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Review

Diversifying Water Sources with Atmospheric Water Harvesting to Enhance Water Supply Resilience

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Abstract: The unequivocal global warming has an explicit impact on the natural water cycle and resultantly leads to an increasing occurrence of extreme weather events which in turn bring challenges and unavoidable destruction to the urban water supply system. As such, diversifying water sources is a key solution to building the resilience of the water supply system. An atmospheric water harvesting can capture water out of the air and provide a point-of-use water source directly. Currently, a series of atmospheric water harvesting have been proposed and developed to provide water sources under various moisture content ranging from 30–80% with a maximum water collection rate of 200,000 L/day. In comparison to conventional water source alternatives, atmospheric water harvesting avoids the construction of storage and distribution grey infrastructure. However, the high price and low water generation rate make this technology unfavorable as a viable alternative to general potable water sources whereas it has advantages compared with bottled water in both cost and environmental impacts. Moreover, atmospheric water harvesting can also provide a particular solution in the agricultural sector in countries with poor irrigation infrastructure but moderate humidity. Overall, atmospheric water harvesting could provide communities and/or cities with an indiscriminate solution to enhance water supply resilience. Further research and efforts are needed to increase the water generation rate and reduce the cost, particularly via leveraging solar energy.

Keywords: water supply resilience; atmospheric water harvesting; fog collection; refrigerated atmospheric water extraction; climate change

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1. Introduction

Promising reliable access to safe water is still a big issue all over the world [1,2]. On the one hand, at least a billion people globally are suffering from severe water shortages, particularly those living in developing countries and regions [3]. As such, the 2021 edition of the United Nations World Water Development Report is rooted in "Valuing Water" and strengthening the societal awareness of water safety [4]. On the other hand, the unequivocal climate change and the resultant extreme weather bring new challenges to water accessibility [5] and explicitly sound alarms to the established water supply system [6]. Currently, surface water is still a principal or sole water source for the water supply systems in most cities, of which the vulnerability has been completely unmasked and experienced, such as the Day Zero water crisis in Cape Town [7,8]. A severe and unanticipated reservoir drought left millions of residents thirsty. As such, increasing reliable access to safe water plays an important role in the sustainable development of society [9].

From a technical point of view, diversifying water sources besides surface water is a fundamental and vital approach to increasing urban water reliability [10]. In another word, this principle is covered by the framework of water supply resilience which highlights the ability of water supply system to promise residents the accessibility to safe drinking water under extreme events like drought [11]. In terms of water sources, seawater desalination, rainwater harvesting [12,13], sewage reuse [14–16], and inter-basin water transfer [17,18] can be supplements to surface water and enhance water supply resilience. However, these approaches have their pros and cons in terms of their applicability. Typically, seawater desalination and rainwater harvesting, are not suitable for inland cities suffering absolute water shortages while inter-basin water transfer is facing vulnerability of water quality or ecological safety [19]. Although sewage reuse is universally applicable enough for cities, public acceptance has been the most serious hurdle for practicing [20]. Moreover, these approaches cannot be relied on to go through water supply emergencies under which bottled water is usually the preferential choice [21–23].

Indeed, there is a kind of water reservation always overlooked, namely atmospheric water or water in the air [24]. As a key and interchange step of the water cycle from ocean to land, the atmosphere is a huge renewable water reservoir [25]. Roughly, it contains 12,900 trillion liters of renewable water, which is about equivalent to 10% of surface water reservation [26]. Even in the arid desert, the moisture content in the air is as abundant as 10 g/m^3 [27]. As such, atmospheric water harvesting has been proposed and developed to link the natural water cycle and the urban water cycle [28]. Moreover, water in the air is distributed everywhere and could be an indiscriminately decentralized water resource [29]. As such, the present study is to introduce and summarize the development of atmospheric water harvesting in comparison with other water sources. By analyzing the pros and cons of atmospheric water harvesting in terms of technology, economy, and safety, the role of atmospheric water harvesting in contributing to water supply resilience is discussed.

2. Characterizing Supplementary Water Sources to Surface Water

Surface water has long been the main water source for potable or non-potable utilization [30]. For a long time, surface water has been the only connection point between the natural water cycle and the urban water cycle as depicted in Figure 1. The water feeding the cities starts from and wastewater also ends in surface water. In general, the water bodies receiving wastewater are located downstream. It is the natural water cycle that refreshes the surface water to meet the demand of human beings [31]. In another word, the renewal of surface water depends on a whole circle (the blue-lined circle in Figure 1), that is, evaporation, condensation, and precipitation. Once the water demand outpaces the renewal capacity of surface water, drought will occur and undermine the safety of the water supply. As a response, various water sources have been explored to supplement surface water-based water supply as presented in Figure 1, including seawater desalination, rainwater harvesting, inter-basin water transfer, and sewage reuse.

