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Enhancement of atmospheric water generator performance by exploiting historical underground spaces

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ABSTRACT

Many Mediterranean countries are facing a severe water crisis due to climate change both in Southern Europe, Northern Africa and Middle East. One possible solution to mitigate this problem could be the use of cooled Atmospheric Water Generators (AWGs), devices available on the market that can condense the humidity present in the air. AWGs use a simple refrigeration cycle where the humid air mixture reaches dew point temperature, causing the vapor contained within it to condense. The main problem is that in arid or semi-arid areas, where water is most needed, they require huge energy amounts to operate. Such requirement can be mitigated by exploiting the natural insulation phenomenon of the subsoil, which is commonly used for shallow geothermal systems for heating and cooling. The drawback in this case are the drilling, excavations and installation costs. The present study investigates the opportunity of using some historical underground spaces, wells, shafts and tunnels already in the Mediterranean area territory, for boosting the efficiency of AWGs, to fight water shortages in the Mediterranean area.

Acronyms

ASHP	Air Source Heat Pump
AWG	Atmospheric Water Generator
GHE	Ground Heat Exchanger
GSHP	Ground Source Heat Pump

1. Introduction

Water is the essence of life and the key to ensuring peace and prosperity. The availability of freshwater is not equally distributed across the globe: currently, approximately half of the world's population experiences severe water scarcity, while a quarter of the world's population faces extremely high levels of water stress [1].

Among the various strategies to reduce water scarcity, there is the atmospheric water harvesting [2,3]. Fog and dew are potentially major sources of water for arid and semi-arid regions [4]. Various technologies have been developed for water harvesting, among which, it is worth to mention: liquid, solid or compound salts and desiccants operating on various energy sources [5], innovative materials such as bioinspired materials, nanostructured materials, gels and hydrogels [6], thermal infrared radiation through the atmospheric window, generating radiative cooling [7], vapor compression refrigeration systems or other direct cooling technologies [8]. This last method consists of cooling the air humidity mixture to a temperature below dew point, causing moisture condensation and water harvesting, whose amount depends on the physical conditions of the atmospheric air. The ambient air is in fact a huge and renewable water deposit: it contains around 0.001% of the total water volume of the Earth, equal to around 1,390, 000, 000 km^3. Of the resulting 13,900 km^3, 98% are in the form of vapor, and 2% in the form of clouds. On the other hand, 35, 000, 000 km^3 are fresh water on earth. Therefore, the water vapor contained in the atmospheric air equals to a potential of 0.04% of the available freshwater [9]. The devices that harvest water from the atmosphere through direct cooling are called Atmospheric Water Generators (AWGs); they are usually equipped with water purification systems to make it drinkable, and can be used successfully both in arid areas with low moisture content and in humid areas with high moisture content [10,11]. The main limitation of condensing liquid water from water vapor is related to the AWGs energy consumption: to operate the refrigeration cycle, they require electricity to power the compressor, the fans and the pumps. The compressor can

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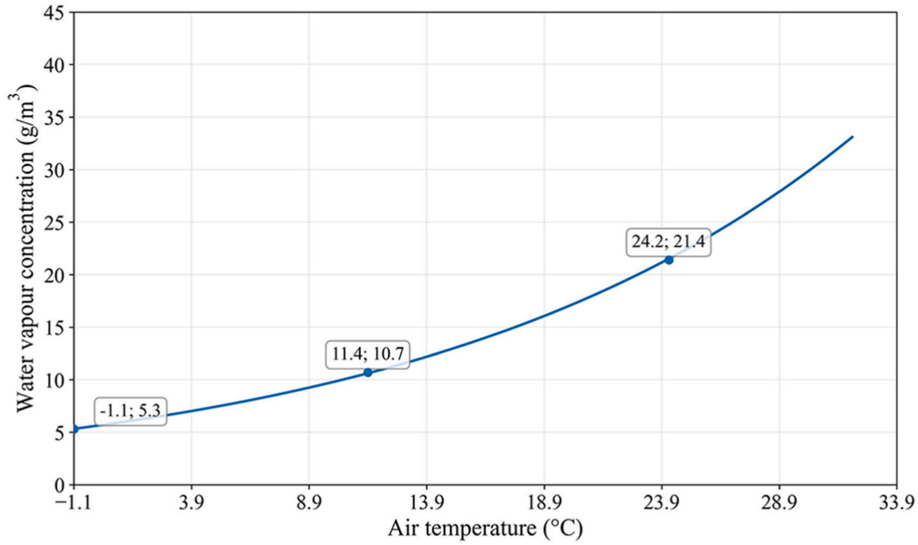

Fig. 1. Variation of the concentration of water vapor in the air, due to temperature changes.

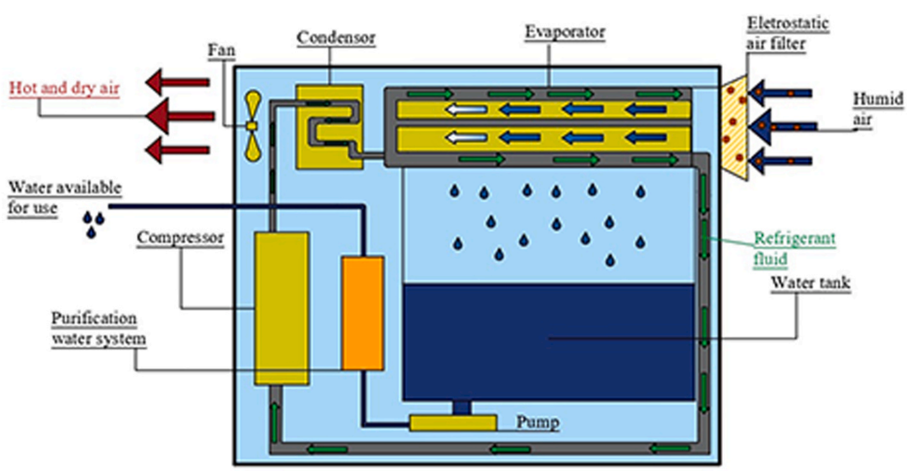

Fig. 2. Schematic of an atmospheric water generator device (modified from Wikipedia).

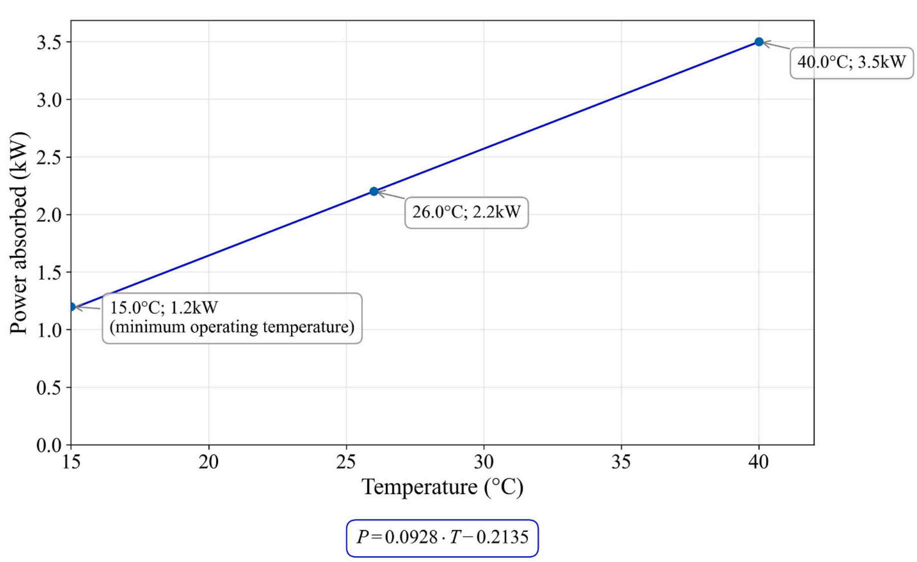

Fig. 3. Relationship between temperature and power absorbed (modified from Watergen™).

