BOTTLED WATER TECHNOLOGY AND ITS GLOBAL RAMIFICATIONS: AN OVERVIEW

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ABSTRACT

Since ancient times, humans have used some form of water carrying vessel to transport water for consumption. In modern times, bottled waters of various sizes and volumes, predominately made of plastic, are produced for public consumption. Particularly since 1990s, bottled water has become a major global commodity available in every corner of the world. From technology perspective, bottled water can be considered a decentralized technology which distributes water for human consumption via a portable container, i.e., bottle, instead of a pipeline which is a required component for transporting water in conventional centralized water infrastructure, i.e., public water supply system. In general, decentralized water systems refer to small-scale water supply systems that use available local water resources and supply drinking water to small communities or low population areas. However, the decentralized concept also applies to water bottling industries that produce bottled water in a certain location and then export it to distant lands for consumption. This article discusses the rational beyond global expansion of bottled water, components of bottled water technology, and its ramifications related to community development, human health, energy consumption and environmental impacts.

Keywords: decentralized water infrastructure, plastic bottles, health concerns, environmental impacts, sustainability

1. INTRODUCTION

In 2005, when the United Nations started promoting the “International Water for Life Decade”, 1.1 billion people did not have access to clean drinking water. Most of the un-served populations, about 84 percent, live in rural areas and according to the UNICEF, 1.6 million children die every year due to the lack of clean water (WHO/UNICEF [37]; WHO/UNICEF [38]). In recent decades, in many countries, providing clean drinking water has become a high priority. However, due to governmental policies a majority of drinking water projects are implemented in urban areas and most rural population are left behind. It is predicted, that by 2025, about two-thirds of the world population will be living in water stressed regions and 1.8 billion people will be without clean drinking water and (FAO [9]).

2. BOTTLED WATER AS DECENTRALIZED WATER SYSTEM

At present, centralized water treatment and distribution infrastructures are the common mode of drinking water supplies around the world. However, implementing the conventional centralized drinking water infrastructure is cost prohibitive particularly in rural and sub-urban and low population density areas. Decentralized water systems are considered a viable and affordable alternative for providing safe drinking water to under-served communities around the globe. In general, decentralized water systems refer to small-scale water supply systems that treat and distribute local water resources for human consumption and other uses. Although decentralized systems mostly serve rural and low
density population areas, the technology can be implemented to specific urban environments such as shopping centers, hospitals, hotels and schools. A rainwater harvesting system is a typical decentralized water supply system with great potential for providing water to isolated communities as well as specific urban settings (Younos [44]).

Since ancient times, humans have used some type of vessel, made from animal skin or clay, to carry small and large volumes of water from the water source for use in royal palaces, peasant households, and other purposes such war zones (Siskos [31]). In modern times, a water carrying vessel manifested in the form of bottle of different sizes is used to provide drinking water to poor and rich of urban and rural populations. The bottled water technology as described later are implemented in two ways: 1) available local water sources is used to produce bottled water for local consumption; and 2) bottled water is produced elsewhere and then transported for public consumption via markets.

3. BOTTLED WATER AS A COMMODITY

The foundation for modern bottled water production was established in 1960s-1970s when the industrial world was revolutionized with the invention of plastic. The major expansion of plastic bottle industry occurred in the 1990s with the invention of polyethylene terephthalate (PET) plastic, a light weight yet strong plastic. As a result, worldwide water bottling production grew from a $115 million industry in 1990 to a $4 billion industry in 1997 (Columbia Water Center [7]). In the 21st century, bottled water has become a major global commodity available in every corner of the world. It is a $22 billion global industry that ranges from very small local bottling operations to giant corporations (Arnold and Larsen [1]; Wilk [39]).

Several factors have contributed to worldwide consumption of bottled water. In urban areas around the globe, high consumption of bottled water is attributed mostly to consumer preferences and convenience. Several researchers have reported on the reasons for consumer preferences and using bottled water versus conventional public tap water (Hu, et al. [15]; Johnstone and Serret [20]; Meerveld, et al. [23]; Niccolucci, et al. [24]; Wells [36]. Most studies indicate that a lack of confidence in quality of public water supplies (tap water) has significantly contributed to increased use of bottled water. Many consumers perceive bottled water as “cleaner” and “healthier” and a safe alternative to public water supplies. In addition, for most urban consumers, portability of bottled water ensures all time availability. Factory and office workers, athletes, students, celebrities, politicians, and many others use bottled water on a daily basis due to its ease of portability and convenience.

