Dew and Rain Contributions

In order to assess the benefit of dew water collection in addition to rainwater, monthly dew yields (mm/month) are compared to monthly rainfall (mm/month). Fig. 4 compares the dew contribution with respect to rain (in %). In the summer months (July and August), dew water contribution is important, especially in Zadar with 34% and 38%, respectively, in 2004. In both July 2003 and 2006, the ratio in Zadar was about 120%, during a period where an important rainfall deficit occurred in Europe. For the whole period, dew represents 11.7% of rainfall, with a monthly variability of 26.5% of the water balance in Zadar and 1.6%, with a monthly variability of 3.1% in Komiža. It is interesting to note that, even in drought conditions such as during summer 2003, dew continues to provide a consistent (and sometimes only available) amount of water. Low-cost modifications of thermal and wetting properties of already existing roofs, such as in the neighboring island of Biševo (see [11]), or the coating of existing rain collectors (impluviums) that need only a moderate investment, represent obvious opportunities to augment water supply.

IV. PHYSICO-CHEMICAL ANALYSIS

A. General

The statistical analysis of the elements characteristic of dew and rain water is presented in Tables II & III. The physicochemical analysis shows that the nature of this water is alkaline and average conductivity does not exceed 200 μS/cm. The concentration of the various ions show that the sum of the cations is higher than the sum of the anions.
TABLE II
VARIOUS PHYSICOCHEMICAL PROPERTIES OF DEW WATER BETWEEN YEARS 2004 AND 2006

<table>
<thead>
<tr>
<th>Measurements</th>
<th>2001 (μS/cm)</th>
<th>2003 (μS/cm)</th>
<th>2005 (μS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.37</td>
<td>6.33</td>
<td>8.65</td>
</tr>
<tr>
<td>CON</td>
<td>671.16</td>
<td>496.16</td>
<td>240.16</td>
</tr>
<tr>
<td>Na+</td>
<td>0.02</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Ca2+</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Mg2+</td>
<td>0.29</td>
<td>0.18</td>
<td>0.27</td>
</tr>
<tr>
<td>Na+—Mg2+</td>
<td>0.02</td>
<td>0.18</td>
<td>0.27</td>
</tr>
<tr>
<td>Na+—Ca2+</td>
<td>0.01</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Na+—CON</td>
<td>0.11</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>EC 2001-2005</td>
<td>19 μS/cm</td>
<td>1117 μS/cm</td>
<td>191,09 μS/cm</td>
</tr>
<tr>
<td>EC 2003-2005</td>
<td>6 μS/cm</td>
<td>1591 μS/cm</td>
<td>132,47 μS/cm</td>
</tr>
</tbody>
</table>

B. pH

The evolution of pH for dew and rain is presented in Fig. 5. For both dew and rain, a seasonal variation is observed with a bump in summer. The dew pH ranges between 6 and 7.5, with a mean value of 6.71 and the rain pH between 5.3 and 7.3, with a mean value of 6.33. The seasonal variation (pH is larger in summer) can be attributed to the difference in quantity of water collected for each season, the lower volumes in summer showing a higher pH (Fig. 5). The pH of rain is in average slightly more acidic than dew’s, by about 0.4 pH unit. The season dependence is firstly due to the variation of the pH with respect to the collected volume, with the highest value for the lowest volume (Fig. 6). The pH distribution spread from about 7 for small volumes and then short $dt$ for high volumes (Fig. 5 to 6) to 5.5 for long $dt$. For high volumes, the contact time of CO₂ and acidic gases is higher, solid alkaline species are more diluted and then dew is more acidic.