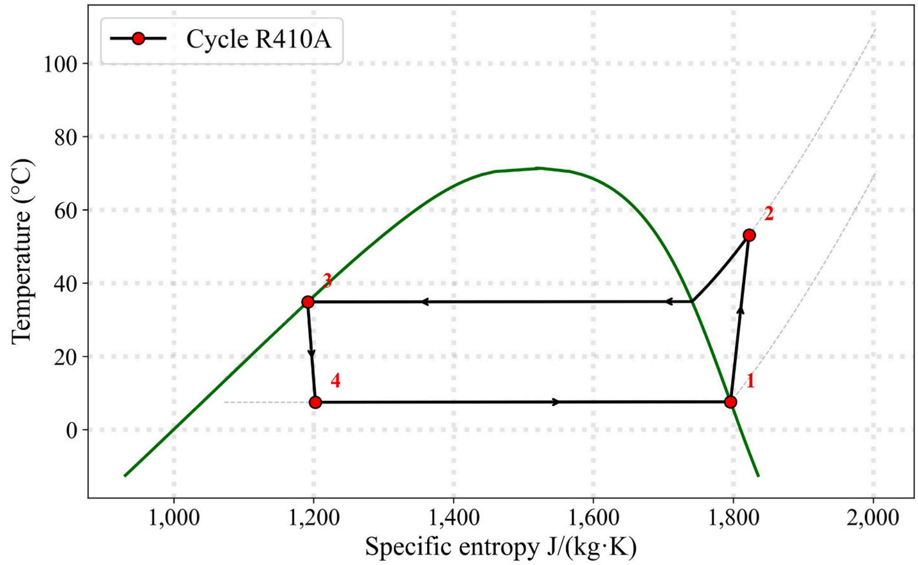

Fig. 4. Thermodinamic model of the vapor compression refrigeration cycle of the AWG: 1-2: compression; 2-3: heat dissipation in the condenser; 3-4: expansion; 4-1: heat absorption in the evaporator.

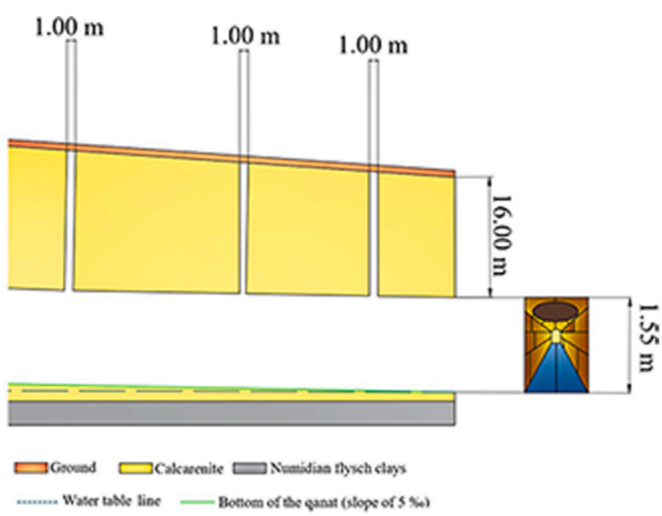

Fig. 5. Simplified scheme of the qanat: lateral section (left); front view (right).

work in different conditions of favorability, thus varying its energy consumption, basically depending on two factors:

- The physical conditions of the incoming air-vapor mixture (temperature and relative humidity): the higher the temperature of the incoming flow, the more energy is required to exploit liquid water. Furthermore, at equal temperature levels, the higher the relative humidity, the greater the quantity of water that can be exploited [12];
- The external environmental conditions in which an AWG operates: the heat that it is able to exchange is proportional to the temperature difference between the hot refrigerant fluid passing through the condenser and the final heat sink (i.e. the external environment) [13].

The working efficiency of the AWGs, affected by the physical and environmental conditions, have some similarities with the air source heat pump systems (ASHP) when operating in cooling mode. In such systems, on the external side, the air exchanges thermal energy in the condenser with the hotter refrigerant fluid, which releases heat in the environment. On the internal side, the cold refrigerant fluid exchanges thermal energy in the evaporator with the ambient air, extracting heat from the building. In such process, some water vapor is condensed into liquid water, due to the temperature difference between the refrigerant (colder) and the internal ambient air (hotter). The efficiency of the system increases (and the consumption of electric energy decreases) with higher temperature difference in the condenser, which specifically means that the external ambient temperature should be as colder as possible, to be able to receive the heat by the refrigerant during the condensation process [14,15].

In order to get high efficiencies, the use of ground can be exploited, which is at lower and more stable temperature than the external air. In fact, it is well known that, between approximately 10 and 50 m deep, the ground temperature is constant, almost equal to the atmospheric yearly average, but partially affected by presence of urbanization [16]. Below the depth of 50 m, the geothermal heat flow becomes prominent and temperature starts to rise, following the geothermal gradient [17].

Many case studies of using ground source heat pump (GSHP) for both cooling and heating but also for only cooling have been installed and are currently operational [18]. The main drawback and limit of such system, with respect to ASHP, resides in the installation cost of the ground heat exchangers (GHE), overall, when using the heat pump only in cooling mode, which results in long-term Return on Investment [19].

The same concept of exploiting the ground to limit the work of the compressor, thus reducing the electric energy consumption, can be applied to the AWG refrigerant circuit. On the other hand, the same issue of the installation cost exists [20].

In this work, we present a possible coupling of AWGs with existing and historical underground spaces in arid and semi-arid zones of the Mediterranean areas, which can be reused to boost the efficiency of the AWGs, and at the same time avoiding much of the installation costs of the GHEs. In the Mediterranean Region, ancient and more recent underground tunnels exist, which have been used for centuries to transport water from the mountains to the urban and farming areas. Across the Region, they are called with different names (*khettara*, *foggara*, *galeria*), but they basically belong to the same water system concept developed in the Ancient Persia: the *qanat* [21]. Some of these water systems can be found in Southern Europe, in countries such as Spain [22,23] and Italy [24–27], while others are located in Algeria [28–30] and Morocco [31,32]. The ideal advantage of reusing such structures is that they have been already designed and prepared for transporting fresh water to

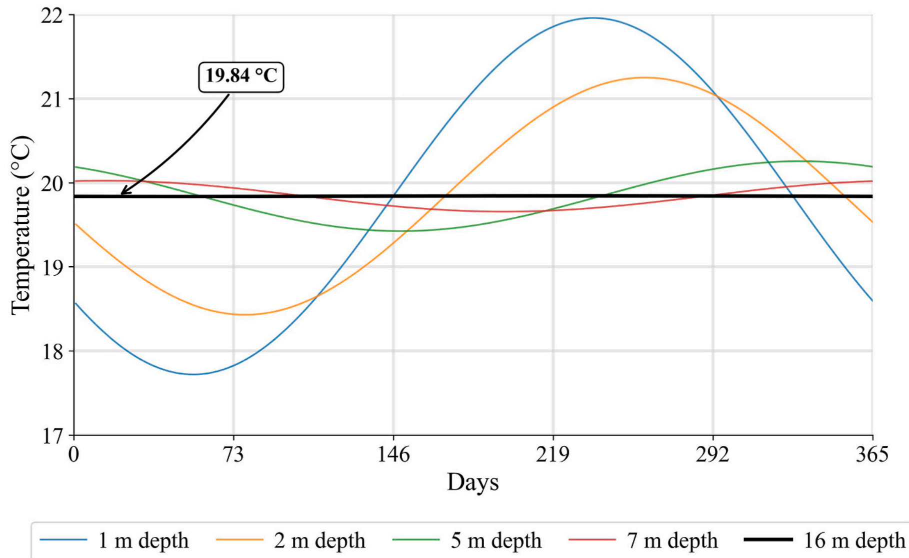

Fig. 6. Temperature variation for different periods of the year at different depths.