As presented in Figure 1, desalination enables seawater to feed the residents by artificially bypassing the step of water vapor transport. At present, there are about 17,000 desalination plants globally in operation with a total capacity of ~95 million m^3/d [32]. Although the accounting percentage of desalination in water supply structures is still very small, it provides a promising direction to strengthen water supply resilience. However, desalination is still considered to be an energy and cost-intensive technology and is mainly implemented by high-income countries and small island countries [33]. As such, geographical constraints and high capital & operating expense are two hurdles to practicing seawater desalination [34].

As one of the simplest and oldest water sources, rainwater harvesting can be more flexible in terms of capacity, sites, and applications [35]. With proper purification treatments, the rainwater collected can be utilized for potable or non-potable purposes [36]. As such, rainwater can provide a useful supplementary supply and important backup to the water supply system. The biggest obstacle to rainwater harvesting is the temporal variation and geographic locations of rainfall [37]. Although artificial rainfall seems to solve this problem, this technology is still controversial [38].

Inter-basin water transfer (IBT) is an artificial reallocation of surface water resources from a donor watershed to a recipient [39]. In other words, IBTs improve the water supply also by accelerating the water cycle (the blue-line circle) by avoiding evaporation and precipitation [40]. However, the solution of IBT to improve the water supply has been under hesitation and debate since the 1980s [41]. Specifically, hydrological and ecological risks are associated with the donating and recipient basins [42]. Moreover, the donating watershed, IBTs' water source, is also subject to uncertainties from climate change.

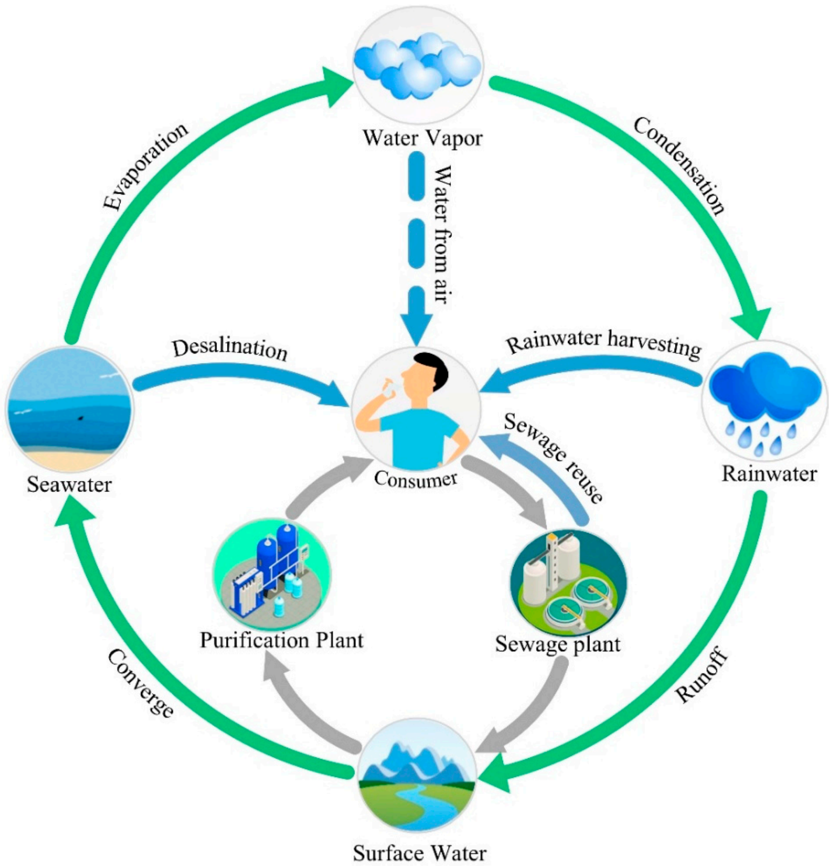

Figure 1. Diagram of the water cycle and water sources available for human beings.

Sewage reuse is another long-history-applied approach to conserve water and improve water supply [43]. Sewage reuse is the one shortening the water cycle most significantly by bypassing the natural water cycle directly. Compared with the above approaches, one of the advantages of sewage reuse is its on-site and stable water supply. As such, this feature endows sewage ruse an indiscriminately applicable solution for cities to enhance water supply resilience. However, sewage reuse as drinking water is currently unacceptable to most people, and public attitudes hinder the sewage reuse plans in many developing countries [20]. Fortunately, aquifer recharge with treated sewage instead of reuse directly could be a solution to leverage sewage.

These approaches have been applied separately or jointly to enhance water security by offering more choices and supplements to surface water. According to Figure 1, a common feature of these water sources is to offer more connection points between the urban water cycle and the natural water cycle. In other words, these alternatives get the natural water to the tap of residents (urban water cycle) more quickly [44], which seems to be a principal justification for whether a supplement is qualified to be an alternative to surface water. Obviously, atmospheric water owns the potential to be another connection point between the natural water cycle and the urban water cycle. It means that the water in the air can be extracted mandatorily (the dotted line) instead of via passive precipitation.