The necessity for using bottled water cannot be overlooked. In small towns, rural and isolated communities of developed world and sub-urban and rural communities of developing countries, bottled water consumption is considered a matter of necessity. For example, in Veron, a small town in the southern tip of the Dominican Republic, where centralized water supply infrastructure does not exist, about 85 percent of town population depends on bottled water as a matter of necessity (Pichardo [29]). In some areas of developing countries, bottled water industries in collaboration with community and/or local government have launched bottled water production projects not only to provide safe drinking water to local population but also incorporate small bottled water industry as a vehicle for community development, small business and job creation at the local level (Bogle and Younos [2]).

It should be noted that bottled water availability is an absolute necessity in areas where public water supplies are disrupted, at least temporarily, due to natural disasters and terrorist activities. During emergency situations, bottled water is often transported and distributed to refugee centers, hospitals and other locations.

As noted above, for several reasons there is worldwide need for bottled water. However, in recent years, in some European countries, the U.S. and other countries, increasing trend in bottled water use
has instigated a debate over the necessity and appropriateness of this commodity. An argument is made that the use of reliable and safe public water supplies should not be replaced by bottled water which is more expensive and energy intensive, and its production causes environmental degradation due to disposal of used plastic bottles. In the U.S. and a few other countries there is a movement to ban bottled water use and encourage increased use of public water supplies.

4. BOTTLED WATER TECHNOLOGY

Two major components of bottled water technology are bottle production and water treatment. Although some glass bottles are produced, most bottled water industries use plastic bottles due to its low cost and ease of transport. A comprehensive discussion of the process for plastic bottle production is beyond the scope of this article. As mentioned earlier, the most common plastic used in bottled water industry is polyethylene terephthalate (PET) plastic. PET which is derived from petroleum hydrocarbons is a polymer, a substance consisting of a chain of repeating organic molecules with great molecular weight. A disadvantage of PET is that it is not easily decomposed in natural environments.

In general, water treatment technologies for producing bottled water are identical to those for public water supplies or tap water. Advances in water treatment technology have resulted in expansion of bottled water production as a reliable small decentralized water system. For example, the a typical small-scale drinking water processing and bottling system unit size, introduced by Portaqua, is 1.2m long, 1.0m wide and 2.1m high and can easily fit in a small room (Bogle and Younos [2]). It provides multi-process purification of water and can remove a broad range of contaminants including arsenic, pesticides and metals from any source water. The system is equipped with a programmable logic control (PLC) component which facilitates automated operation of the system. It allows for easy operator training and enables the operator to run the system without supervision.

Water treatment and bottling systems similar to Portaqua can be installed to provide safe drinking water to localities without a centralized infrastructure with significant cost savings in pipeline construction and energy needs for pumping. A study conducted in Virginia, U.S., estimated that it will cost more than $300 per meter to lay or extend a new water supply pipeline (Grady and Younos [14]). The pipeline construction cost may be lower in some other locations and countries but still it will be cost prohibitive in low population areas. Furthermore, for a typical centralized water distribution system, where water is transferred via pipelines from a treatment system to homes and buildings, about 2/3rd of energy is consumed by water distribution pumps and 1/3rd energy consumption is attributed to water treatment (Chen, et al. [5]; Younos, et al. [43]). Thus, small decentralized systems will minimize water distribution costs. Several Portaqua water bottling plants are installed in suburban Mexico towns. In these plants, the bottled water plant owner provides large plastic bottles (20 liters volume) to community members. Users return empty containers to the plant where it is rinsed and refilled (Bogle and Younos [2]). This is an effective approach for saving energy and cost in small communities as compared to a conventional pressurized water distribution system which depends on electricity for household water distribution.

The water treatment technology used by global scale bottled water industries, where bottled water is exported to distant lands away from the water source, is very similar to a public water treatment system. However, for large industries, packaging and transportation of bottled water are critical components that affect bottled water cost. Bottled water industry depends on energy for plastic bottle production and transportation of bottled water to the market. Cost of plastic bottle, packaging and transportation are added to bottled water cost making commercial bottled water several times more expensive than public tap water. Major aspects of energy use in bottled water industry are discussed in later part of this article.
5. BOTTLED WATER REGULATION

It is important to note the difference in regulatory requirements for public water supplies and bottled water production. In general, the World Health Organization (WHO) Guidelines for drinking-water Quality are applicable to packaged bottled water. Several countries have established guidelines to regulate bottled water industry. Typical bottled water regulations for a few countries are briefly described below.