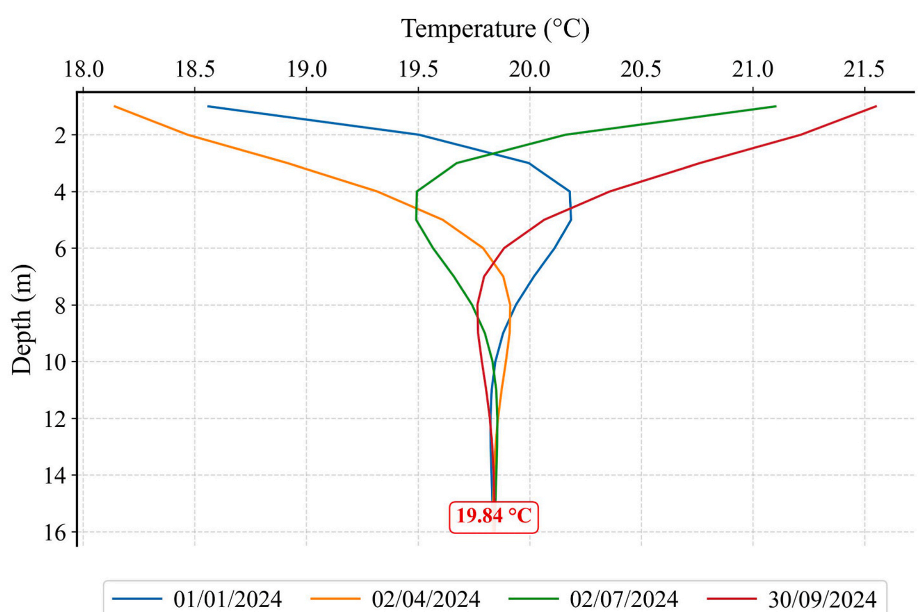

Fig. 7. Temperature as the depth varies recorded at specific times of the year.

valleys. On the other hand, the drawback is that many of them are currently unusable due to the poor state of conservation [33]. The presented proposal can be also applied to modern structures, such as active and abandoned underground mines, metro stations, underground parking and other anthropic artifacts. However, for such applications, the issue of water transport would remain, with the associated costs.

2. Theoretical background

When dealing with water vapor, keeping the gaseous state or transitioning to the liquid state depends on a precise balance between the average energy of the molecules and the cohesive forces among them. The two forms of energy act in opposite directions, and it is the prevalence of one or the other that hinders or favors condensation. As the temperature increases, the energy of the molecules and their speed also increases: under such conditions, condensation is hindered and keeping the gaseous state is favored. On the contrary, when temperature decreases, molecular energy also decreases, and the cohesive forces prevail, allowing condensation. The physical state of air containing the maximum amount of vapor is called saturation, over which condensation occurs. Given the same volume, hot air can hold more vapor than cold air before reaching saturation. Therefore, saturation of an air mass, with subsequent condensation of vapor, depends on:

- the humidification of the air mass until it reaches the maximum value allowed at that temperature;
- the cooling of the humid air mass: by reducing the temperature, the air approaches saturation since the amount of vapor it can hold decreases.

The relationship between the concentration of water vapor in the air and changes in temperature is illustrated in the graph in Fig. 1.

The parameter used in this analysis is the relative humidity (*RH*). This expresses the saturation level of an air mass as a percentage; it is the

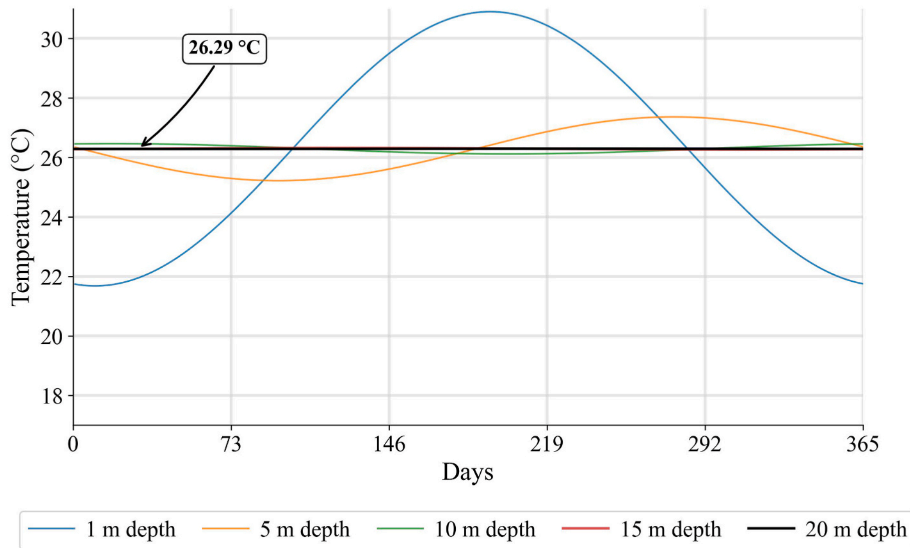

Fig. 8. Temperature variation for different periods of the year at different depths.

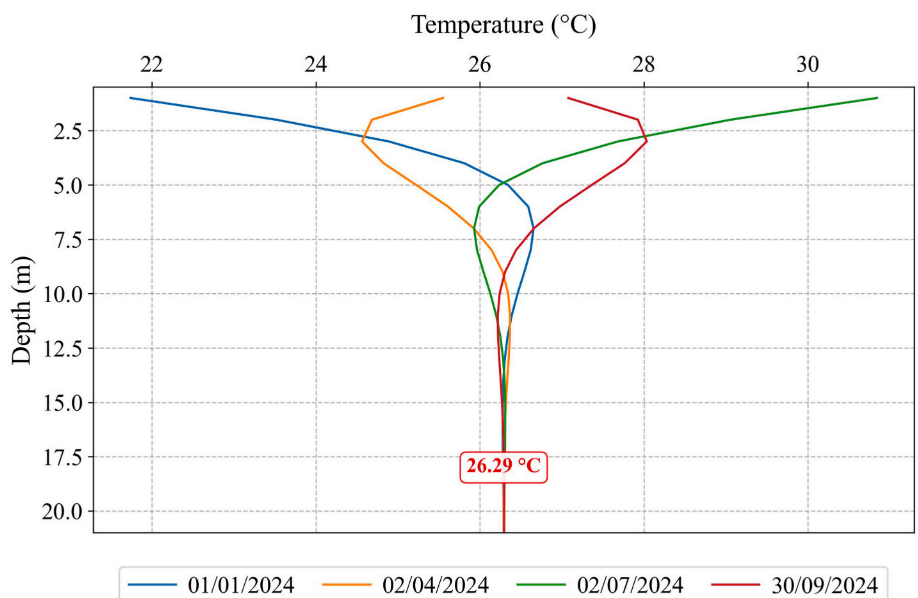

Fig. 9. Temperature as the depth varies recorded at specific times of the year.

ratio between the amount of vapor (m_v) in a given volume and the maximum amount of vapor (m_{vs}) allowed at that value at that temperature (Equation (1)).

$$RH = \frac{m_v}{m_{vs}} \tag{1}$$

The partial pressure of vapor (e) indicates the quantity of steam present in the air and represents the steam's pressure exercised on liquid surface when the two phases are in thermodynamic equilibrium. It is measured in Pa (Equation (2)).

$$e = E \cdot RH \tag{2}$$

On the other hand, the steam in saturated conditions (E) happens when the same quantity of molecules that evaporate, also condenses. It is measured in Pa (Equation (3)) [34].

$$E = \frac{exp\left(34.94 - \frac{4{,}924.99}{T+237.1}\right)}{(T+105)^{1.57}} \tag{3}$$

The atmospheric water generator used in this analysis is the "Gen-M1" device [35] from the Watergen company: it works by exploiting a refrigeration cycle (Fig. 2), condensing the water vapor present in the air. It produces water starting from 15°C to 20% RH.