3. Technologies for Atmospheric Water Harvesting

As depicted in Figure 1, atmospheric water is an indispensable part of the natural water cycle and is the prerequisite and prior step for precipitation. Via evaporation and transpiration, a vast quantity of water out of water bodies and plants enters the air and exists in gaseous water vapor. All this vapor goes up with the rising air currents and condenses into clouds or fogs in the cooler air [45]. Generally, we can only get access to this part of water after they drop down on the ground via condensation albeit passively and intermittently [46]. By contrast, various technologies can be leveraged currently to help extract water directly and constantly from air depending on relative humidity. According to Figure 2, the water content capacity in the air (humidity ratio) is positively correlated with temperature and the isohume curves (100%, 80%, and 30%) separate the area into four zones. The blue line in Figure 2 represents a constant water quantity in the air termed g-H_2O/kg air [47], however, under each zone, the water is in a specific form. In Zone a, the relative humidity is higher than 80% and close to 100%, and the water will be in the form of mist or fog, which could easily be adsorbed and captured via proper materials. This phenomenon always occurs at high altitudes or on the top of high mountains with a low temperature and 100% relative humidity [48]. In Zone b, the relative humidity of the blue line is around 30–80%, the air contains a large amount of water vapor that does not readily nucleate into water droplets [49]. It needs to be artificially converted into liquid water first. Most living environments are in this zone. In Zone c, the relative humidity is lower than 30%, which makes the water vapor difficult to transform into liquid droplets even artificially [50]. The blocks divided by relative humidity and temperature in Figure 2 can help determine the proper method to do atmospheric water harvesting in a specific area, which will be discussed in detail below.

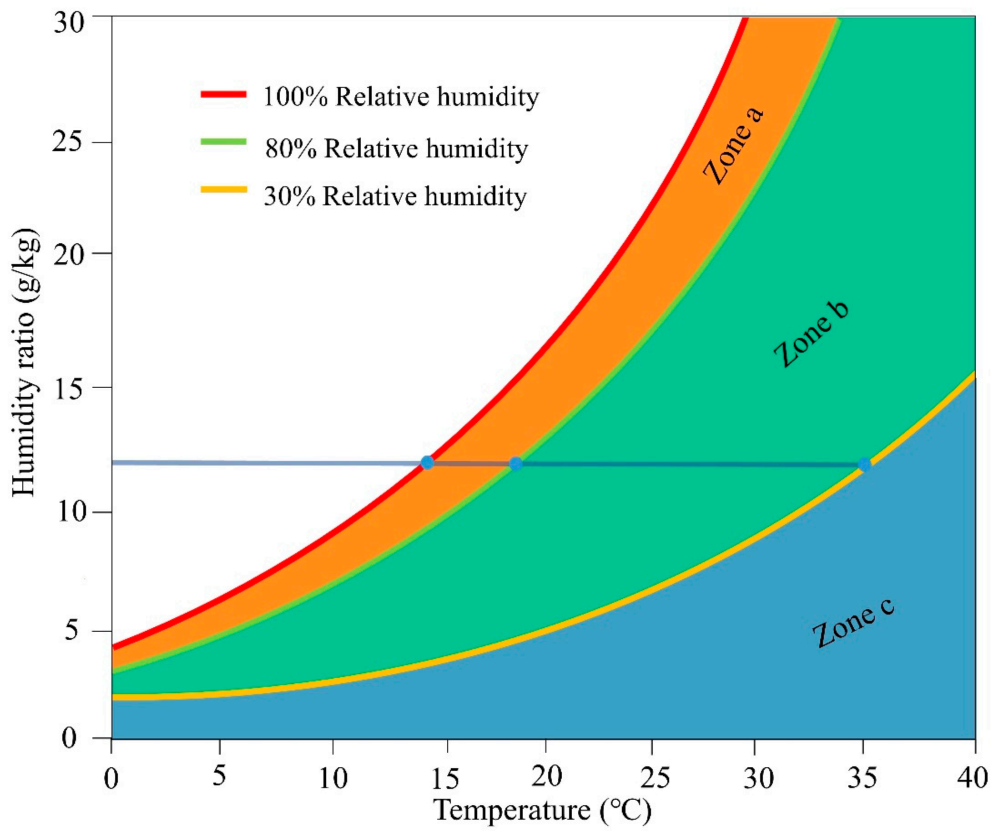

Figure 2. Water content in the air against various temperatures.