C. Electric Conductivity

The electric conductivity EC of dew for all the period takes values from 19 μS/cm to 1117 μS/cm with an average of 191.09 μS/cm and a standard deviation of 174.04 μS/cm. These values are comparable to the conductivity of rain whose EC values extend from 6 μS/cm to 1591 μS/cm and mean EC = 132.47 μS/cm, with a standard deviation of 214.35 μS/cm. The mean values are somewhat smaller than the standard value (400 μS/cm at 20°C) for potable water as requested by the European Commission [26].
the dew conductivity presents seasonal variations more important than those observed with rain, the largest values being in June and July and June (Fig. 7). Alike pH, the electric conductivity decreases with largest volumes, in agreement with the dissolution of gases and particles deposited on the condenser surface (Fig. 8). The same observation was made in a study carried out in Bordeaux [14] and in other reports concerning fog and rain in India [23], [24].

whereas during year 2006, NH$_4^+$ > K$^+$. The concentration of anions follows the same evolution, with Cl$^-$ > SO$_4^{2-}$ > HCO$_3^-$ > NO$_3^-$, except in 2006 where NO$_3^-$ > HCO$_3^-$. Concerning rainwater, the concentration of ions is different from what is observed in dew. For cations, one observes:

- year 2004, Na$^+$ > Ca$^{2+}$ > Mg$^{2+}$ > NH$_4^+$ > K$^+$
- year 2005, Na$^+$ > Ca$^{2+}$ > Mg$^{2+}$ > K$^+$ > NH$_4^+$
- year 2006 Na$^+$ > Mg$^{2+}$ > Ca$^{2+}$ > K$^+$ > NH$_4^+$

In contrast, the anions evolve/move in the same way for all the period of study, Cl$^-$ > SO$_4^{2-}$ > HCO$_3^-$ > NO$_3^-$. The sources of Ca$^{2+}$, Mg$^{2+}$, K$^+$ are aerosols, that is dust coming from the soil that are suspended in the lower layer of the atmosphere and brought to the surface of the condenser by the wind. The high presence of Cl$^-$ and Na$^+$ is mainly due to the sea salts that are convected in the neighbourhoods of the sites of study. These aerosols modify the pH (5.6) of water vapour in equilibrium with atmospheric CO$_2$, as shown by the mean pH for dew and rain water, respectively 6.7 and 6.35 > 5.6. This alkalinity is due to the low content of sulphuric acid (SO$_4^{2-}$) and nitric acid (NO$_3^-$) and the large cation concentrations ($\sum$ cations > $\sum$ anions) responsible for the neutralization of these anions. Thus the ratio: (SO$_4^{2-}$ + NO$_3^-$) / (Ca$^{2+}$ + Mg$^{2+}$), or total acidity/ total alkalinity TA/TC, can be regarded as an indicator of acidity. A ratio TA/TC < 1 indicates the alkaline nature of water and if TA/TC > 1, it indicates the presence of free anions responsible for a weak pH (Table IV). The comparison of the ionic composition of dew and rain water shows that dew is richer in Ca$^{2+}$, K$^+$ et SO$_4^{2-}$ than rain where Na$^+$, Mg$^{2+}$ and Cl$^-$ are dominant (Fig. 7).

**D. Ionic Concentration**

The average ionic concentrations (in mEq/L) of the major chemical species as obtained from the analysis dew and rain water for the three years of study are presented in Fig. 9. In dew water, the cations concentrate in different ways. For years 2004 and 2005, Ca$^{2+}$ > Na$^+$ > Mg$^{2+}$ > K$^+$ > NH$_4^+$, whereas during year 2006, NH$_4^+$ > K$^+$. The concentration of anions follows the same evolution, with Cl$^-$ > SO$_4^{2-}$ > HCO$_3^-$ > NO$_3^-$, except in 2006 where NO$_3^-$ > HCO$_3^-$. Concerning rainwater, the concentration of ions is different from what is observed in dew. For cations, one observes:

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TABLE IV

COMPOSITION OF DEW WATER IN ZADAR (CROATIA) AS COMPARED TO RAIN WATER AT THE SAME LOCATION, TO WHO REQUIREMENTS AND TO A LOW MINERALIZED SPRING WATER (MONT ROUCOUS, FRANCE)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Max</th>
<th>WHO</th>
<th>Mont. Roucous</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.25</td>
<td>0.15</td>
<td>5.5</td>
<td>6.0</td>
<td>5.0</td>
</tr>
<tr>
<td>EC[mS/cm]</td>
<td>10.6</td>
<td>3.4</td>
<td>15.6</td>
<td>9.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Ca²⁺+mEq/L</td>
<td>0.18</td>
<td>0.05</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Mg²⁺+mEq/L</td>
<td>0.16</td>
<td>0.04</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Na⁺+mEq/L</td>
<td>0.19</td>
<td>0.06</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Cl⁻+mEq/L</td>
<td>0.19</td>
<td>0.06</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>SO₄²⁻+mEq/L</td>
<td>0.19</td>
<td>0.06</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>NO₃⁻+mEq/L</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>TDS/mL</td>
<td>0.65</td>
<td>0.30</td>
<td>2.5</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Fig. 10 Comparison between dew and water ion concentration

E. Marine Contribution

In order to estimate the contribution of the different ions constituting dew and rain water, the sea-salt fraction, SSF, was calculated. The other species are expressed to be as no sea origin (no sea-salt fraction NSSF). The totality of Na⁺ considered of sea origin is the principal reference of the present calculation [27]-[29] as well as the ionic concentration of sea water given by Riley and Chester [30]. The parameters SSF and NSSF are described by the following equations:

\[ \%_{\text{SSF}}X = \frac{\text{Na}_X}{\text{Na}_X} \times 100 \]  
\[ \%_{\text{NSSF}}X = 100 - \%_{\text{SSF}}X \]

where X is the component whose origin has to be determined. The results presented in Table V show that in dew Ca²⁺, K⁺, SO₄²⁻ and NO₃⁻ (83.3 % of the total ions) are not of sea origin; Mg²⁺ seems affected by the particles of the marine salt as well as the Cl⁻ whose %SSF is equal to 54.76. In contrast, in rain water, the high NSSF of Ca²⁺ and NO₃⁻ indicates that they are not influenced by sea, whereas the other ions shows a strong sea contribution, especially for Cl⁻.

F. Neutralisation factor

The acid substances (SO₄²⁻, NO₃⁻) contained in dew and rain water react with the basic components (Ca²⁺, Mg²⁺, NH₄⁺, K⁺). During this reaction, acidity disappears and water becomes neutral. In order to determine the part played by the cations to neutralize sulphuric and nitric acids, a factor of neutralization (NF) can be calculated according to the following formula (Das et al., 2005):

\[ NF_X = \frac{[X]}{[NO_3^- + SO_4^{2-}]} \]  

where X is the species responsible for neutralization (Table VI). The important Ca concentration compared with the other ions in dew and rain water implies that the more neutralizing cation is Ca²⁺, which shows the highest NF, followed by Mg²⁺, K⁺ and NH₄⁺. The dew NFs are higher than those of rain, this is presumably because dew forms near the ground, collecting more neutralizing particles (Ca²⁺, Mg²⁺) than water that forms in higher elevation.

TABLE V

COMPARISON OF THE RATIO %SSF X AND %NSSF X FOR DEW, RAIN AND SEA WATER

<table>
<thead>
<tr>
<th>Ions</th>
<th>Dew</th>
<th>Rain</th>
<th>NF Dew</th>
<th>NF Rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca²⁺+mEq/L</td>
<td>0.044</td>
<td>0.504</td>
<td>0.6163</td>
<td>1.7588</td>
</tr>
<tr>
<td>Mg²⁺+mEq/L</td>
<td>0.227</td>
<td>0.3749</td>
<td>0.30249</td>
<td>0.09455</td>
</tr>
<tr>
<td>Na⁺+mEq/L</td>
<td>0.023</td>
<td>0.03607</td>
<td>0.12769</td>
<td>0.03932</td>
</tr>
<tr>
<td>Cl⁻+mEq/L</td>
<td>0.196</td>
<td>0.2103</td>
<td>0.22399</td>
<td>0.0489</td>
</tr>
<tr>
<td>SO₄²⁻+mEq/L</td>
<td>0.04</td>
<td>0.36462</td>
<td>0.08084</td>
<td>0.0078</td>
</tr>
<tr>
<td>NO₃⁻+mEq/L</td>
<td>0.0002</td>
<td>0.65584</td>
<td>0.75116</td>
<td>0.1240</td>
</tr>
</tbody>
</table>