The power absorbed (P) depends on the temperature (T) of the incoming air flow (Fig. 3), following the relationship of Equation (4):

$$P = 0.0928 \cdot T - 0.2135 \tag{4}$$

The device was tested in a variable temperature range: from 15 to 40°C. For temperatures below 15°C, the device is not capable of condensing water vapor, while for temperatures over 40°C the performances are costants (same consumptions at 40°C). It was observed that for a temperature of 15°C, the absorbed power is 1.2 kW, while for 26°C

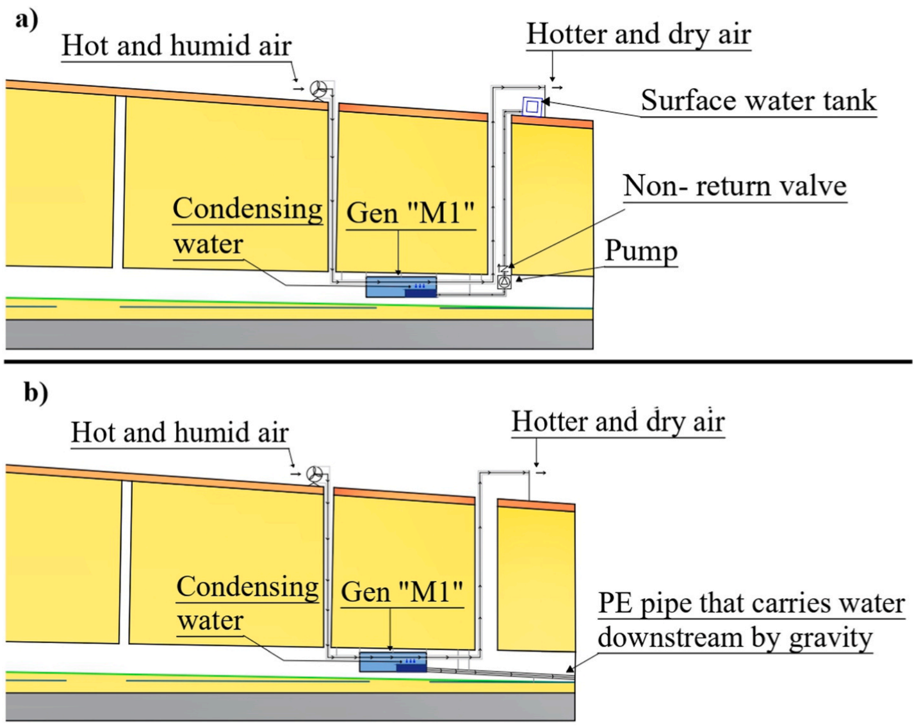

Fig. 10. Atmospheric Water Generator scheme installed inside the "Gesuitico Alto" Qanat, with two possible configurations: with water extracted through the nearest shaft directly towards surface (a) and with water carried downstream by gravity (b).

the absorbed power is 2.2 kW, and finally for 40°C it is 3.5 kW.

The full thermodynamic model of the vapor compression refrigeration cycle of the AWG is illustrated in Fig. 4.

In order to evaluate the temperature in the subsoil, the following Equation (5) is used [36], which relates the temperature to time t and depth z.

$$T(z,t) = T_m - A_s \cdot exp\left(-z\cdot\sqrt{\frac{\pi}{365\cdot\alpha}}\right)\cdot\cos\left[\frac{2\cdot\pi}{365}\cdot\left(t - t_0 - \frac{z}{2}\cdot\sqrt{\frac{365}{\pi\cdot\alpha}}\right)\right] \quad (5)$$

The parameters are defined as follows:

- T_m and A_s are the yearly average and amplitude of the surface temperature (°C);
- t_0 is the day of the year with the lowest surface temperature (days);
- α is the soil thermal diffusivity (m^2/day).

α is related to thermal conductivity λ (W/(m·K)), density ρ (kg/m^3) and heat capacity C (J/(kg·K)) of the soil layers by the following Equation (6).

$$\alpha = \frac{\lambda}{\rho\cdot C} \quad (6)$$

3. Case studies

3.1. Application to the qanat of palermo (Italy)

In the city of Palermo, Sicily, some underground qanats are present, dating back to the Arab domination on the island of the 10th century. They range in depth from 10 to 16 m and were built to transport water from the mountains to the city. The specific scheme prevented the water from evaporating due to the high temperatures, and simple topographic gradients allowed easy transportation and access to the water. The qanats are interspersed with vertical wells connected to the ground level, called inspection wells, which allowed removal of debris from excavation works and at the same time guaranteeing natural ventilation of the tunnels (Fig. 5-left, lateral section; Fig. 5-right, front view) [25].

Equation (5) describes the heat conduction phenomena happening underground and allow to estimate the ground temperature at the level of qanat in the exact location, different according to the depth and the ground thermal properties. The preliminary study omits the convective effects due to the air movement inside the tunnels, which may affect the temperature of the chambers.

The stratigraphy of Palermo is characterized by a large expanse of calcarenites dating back to the Pleistocene. The rocks are all permeable: in the case of calcarenites they are masses with considerable porosity, in the case of limestones there are very fissured bodies: this, with the aid of an impermeable layer of hard clays (Numidian flysch), has allowed over time the accumulation of water in the subsoil giving rise to water tables ending in the sea, at a depth of no more than 20 m [25]. To evaluate the temperature trend in the subsoil, the annual temperature data discretized on an hourly basis (for 2024) in Palermo were taken from "Open-Meteo api" [37] The ground thermal diffusivity of the calcarenite was used, equal to $0.60\cdot10^{-6}$ m^2/s or 0.05184 m^2/day.

As can be appreciated from Figs. 6 and 7, the temperature tends to stabilize as the depth increases, and the oscillatory seasonal behavior attenuates until it reaches 19.84°C. This happens around 7 m and then ends completely at 16 m. At such depth, the soil is no more affected by solar radiation and by the sensible solar convective heat of the environment.

The estimated temperature falls in the range of the measured temperature inside the qanat of Palermo, which varies between 18 and 20°C at a depth around 15 m.

The only qanat in the city of Palermo available for inspection with a well still active today is the "Gesuitico alto" qanat. Water is still extracted nowadays from the "Casa Miciulla" well for irrigation purposes. Therefore, the potential installation of an AWG inside the qanat system of Palermo can be performed here.

The preliminary design encompasses that the external air is channeled down through a pipe inside the inspection well. Upon contact with the ground inside the tunnel, the air exchanges heat, reaching a constant