3.1. Passive Fog Collectors

Passive fog collectors target the fog in the air by mimicking the oldest practice of collecting drinking water from the leaves in the early morning by our ancestors. From the relative humidity perspective, Zone a in Figure 2 is the prerequisite condition for scaling this technology, and such places are usually located in coastal regions and/or mountainous areas such as Chile, Mexico, Oman, South Africa, and Morocco [51,52]. Generally, a fog collector is comprised of a flat-panel mesh that is stretched and fixed over a rigid frame. With wind current, the fog water contacts with and deposits on the surface of the mesh, and then aggregates into large droplets enough to drain into the container [53,54]. According to the full-scale project, the water collection rate is in the range of 1.5–12 L/(m^2·day) and can reach 1416 L/(m^2·day) with modification (Table S1). On the one hand, passive fog collectors are energy-free while, on the other hand, their water collection performance is highly associated with interior and exterior factors. Herein, the key interior factor is the mesh type including mesh material and weave design. Currently, stainless steel and plastics are two commonly-used mesh materials in large-scale projects [55]. Stainless steel is hydrophilic and can resist strong wind loading albeit heavy. The typical plastics available include polyethylene, polypropylene, and nylon [56]. They usually own the advantages of hydrophobicity, lightweight, low price, and good anti-aging performance. The properties of these materials are vitally important as they provide the direct sites to capture fog water. Besides this, the weave configuration is another principal factor determining the performance even with the same mesh material. As depicted in Figure 3, there are three geometric shapes generally adopted in field projects, simply denoted by triangular mesh, rectangular mesh, and hexagonal mesh [55,57]. Other key variations associated with performance include the width of mesh wires, pore area, and shading coefficient. The rectangular mesh is the most simple one made of stainless steel with a pore area of 0.16×0.16 cm^2 and a shading coefficient of 49%. Raschel mesh [58] is a typical representative of triangular mesh and is interweaved by doubled layered polypropylene ribbons with a width of 1–1.6 mm (shading coefficient of 35%). FogHa-Tin mesh is a proprietary product and is made of 0.13 mm diameter polypropylene thread into a springy structure with interleaved sets of embedded hexagonal patterns.

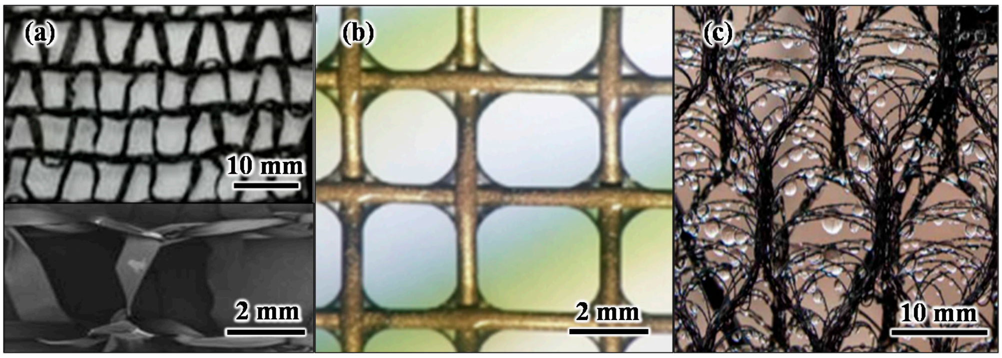

Figure 3. Various weave designs of water collector mesh (**a**) Raschel mesh (triangular mesh) [59]. (**b**) stainless-steel mesh (rectangular mesh) [60]. (**c**) FogHa-Tin mesh (hexagonal mesh) [55,57].

Rivera proposed Equation (1) to calculate the water collection efficiency, which is determined jointly by aerodynamic collection efficiency, capture efficiency, and draining efficiency [61]. The pore area or shade coefficient is the key factor influencing aerodynamic efficiency [62,63]. On the one hand, a large shade coefficient seems to provide more deposition sites, but a too-large coefficient can divert the wind flow due to resistance and reduce the water-mesh contact. On the other hand, too small a pore size could cause liquid film clogging which then jeopardizes the aerodynamic efficiency. In terms of Raschel and FogHa-Tin mesh (Figure 3a,c), wider ribbons instead of thread and embedded wires in the pore areas are designed respectively to offset the large pore areas [64]. By contrast, the pore size of stainless-steel mesh is too small to easily be clogged. Then, a harp mesh by only placing wires vertically instead of crossing reduces the adhesion to fog droplets and creates an unobstructed path for fog droplets to move and fall freely [65]. As a result, the water collection capacity of the parallel arrangement of wires can be 2–20 times higher than cross arrangement [66]. In addition, this problem can also be solved by co-knitting or coating with poly material [55]. Indeed, modification of mesh wires with coating materials can not only improve the aerodynamic efficiency but also optimize the capture and draining efficiency (Table S1). Knapczyk-Korczak et al. [64] deposited PVDF fibers on the Raschel mesh and, as a result, the effective surface area to catch droplets increased without sacrificing wind permeability. With the optimization of wetting properties and draining efficiency, the water collection rate increased by 300%.

$$\eta = \eta_{ace} \cdot \eta_{cap} \cdot \eta_{dra}, \tag{1}$$

where:
η represents the overall collection efficiency,
η_{ace}, η_{cap}, η_{dra} represent the aerodynamic collection efficiency, capture efficiency, and drainage efficiency, respectively.