TABLE VI

NEUTRALISATION FACTOR FOR SOME CATIONS

<table>
<thead>
<tr>
<th>Ions</th>
<th>Dew</th>
<th>Rain</th>
<th>NF Dew</th>
<th>NF Rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>K⁺+mEq/L</td>
<td>0.059</td>
<td>0.024</td>
<td>0.63441</td>
<td>0.27907</td>
</tr>
<tr>
<td>Ca²⁺+mEq/L</td>
<td>1.72</td>
<td>0.53</td>
<td>18.49462</td>
<td>6.16279</td>
</tr>
<tr>
<td>Mg²⁺+mEq/L</td>
<td>0.23</td>
<td>0.32</td>
<td>2.47312</td>
<td>3.72009</td>
</tr>
<tr>
<td>NH₄⁺+mEq/L</td>
<td>0.051</td>
<td>0.022</td>
<td>0.54339</td>
<td>0.25581</td>
</tr>
</tbody>
</table>

V. Conclusion

Passive dew harvesting requires a small financial investment but can exploit a free, inexhaustible and environmental friendly water source. In the Mediterranean Dalmatian area, it can serve as a useful complementary source of water when other sources are lacking. The two sites investigated here, Zadar on the coast and Komiza in the Vis island, provide an overview of the range of dew water production that can be obtained from an unfavorable site (Komiza, 9.3 mm/y) and a more favorable one (Zadar, 20 mm/y). In the summer dry season (May – October), the monthly contribution of dew water compared to rainfall is on order of 38% (July 2004) and has reached 120% (Summers 2003 and 2006). Refurbishing abandoned traditional rain collectors (impluviums), which are numerous in the Dalmatian area, is a viable option to collect rain and dew water. For example, the impluvium at Podšpilje near Komiza, with a moderate surface area of 1300 m², could provide about 17 m³ supplementary water per year, a useful supplementary amount especially during the dry summer season when rainfall is lacking.

Concerning the chemical quality of dew, during the period of study (3 years), the mean pH of dew of rain was neutral.
respectively 6.7 and 6.35. The chemical composition reveals in both dew and rain the importance of cations Ca\(^{2+}\), Na\(^{+}\), Mg\(^{2+}\), and cations Cl\(^{-}\) for the anions. The high percentage of SO\(_4\)\(^{2-}\) with respect to NO\(_3\)\(^{-}\) suggests that the former is mostly responsible for lowering the pH. This acidity is neutralized firstly by Ca\(^{2+}\), whose factor of neutralization is the largest when compared to Mg\(^{2+}\) and K\(^{+}\). The calculation of the fraction of sea salt shows that, rather surprisingly, most of ions in dew are not influenced by the sea vicinity, except Cl\(^{-}\). For rain water, the marine contribution is important for ions Cl\(^{-}\), K\(^{+}\) and Mg\(^{2+}\).

Both dew and rain water meets in average the WHO requirements for potable water, except for Mg\(^{2+}\) whose concentration is about 6 times larger than the maximum value (0.5 g/L). However, dew and rain can be still considered as potable when regarded as a spring water.

**ACKNOWLEDGMENT**

We thank Andelko and Anita Vidovic for the measurements in Zadar and to Ivan Vitalvić and Aldo Martinis for the measurements in Komiza..

**REFERENCES**