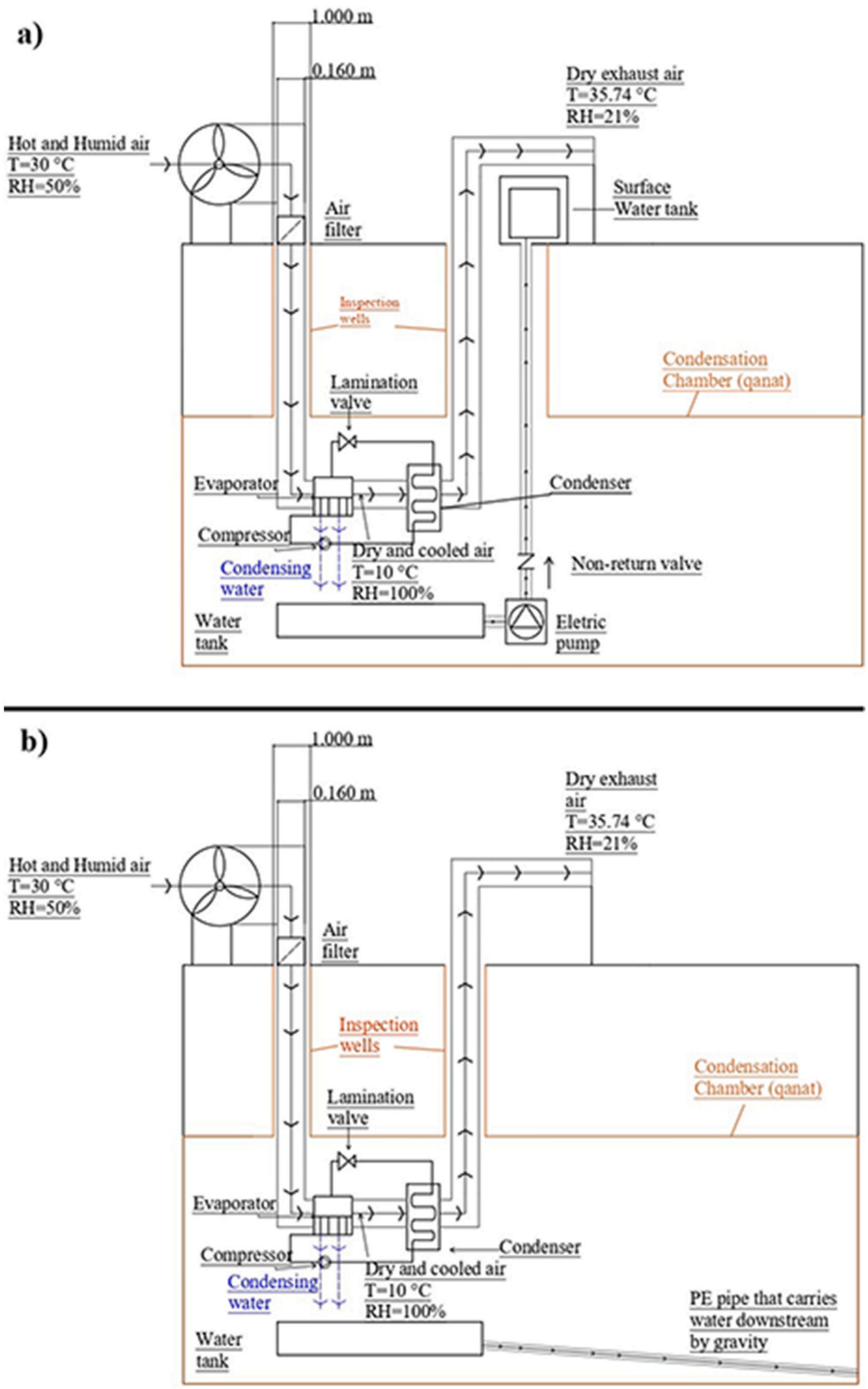

Fig. 11. Atmospheric Water Generator scheme installed inside the "Gesuitico Alto" Qanat (exaggerated dimension of air conduits for better visualization), in the two possible configurations: with water extracted through the nearly shaft (a) and with water carried downstream by gravity (b).

temperature of 19.84°C. This allows the air mixture to cool (or heat, depending on the time of year), before passing through the evaporator of the AWG. After dehumidification and water recovery, the air is released back to the surface. This hypothetical configuration achieves a threefold advantage:

- The temperature reduction of the external air, by the heat exchange with the ground, decreases the workload of the refrigeration cycle, thus enhancing the work of the AWG device;
- The air in the subsoil is cooled at a constant temperature of 19.84°C, which is suitable for the work of AWG, being inside the working limits. Therefore, the device can work all year long, no matter the external ambient conditions.
- The qanat and its inspection well already provide water for irrigation, therefore almost no costs for water moving are present.

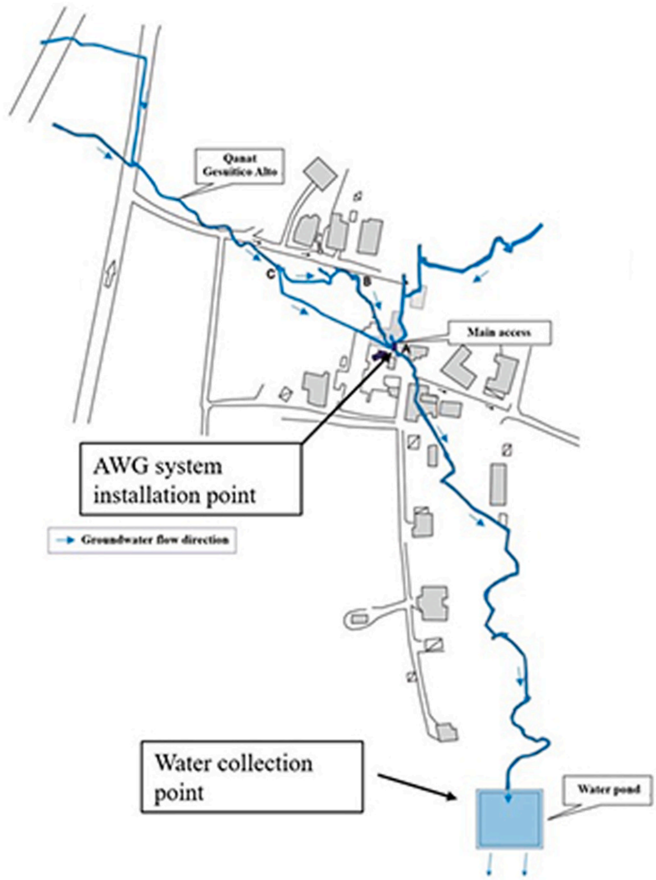

Fig. 12. Plan of the "Gesuitico Alto" qanat of Palermo, with evidence of a suitable location for installing the AWG.

3.2. *Application in the framework of the "foggara project" in Algeria*

Similar to qanats, in Algeria foggaras are found: underground tunnels that transport water to the surface by gravity, where artificial springs form. They vary in depth from 5 to 20 m and in length from 3 to 10 km.

The foggara are widespread in the Touat-Gourara and Tidikelt regions of Algeria. The analysis focused on the municipality of Timimoun, which is characterized by oases that receive water from the foggara. The stratigraphy features an initial zone of dry and wet sand, followed by a thick layer of arenaceous clay below 20 m, containing numerous confined aquifers at constant pressure [28]. The value of thermal diffusivity of $7.5{\cdot}10^{-7}$ m^2/s or 0.0648 m^2/d was used for the analysis. It was obtained as a weighted average from the values of the various ground layers. By applying Equation (5), it was then possible to reconstruct the ground thermal behavior (Figs. 8 and 9). The temperature stabilizes already after 15 m at 26.29°C.

4. Results

4.1. *Preliminary results for the application in sicily*

For the analysis, hourly data on air temperature and relative humidity were collected for the city of Palermo for 2024 (a 366- day leap year). The water produced and electricity consumed were analyzed in two cases:

- "Gen M1" placed on the surface (normal setting);
- "Gen M1" placed inside the qanats (boosted setting: Figs. 10 and 11).

The boosted setting, with the application of the AWG in the "Gesuitico Alto" qanat, is formed by the following components:

- 1 fan (power 200 W) channeling the outside air inside the qanat;
- 1 AWG (dimension 1.6 m × 0.8 m × 1.3 m) placed in the qanat tunnel, fixed at the tunnel roof, through bolts.
- 1 air conduit in PVC, 160 mm diameter, collecting the humid hot air from the outside ambient to the AWG placed in the qanat tunnel; the air conduit is fixed, with dedicated bolts, along one existing well, and then along the roof of the tunnel;
- 1 air conduit in PVC, 160 mm diameter, collecting the exit air of evaporator and condenser and the exhausted heat of the compressor, and expelling them in the outside ambient, through the same well; again, such air conduit is fixed, with dedicated bolts, along the roof of the tunnel and along the well.
- 1 external tank (dimension 1.6 m × 0.4 m × 0.3 m) placed on the surface, collecting the condensed water;
- 1 water pipe in PE, 40 mm diameter, allowing the condensed water to reach the exit of the qanat, attached to the wall of tunnels towards the water pond;
- (eventually) 1 water pump (power 100 W) allowing overcome the pressure losses through the shafts towards the surface.

The average height of the selected "Gesuitico Alto" qanat is 1.5 m, while its maximum height is 4 m. On the other hand, the width varies between 1 and 2 m. Considering the dimension of the selected AWG, specific suitable locations are selected, where the machine can fit inside the qanat (Fig. 12). Most of the wells have diameter 1 m, too narrow for lowering the machine down. However, some big wells exist, 2 m diameter, where that would be possible. Another possibility, more complicated, is assembling the AWG on site. The machine, with its internal tank, are supposed to be attached to the roof, so not to enter in contact with the natural flowing water of the qanat. Regarding the air conduits and water pipes, their dimension is much lower of even the smallest wells; therefore, they can be easily installed inside the wells, attached to the roof of the qanat and connected with the AWG machine.

Table 1 reports the performances of the "GEN M1", linking the produced water (l) on a daily basis with the ambient temperature and relative humidity conditions.

The performances of the evaporator and compressor of the AWG are presented in Fig. 13.