Another factor that should be taken into consideration is the wind speed [67]. Generally, the most favorable wind speed for passive water collectors is 4–10 m/s [68]. Noteworthy is that the effect of wind speed on the efficiency of fog collection is also related to the diameter of the droplets and types of mesh. Fernandez et al. [55] evaluated the water collection performance of Raschel mesh, modified stainless steel mesh, and FogHa-Tin mesh. The results showed that Raschel mesh collected 160% more fog water than FogHa-Tin mesh at wind speeds less than 1 m/s while 45% less with wind speeds higher than 5 m/s. This is because the three-dimensional textile mesh will form some sort of a "blockage" at lower wind speeds while capturing some of the coalesced water droplets that tend to re-entrain in higher winds. As for modified stainless steel mesh, it collected more water than Raschel mesh at all wind speeds.

3.2. Refrigerated Atmospheric Water Harvesting

In terms of an environment with a relative humidity of around 30–80%, there are no readily available water droplets. To capture them, the prior step is to condense the vapor into droplets artificially [50], which, along with the following capture unit, represents a typical principle to carry out atmospheric water harvesting in Zone b (Figure 2). According to Figure 2, lowering the temperature is a simple and direct method to produce water droplets, by which refrigerated atmospheric water harvesting works [49]. A typical refrigerated atmospheric water harvesting unit is comprised of four parts, including the evaporator, condenser, compressor, and throttle valve (Figure 4) [69]. The humid air enters the evaporator part of the cooling unit, then it is cooled to the dew point temperature and condensed, purified, and collected on the evaporator coil [70].

The cooling unit (condenser) is the key factor that determines the water extraction efficiency of refrigerated atmospheric water harvesting. Currently, there are two cooling categories commonly adopted, passive condenser and active condenser. A passive condenser refers to one operating without any energy input [71]. One such unit is the radiant condenser, which is commonly used [71,72]. The key function unit in the radiant condenser is the cooling foil which owns the hydrophilic property and a high emissivity in the near-infrared. It emits thermal radiation in the wavelength range (8 to 13 μm) where the atmosphere is transparent and can emit heat radiatively to space [73]. This effect cools the foil below the dew point temperature of the air, causing water to condense upon it. A most commonly used cooling foil consists of TiO_2 and $BaSO_4$ microspheres embedded in a polyethylene film [74]. At present, this radiant condenser has a low water production rate. When the relative humidity is greater than 60%, the water production is commonly less than 0.8 $L/(m^2 \cdot day)$ [75]. To improve the water yield performance, some new materials have been explored and evaluated [76]. Raveesh et al. prepared a polystyrene film with hydrophilic bumps that secured a water yield of 1.8 L/(m^2·day) [76]. Chen et al. used a wettability and spectral selectivity engineered coating, and the water collection rate even reached 251.25 L/(m^2·day) [77]. Another challenge of the passive radiant condenser is the low solar absorption and high mid-infrared emissions required to operate during the day. Additionally, the process is not completely passive and the condensate needs to be manually removed. Haechler et al. combined a geometrically optimized radiation shield and a hydrophobic coating to the surface of the selective emitter to promote the condensation and removal of droplets which enabled dew mass fluxes up to 1.2 L/(m^2·day) [74].

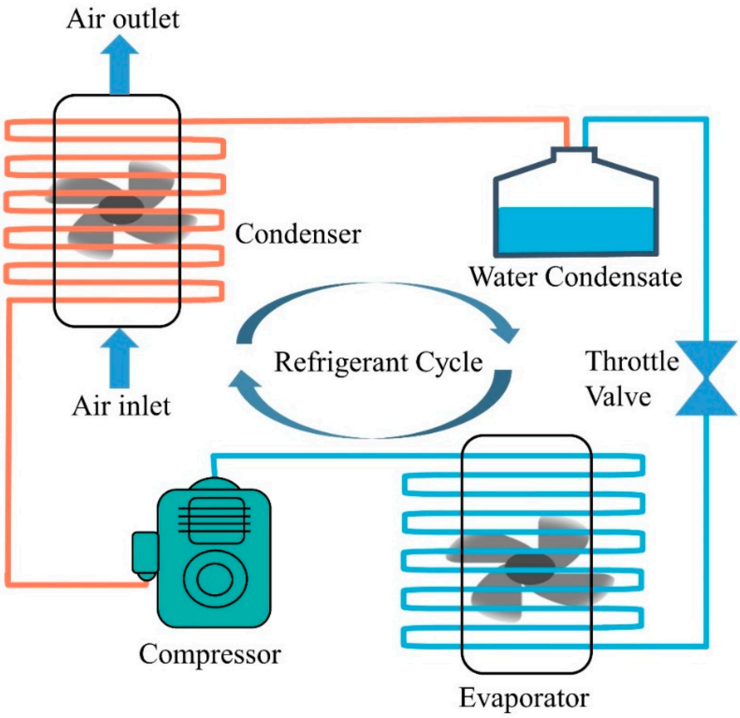

Figure 4. Diagram of refrigerant evaporation–condensation cycle.

In comparison, active condensers exert functions by leveraging external energy to accelerate the condensation process [78]. Thus, they are working more efficiently than passive condensers. The two most commonly used cooling methods in refrigerated atmospheric water harvesting are vapor compression refrigeration and the thermoelectric cooling process [79]. The vapor compression refrigeration process is similar to air conditioners and achieves cooling by changing the state of refrigerants such as Freon [80]. By contrast, thermoelectric cooling converts electrical energy into heat energy for cooling through the Peltier effect and reducing the temperature below the dew point. As such, thermoelectric cooling could avoid the drawbacks of vapor compression refrigeration causing ozone layer depletion and global warming problems [81]. However, in terms of the water yield performance, vapor compression refrigeration owns a higher capacity and is easy to scale up. With a relative humidity of 90%, vapor compression refrigeration can produce 22–26 L/day freshwater with energy input around 0.22–0.30 kWh/L [82]. This technology has been applied in the Middle East such as in Iran and Abu Dhabi [83]. Although the cooling capacity of thermoelectric cooling is low [84], it has the advantages of energy-saving, environmental protection, low maintenance, and high portability [85]. It is applicable and useful for cyclists, hikers, expeditions, and scientific research teams. In general, with a relative humidity of 60–90% and an input power of 0.8–3.5 kWh/L, the water production rate of thermoelectric cooling reaches 0.48–0.8 L/day [76].

Indeed, along with the trial to increase the water yield capacity, research effort is also placed on reducing the energy input associated with refrigerated atmospheric water harvesting, particularly under a hot environment but with low relative humidity. Precooling the inlet air with the cold exit air from the evaporator or providing a preconditioning unit to improve the psychometric properties of incoming air on the vapor compression system has become a common way to increase energy efficiency [76]. Ibrahim et al. used condensate to pre-cool the air entering the condenser, the compressor power input was decreased by 6.1% and the coefficient of performance was improved by 21.4% [86]. In addition, the use of polymer electrolyte membranes or water vapor selective membranes before the cooling process to separate water vapor from other molecules in the air can also achieve energy savings [75]. Roughly, this could reduce energy input by more than 50%. Meanwhile, this dense polymer membrane can also retain pollutants or pathogens, thereby purifying water [87]. Moreover, leveraging renewable energy such as solar and wind power could also be a potential solution to reduce the energy further [88].

3.3. Desiccant-Based Atmospheric Water Harvesting

As discussed above, fog collectors and refrigerated atmospheric water harvesting have their favorite application environments with a relative humidity higher than 80% and 30%, respectively. In terms of relative humidity less than 30%, the above processes do not work or work but with a large quantity of energy input. As such, desiccant-based atmospheric water harvesting was proposed to extract water from air under low relative humidity (below 15–20%) or low dew point temperature (below 5–10 °C) [89]. In general, desiccant-based water harvesting works in a batch mode [90]. At the beginning of a cycle, the desiccant is exposed to the atmosphere and adsorbs water vapor in the air. Once the desiccant is saturated, the system is closed and the water will be released as vapor out of the desiccant at a rising temperature of 160 °C (Figure 5). Then, the vapor condenses on the enclosure walls and can be collected, meanwhile, the reactivated and unsaturated desiccant will be cooled down for the next water-capture cycle [74].

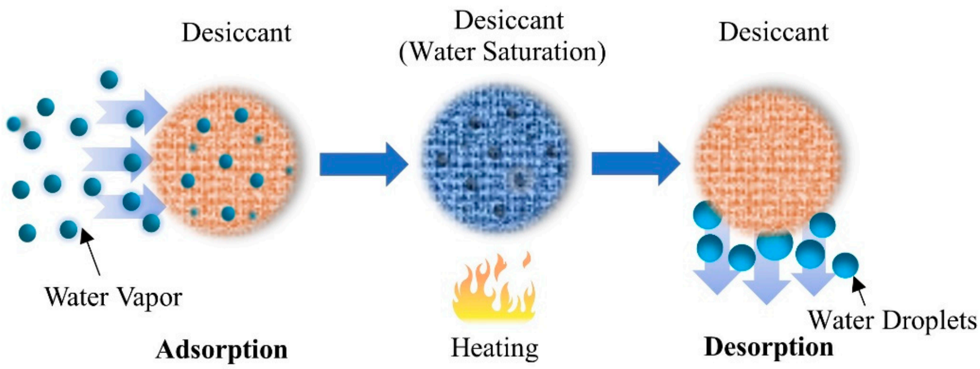

Figure 5. Diagram of the desiccant-based atmospheric water harvesting.

One of the key units is the desiccant, which performs the cycle of water vapor adsorption and water desorption [91,92]. The desiccant not only determines the water collection rate but also is associated with energy consumption. Currently, a series of single solid desiccants and composite materials have been developed and studied [93]. Some typical single solid desiccants include silica gel, activated carbon, and inorganic salts. However, they need a high temperature to release water after saturation which is energy-intensive and cannot be completed by conventional solar thermal equipment [94]. By contrast, some novel composite materials have drawn attention (Table S2). For example, a kind of salt gel beads made of an alginate-derived matrix with calcium chloride owns a water holding capacity of 660 kg water/m^3 and can release water at a temperature of 100 °C [95]. In addition, some MOF-based desiccants were also explored and presented promising water adsorption ability [91,96].