Table 1
Performances of the "GEN M1" atmospheric water generator.

Condensed water (l/day)		Relative Humidity (%)						
		20	30	40	50	60	70	80
Temperature (°C)	*15*			22.0	43.1	65.3	92.2	109.4
	20	1.8	18.4	41.5	73.4	120.0	139.0	174.4
	25	10.5	27.8	78.0	118.1	166.0	187.5	214.1
	30	16.6	60.2	110.5	153.0	190.4	217.0	247.1
	35	36.5	80.0	126.3	174.0	202.8	218.6	229.1
	40	46.1	95.7	142.2	184.2	204.4	209.2	216.0
	45	61.0	123.2	156.8	179.0	190.5	198.8	205.4

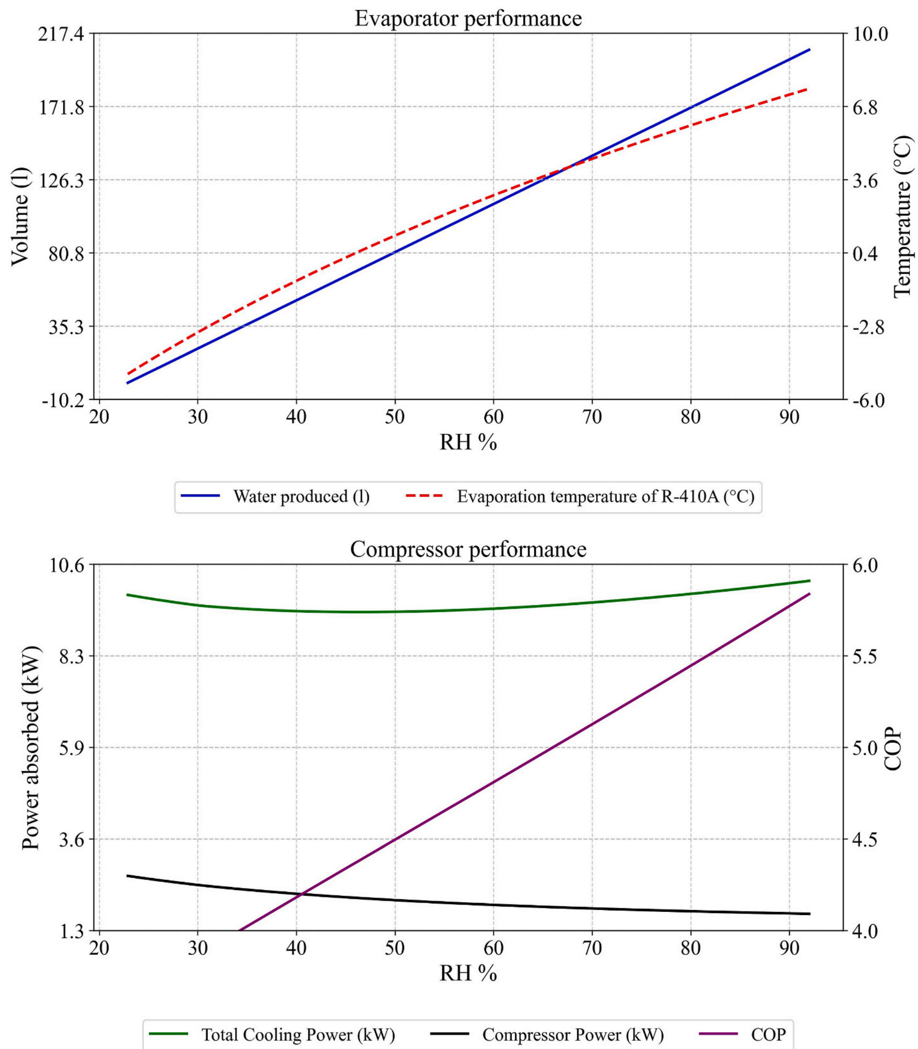

Fig. 13. Evaporator and compressor performance of the AWG.

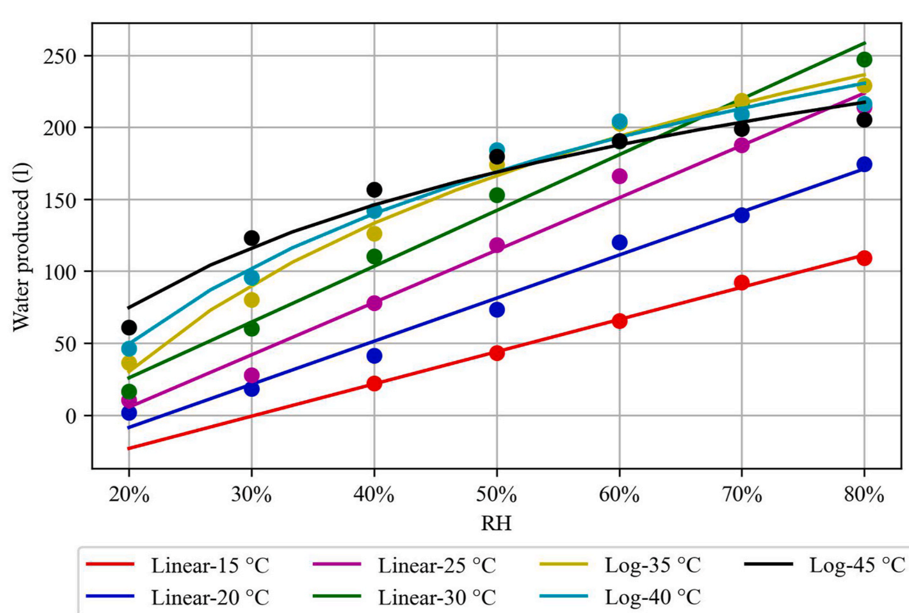

Fig. 14. Linear and logarithmic regressions linking relative humidity to daily water condensation, for different temperature levels.

Table 2
Water production in the three different Scenarios for the case study of Palermo.

	Water Produced (l)		
	Scenario A	Scenario B	Scenario C
	Surface AWG 6297 h/year	AWG in Qanat 6297 h/year	AWG in Qanat 8784 h/year
January	751.1	764.9	2466.5
February	660.4	679.4	2267.1
March	1367.7	1439.1	2754.0
April	1715.0	1795.0	2451.0
May	4218.5	4427.8	4619.0
June	4659.2	5473.7	5473.7
July	5285.9	7019.2	7019.2
August	5912.5	7921.9	7921.9
September	5222.2	6157.2	6157.2
October	5048.8	5333.8	5333.8
November	3217.1	3300.9	3805.9
December	628.9	650.8	2524.4
Total	**38,687.5**	**44,963.7**	**52,793.7**

Table 3
Electricity consumption in three different Scenarios for the case study of Palermo.

	Electricity consumption (kWh)		
	Scenario A	Scenario B	Scenario C
	Surface AWG 6297 h/year	AWG in Qanat 6297 h/year	AWG in Qanat 8784 h/year
January	252.1	295.0	1211.0
February	254.0	308.1	1132.8
March	505.3	564.0	1211.0
April	729.8	775.9	1171.9
May	1159.3	1136.1	1211.0
June	1487.9	1173.6	1171.9
July	1762.7	1212.7	1211.0
August	1797.6	1212.7	1211.0
September	1462.6	1173.6	1171.9
October	1324.3	1212.7	1211.0
November	832.4	945.4	1171.9
December	200.9	254.3	1211.0
Total	**11,768.9**	**10,264.1**	**14,297.3**

By using the data, through regression, it was possible to get practical equations linking the daily water production to all levels of relative humidity (HR) and temperature (T). For temperatures in the range of 15-30°C, a linear regression was chosen, while for temperatures in the range of 35-45°C, a logarithmic regression was chosen, better adapting to the data behavior (Fig. 14).