Another key issue associated with a desiccant-based water extraction system is to reduce the energy input as low as possible [69,97]. One of the basic and most greenway is to leverage solar energy [98]. The glass-covered greenhouse (also called solar still) is the simplest device, it uses solar energy to distill out the water molecules adsorbed in the desiccant [99]. However, the water generation rate (1.0–2.5 L/(m^2·day)) is limited due to the diurnal variation [75]. Therefore, employing an additional condenser as a supplement to a solar heat collector to ensure a continuous operation is one of the possible solutions [50]. In addition, transforming and/or storing solar energy in the form of either electricity or heat via thermal collector or photovoltaics can also be coupled to a desiccant-based water extraction system to utilize the solar energy as more as possible [100]. Especially in extremely dry climate regions such as deserts, solar photovoltaic modules can be used to power atmospheric water harvesting. The solar modules developed by Panchenko have an extended service life and polysiloxane compounds, which do not degrade in such difficult climatic conditions and are tolerant to cyclical temperature fluctuations [101,102].

4. Link between Atmospheric Water Harvesting and Water Supply Resilience

A reliable water supply is vital to life, and having either too much or too little has very serious consequences, leading to drought and fires at one extreme, and floods at the other [103]. Recently, the Intergovernmental Panel on Climate Change (IPCC) released a new assessment report in August highlighting the changes in the water cycle due to the temperature rising. As 1 °C increases in the air could increase its water holding capacity by 7%, and continued global warming will make air retain more moisture [104]. Specifically, the rainfall amount will be larger as there is more water to condense and fall out of the air [105]. Meanwhile, a warmer climate will intensify the evaporation and result in droughts developing more quickly and lasting longer [106,107]. Indeed, all these extreme weather patterns have been tangible and jeopardized our water supply system [108,109]. The more recent flooding disaster in Germany and ongoing extreme droughts in the western USA consequently make drinking water unavailable or shortage [110,111]. Thus, it is urgent for each city to proactively enhance its water supply resilience and get ready for the projected worsening global warming [112,113].

The National Infrastructure Commission of the UK advised a twin approach to address the resilience of water supply, which includes demand management and supply infrastructure [114]. Demand management focuses on increasing water efficiency while supply infrastructure highlights diversity which refers to developing a range of different water sources. The different source types have different strengths and vulnerabilities; therefore, resilience is increased by being used together. Hereinto, how to define the role of atmospheric water harvesting in building water supply resilience remains to answer. The current centralized water supply is a symbiotic system composed of four elements, that is, sources for water intake, treatment at drinking water treatment plants, storage, and distribution via a pipe network [44]. As discussed by Deng [115], once a natural hazard impairs one of them due to water source pollution, pipeline destruction, power outage, personnel shortage, or other causes, the entire water supply system may fail. As such, Deng proposed a concept of household water treatment highlighting a decentralized water supply system to respond to possible disruption of the centralized water supply [115]. From a technical point of view, atmospheric water harvesting is just in line with this concept in terms of its indiscriminate presence of water source (air) and the decentralized water supply mode. As such, atmospheric water harvesting seems to be a potential solution to enhance water supply resilience, particularly under extreme weather conditions.

Water yield capacity and affordability are two factors determining the acceptance and applicability of a specific water source. As discussed above, atmospheric water harvesting currently has a much lower water yield than other water sources. In terms of the cost, as depicted in Figure 6, the water price of conventional surface water source is around $1.2/$m^3$, and other typical alternatives, desalination, rainwater harvesting, and reclaimed water, fall within the same level. By contrast, the price of the water from the air is substantially higher than the above sources and is around 20–90 $/$m^3$ [39,46,116]. Along with the low water yield, and the temperature and relative humidity will be correspondingly reduced after the active extraction of water from the air, atmospheric water harvesting is unlikely to be used on a large scale as an accessible infrastructure or alternative water source. However, the water from the air has a price advantage over bottled water which is the only choice currently under the destruction of the water supply system. Besides this, the environmental impacts of bottled water are pretty high in species loss and resource consumption [117]. In addition, considering that atmospheric water harvesting has the characteristics of a decentralized water supply, it is generally used for emergencies or some specific areas at present. As such, atmospheric water harvesting can be considered in the water management portfolio at a community- or city-level to increase the capacity to handle water supply problems [118,119]. Thus, areas that deserve further research are focused on system design, novel materials (e.g., desiccant) development, and green energy-driven design [120,121].

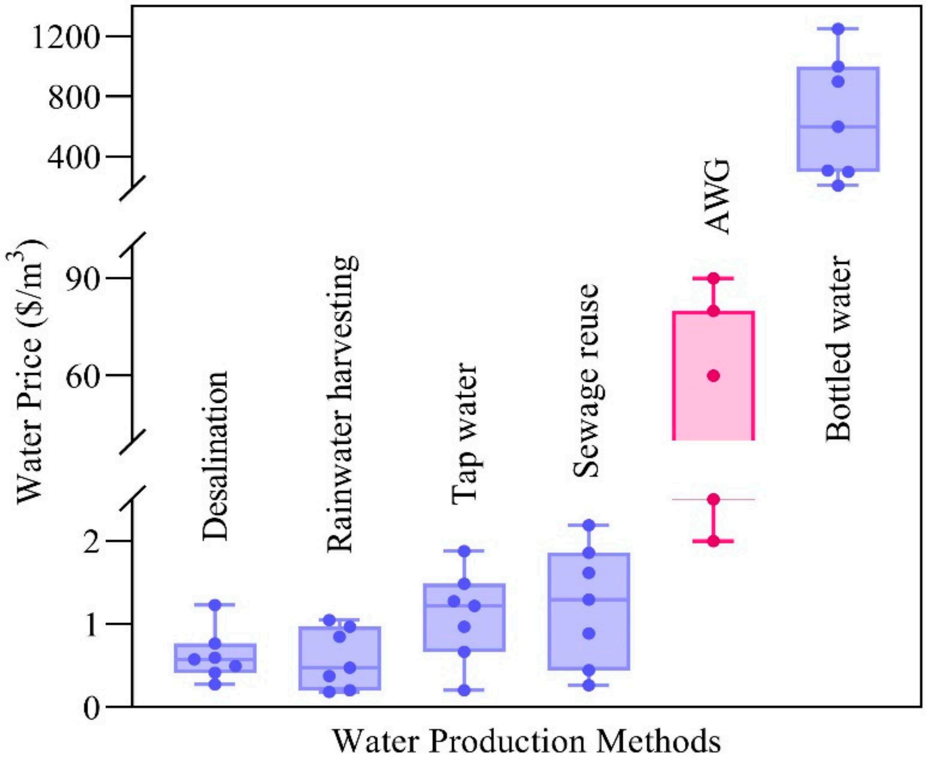

Figure 6. Water prices of various water sources.

In terms of the water quality out of the atmosphere water harvesting process, the water generated is generally clean and pollutant-free. Although the air pollution such as PM2.5 and microplastics in the atmosphere brings concerns about the water quality via atmospheric water harvesting [122,123], it can be solved by simply installing a post-purification module to ensure water quality [46]. Indeed, atmospheric water harvesting technologies manage to filter out any dirt, such as heavy metals, particles, biological organisms, organic compounds remaining in the harvested water, and by artificially adding minerals such as calcium and magnesium, the water quality can be upgraded to the level of natural spring water [124].

Recently, atmospheric water harvesting has been commercialized in many countries and regions (Figure S1) and some off-the-shelf products have been on the market (Table S3). These machines can be divided into three models: large, medium, and small. The water generation capacity is in the range of 2–200,000 L/day to meet the needs of households, emergencies, hospitals, villages, etc. In the parks and beaches of cities such as Abu Dhabi, Al Ain, and Abu Dhabi, water-from-air machines are installed to supply high-quality drinking water for visitors [125]. Indeed, despite the atmospheric water harvesting discussed above, many innovative solutions to leverage the water in the air have been proposed and practiced [126,127]. For example, by laying a mesh overhead the farmland or placing water-adsorbent hydrogel on the surface of the soil, the crops can be irrigated on-site and automatically. In a recent study, Lord et al. thoroughly assessed the global potential of atmospheric water harvesting as a water source by mapping regional horizontal irradiance from sunlight, relative humidity, and air temperature [128]. The results showed that atmospheric water harvesting leveraging solar power could serve the drinking water needs of about 1 billion people. As such, further development and optimization will probably make atmospheric water harvesting more viable and promising to support the water supply system.

5. Conclusions

Diversifying the water sources is necessary to get the cities ready and more resilient to supplement the water supply system. Adoption of atmospheric water harvesting could be such a solution as they provide another connection point between the natural water cycle and the urban water cycle. A series of systems and off-the-shelf products are available on the market to be installed under various relative humidity environments. Although the higher water generation cost makes atmospheric water harvesting uncompetitive, it can be a reliable and decentralized household water treatment system to meet the water demand particularly by leveraging solar power. In addition, it also provides an alternative water source for regions that have a large bottled water consumer base but have no other favorable water sources. Overall, atmospheric water harvesting shall be taken into consideration to enhance the water supply resilience.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14137783/s1, Table S1: Summary of studies or practices of atmospheric water harvesting; Table S2: Summary of desiccants explored and developed in various studies; Table S3: Summary of atmospheric water harvesting machines on the market; Figure S1: Summary of atmospheric water harvesting technologies in practical application. References [129–152] are cited in the supplementary materials.

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