Thus, the function describing the water production A(x) can be defined as a piecewise defined function, based on regressions. For selecting the temperature, an approximation was adopted by setting a tolerance of 2.5°C.

$$A(RH,T)=\begin{cases} 223.90\cdot RH-67.94 & T\leq 17.5^{\circ}C; \quad R^2=0.9966 \\ 299.43\cdot RH-68.46 & 17.5^{\circ}C<T\leq 22.5^{\circ}C; \quad R^2=0.9855 \\ 363.64\cdot RH-67.25 & 22.5^{\circ}C<T\leq 27.5^{\circ}C; \quad R^2=0.9853 \\ 387.50\cdot RH-51.64 & 27.5^{\circ}C<T\leq 32.5^{\circ}C; \quad R^2=0.9883 \\ 148.82\cdot \ln(RH)+269.69 & 32.5^{\circ}C<T\leq 37.5^{\circ}C; \quad R^2=0.9878 \\ 130.61\cdot \ln(RH)+259.70 & 37.5^{\circ}C<T\leq 42.5^{\circ}C \quad R^2=0.9747 \\ 102.86\cdot \ln(RH)+240.26 & 42.5^{\circ}C<T\leq 47.5^{\circ}C \quad R^2=0.9611 \end{cases} \tag{7}$$

The leap year 2024 was chosen as reference for the analysis. The ambient temperature and relative humidity data were extracted from https://open-meteo.com/, an open-source platform. Three scenarios were analyzed:

- The Scenario A evaluated the water production by placing the AWG on the surface, as its standard operation. According to the weather data, the AWG was expected to work 6297 h in the year 2024, which is when the air temperature was above 15°C and the relative humidity above 20%.
- The Scenario B evaluated the water production, by placing the AWG inside the qanat, thus at stable ambient conditions. The total operation period was set at 6297 h, as the Scenario A.
- The Scenario C considered the AWG's operation in the qanat for an entire year, so for 8784 h. This was possible since the ambient temperature and relative humidity inside the qanat are always higher than the working threshold of the AWG.

In order to find the relative humidity inside the qanat at each time step, the initial *RH* at the surface was used. Using the ground temperature value inside the qanat (19.84°C), it was possible to get the saturated vapor pressure *E* hourly; afterwards, it was possible to calculate the

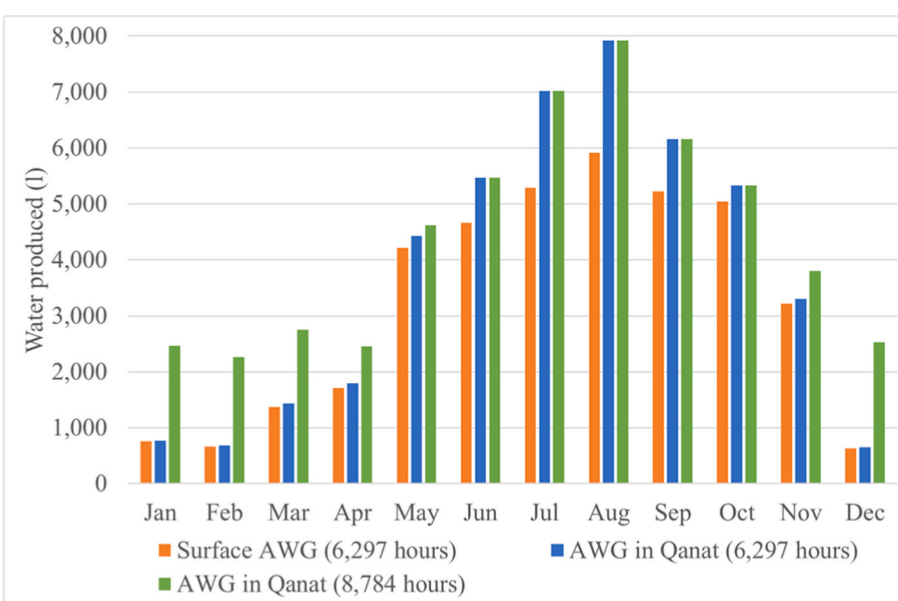

Fig. 15. Results of water produced for each month.

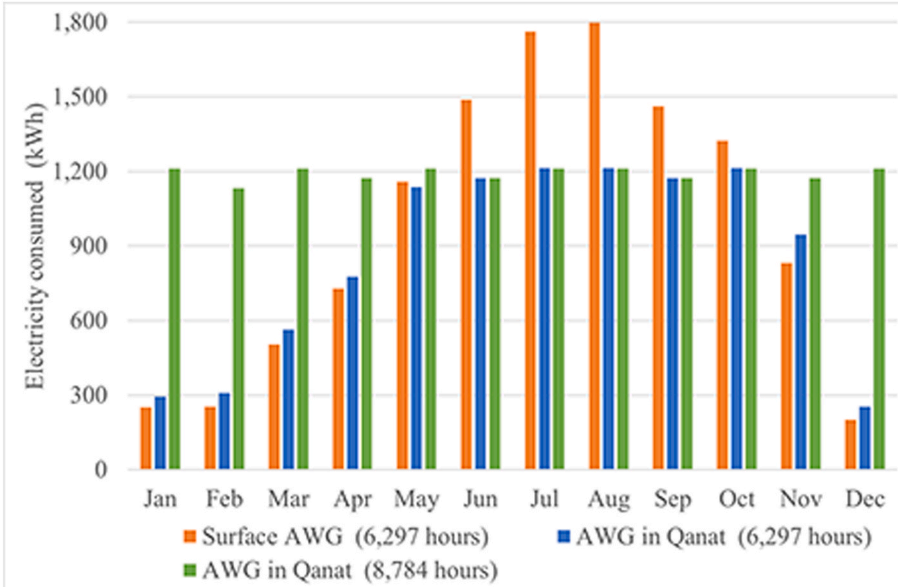

Fig. 16. Electricity consumption during 2024 in the three different scenarios.

Table 4
Water production in the three different Scenarios for the case study of Algeria.

	Water produced (l)		
	Scenario A	Scenario B	Scenario C
	Surface AWG 2696 h/years	AWG In Foggaras 2696 h/years	AWG in Foggaras 8784 h/years
January	108.5	40.3	104.5
February	218.3	110.8	155.3
March	125.4	63.1	70.4
April	225.0	130.5	161.5
May	125.2	124.4	166.9
June	129.7	142.4	296.9
July	33.4	38.6	301.8
August	140.4	168.5	818.8
September	2465.8	2608.9	2887.6
October	1012.9	836.4	1002.4
November	1040.3	710.0	837.8
December	129.8	51.7	152.5
Total	**5754.7**	**5025.6**	**6956.4**

corresponding partial pressure of vapor *e(RH),* using the *RH* at the surface. Finally, it was possible to get the *RH* at the temperature inside the qanat with the following expression:

$$RH(19.84^{\circ}C) = \frac{e(T)}{E(19.84^{\circ}C)} \quad (8)$$

The results are reported in Table 2 and Fig. 15.

The absorbed power and the resulting electrical energy consumed was calculated, too. Results are presented in Table 3 and Fig. 16.

For the AWG in qanat, the consumptions of the fan and of the submersible pump must be added, which are, respectively 1155 kWh/year and 3.92 kWh/year for the scenario B and 1611 kWh/year and 4.60 kWh/year for the scenario C. The procedure for calculating the consumption of fans and pumps is reported in the supplementary material.

4.2. Preliminary results for the application in Algeria

The same procedure has been used for the Algeria case: but in this situation, the air temperature on the surface was above 15°C and the *RH* was above 20% for 2696 h. Table 4 and Fig. 17 report the data for the water produced. Table 5 and Fig. 18 report the data for electricity consumption.

Also in this case, for the AWG in foggara, the consumptions of the fan and of the submersible pump must be added, which are, respectively 685 kWh/year and 0.58 kWh/year for the scenario B and 2232 kWh/year and 0.80 kWh/year for the scenario C. Again, the details for the calculation of such consumptions are reported in the supplementary material.

5. Discussion

The various scenarios can be compared based on water production performance, calculated as the ratio between the produced volume of drinkable water and the electricity consumption. The results for the two case studies are presented in Table 6.

For the case study of Palermo, the installation of the AWG in the qanat is theoretically advantageous, with an increase of water production performance equal to 20%, if considering all the auxiliaries, and 33% by omitting fans and pumps, for the limited operation (working hours equal to the ones of AWG on the surface), while equal respectively to 1% and 12% for the full operation. Such results show how, despite the possibility of additional water production by using the AWG in the qanat at full time work, it is advisable to carefully program its activation in the subsoil, based on ambient and weather conditions, to proper optimize its performance.

For the case study of Algeria, the installation of the AWG in the foggara seems not providing significant benefits, whereas the installation on the surface provides the best water production performance among the three investigated scenarios. This is due by the combination of the following two factors:

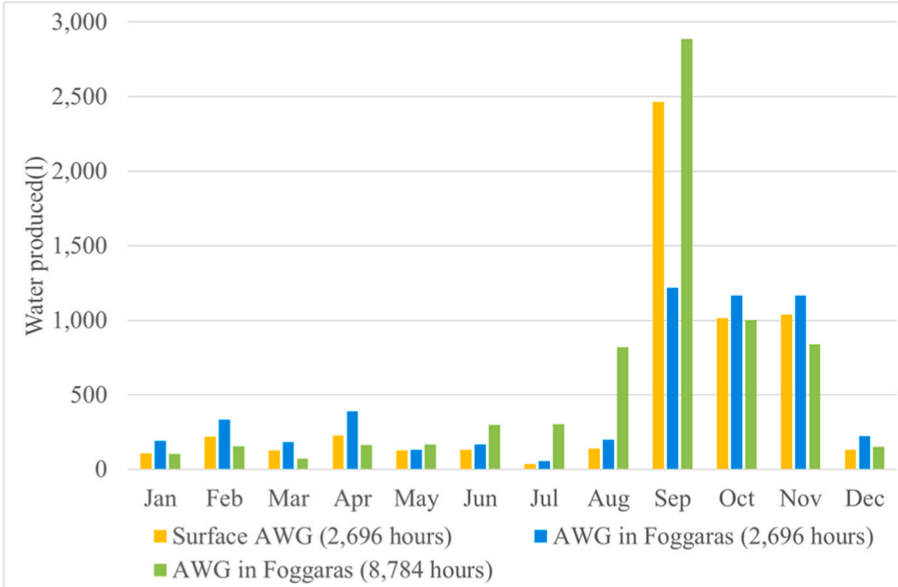

Fig. 17. Water produced each month, in the three different cases.

Table 5
Electricity consumption in three different Scenarios for the case study of Algeria.

	Electricity consumption (kWh)		
	Scenario A	Scenario B	Scenario C
	Surface AWG 2696 h/year	AWG in Foggaras 2696 h/year	AWG in Foggaras 8784 h/year
January	212.0	191.8	369.6
February	342.6	334.5	456.4
March	256.1	182.9	182.6
April	373.9	390.3	418.5
May	180.6	129.3	227.1
June	192.9	165.0	645.6
July	65.3	53.5	805.9
August	245.4	198.5	1498.2
September	1397.00	1217.6	1594.00
October	1105.8	1166.3	1520.5
November	906.3	1166.3	1400.3
December	205.9	220.8	603.3
Total	**5483.9**	**5416.7**	**9721.9**

1 Humidity in Algeria is very low, compared to Palermo. The absolute average for Algeria is 4.68 g_{vapor}/kg_{air}, while for Palermo it is 10.28 g_{vapor}/kg_{air}, around 54% higher.
2 The ground temperature inside the foggara keeps high, as yearly average, above 26°C. Due to this, the relative humidity inside the tunnels is highly reduced, at the point that the AWG performs better on the surface, thanks to the air temperature oscillations.

However, the AWG device used as benchmark does not optimally work with such levels of air temperature and humidity. Therefore, for the specific case of foggara, more investigations by using more appropriate devices are necessary.

Returning back to the case study of Palermo, the contribution of the AWG can be compared to the yearly water shortage, estimated approximately to $5.21 \cdot 10^9$ l/year. The produced drinkable water for the Scenario B, the best in terms of water production performance, would be able to compensate around 0.0009% of the shortage. Therefore, in absolute terms the result of such solution is limited, even in case of multiple installations, due to the limited spaces of the existing underground tunnels. On the other hand, a feasible and practical alternative could be the massive adoption of surface AWG, accompanied by few high performing underground installations, at convenient locations.

In order to cover the full water shortage of the city, around 115,000 AWG devices (most surface and few underground) of the dimension of the investigated case study are necessary. Being the city population around 625,000 units, the adoption of such system by approximately 18% of the inhabitants could theoretically entirely compensate its water shortage. More investigations and analyses are necessary on this matter.

6. Conclusions

The work investigated the feasibility and theoretical performance of installing Atmospheric Water Generation inside underground water channel systems, in two different climatic zones of South Europe and North Africa. Results proved the increase of the performance of such solution with respect to the standard adoption on the surface, with subsequent increase of water production and reduction of electricity consumption, in the climatic zone of Sicily, while no significant benefits were found for the climatic zone of Algeria.

In both cases, the calculated improvements are not sufficient to cover the costs of building from scratch new dedicated storage and channel systems; on the other hand, the reuse of historical water tunnels, such as qanats or foggaras, widespread in the Mediterranean region, seems a feasible and practicable option.

The analysis was conducted by applying analytical equations and a statistical regression approach on some terms of the study. In order to proceed to the next design stage, detailed numerical analyzes of heat dispersion from the AWG compressor and possible heat accumulation within the qanat are planned for future work.

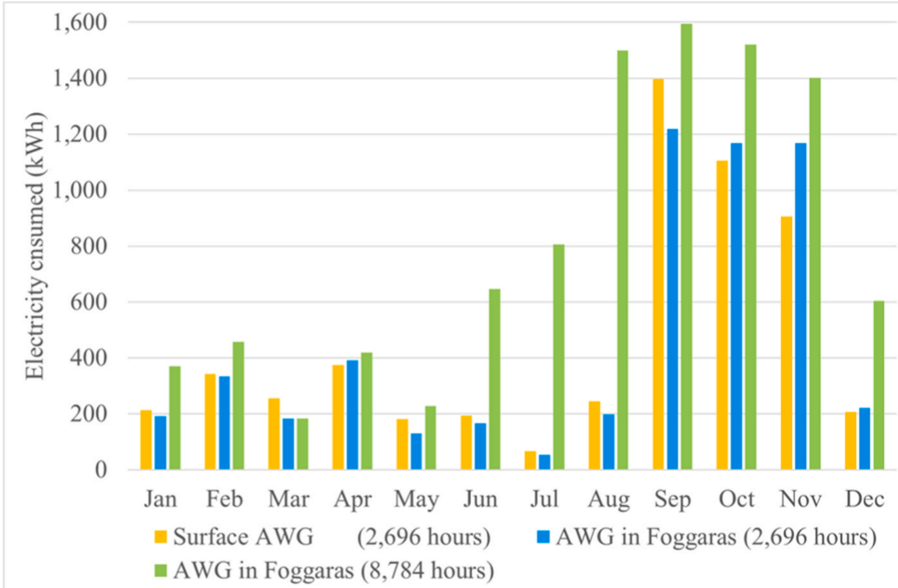

Fig. 18. Electricity consumption for each month.

Table 6
Energy efficiencies of the various scenarios, for the two case studies: qanat of Sicily and foggara of Algeria.

	Water production performance (l/kWh)		
	Scenario A Surface AWG	Scenario B AWG in qanat/foggaras limited operation	Scenario C AWG in qanat/foggaras full operation
Qanat in Palermo (considering only the AWG consumption)	3.29	4.38	3.69
Qanat in Palermo (adding the consumptions of fans)	-	3.94	3.32
Qanat in Palermo (adding the consumptions of fans and submersible pump)	-	3.94	3.32
Foggara in Algeria (considering only the AWG consumption)	1.05	0.93	0.72
Foggara in Algeria (adding the consumptions of fans)	-	0.82	0.58
Foggara in Algeria (adding the consumptions of fans and submersible pump)	-	0.82	0.58

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CRediT authorship contribution statement

Giovanni Pierdiluca: Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Francesco Tinti:** Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uncres.2026.100462.

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