In the U.S., bottled water is considered a packaged good [U.S. Code of Federal Regulations (CFR), Title 21, Part 129 and Part 165.110(b)] and bottled water production is regulated by the U.S. Food and Drug Administration (FDA). Bottled waters labeling is based on type of water source according to the U.S. Environmental Protection Agency (EPA) classifications (US EPA [34]). FDA’s bottled water standard of quality regulations generally mirror national primary drinking water regulations for public water systems (tap water) which is authorized by the Safe Drinking Water Act and regulated by EPA. Therefore, water quality standards for chemicals in bottled water are identical to the allowed Maximum Contaminant Levels (MCLs) in public drinking water systems. Some concerns related to FDA packaging regulation are noted in a later section of this article.

In most European countries bottled water production is regulated by the European Communities Regulations (e.g., FSAI [11]). These regulations cover the definition of natural mineral water, spring water and ‘other water’, their exploitation, treatment, microbiological criteria, chemical contaminants, and labeling and packaging of bottled water. In Canada, similar to the U.S., bottled water is regulated as a food and therefore, it must comply with the Food and Drugs Act and Regulations (CFIA [4]). Canadian regulations include specific microbiological standards, acceptable treatments and labeling requirements. In Japan, bottled water is usually referred to as “mineral water” and is regulated under the Consumer Product Safety Law (Seubert [30]). Japanese regulations for bottled water cover safety, labeling, disposal of containers and importation of bottled water.

6. HEALTH AND ENVIRONMENTAL IMPACTS

Issues of concern related to impacts of bottled water consumption include quality of bottled water and its potential health impacts, energy consumption and its implications, and disposal and management of used plastic bottled water.

6.1 QUALITY OF BOTTLED WATER

In the U.S., regulation of bottled water as a packaged food presents health concerns as noted below (GAO [12]): 1) while the EPA mandates daily testing and/or frequent monitoring of contaminants in public drinking water supplies, the FDA requires only once a year water quality testing for bottled water; 2) FDA does not have the specific statutory authority to require bottlers to use certified laboratories for water quality tests or to report test results, even if violations of the standards are found; and 3) FDA’s bottled water labeling requirements are similar to labeling requirements for other foods, but the information provided to consumers is less than what EPA requires of public water systems under the Safe Drinking Water Act.

The Natural Resources Defense Council (NRDC) conducted a comprehensive related to quality of bottled water (Olson [28]). The study findings were based on published and unpublished literature and data, surveys and expert interviews, and "snapshot" water testing of more than 1,000 bottled waters sold under 103 brand names. The NRDC study found that one-third of bottled water brands contain contaminants that exceed established bottled water industry guidelines and standards. Other researchers have noted concern about quality assurance of bottled water (Ikem, et al. [19]). An Environmental Working Group (EIG) report based on survey of 173 bottled water products found that overall, 18 percent of bottled waters fail to list the location of their source, and 32 percent disclose nothing about the treatment method or water quality (Leiba, et. al. [21]). Furthermore, the EIG report noted that labels of nine of the 10 top-selling domestic brands do not identify their specific water
source or treatment method or provide contact information for consumers seeking additional information on water quality. Another noted concern is that, unlike conventional tap water, bottled water is not packaged with a residual disinfectant such as chlorine which retards bacterial growth, and therefore long-term and poor storage conditions can encourage bacterial growth in bottled water (Olson [28]).

Potential contaminant leakage from plastic bottled water is a noted health concern. The mechanism of contaminant leakage from plastic to water is not well known but some investigators have pointed to plastic water bottle leakage a possible cancerogenic (Ceretti, et al. [3]). The two compounds used in plastic bottle production that have been linked to mutagenic or carcinogenic properties are acetaldehyde and formaldehyde. The International Agency for Research on Cancer (IARC) has cited acetaldehyde as a “possible” human carcinogen that is genotoxic in many biological systems (IARC [16]). Additionally, formaldehyde is a genotoxic chemical that has demonstrated DNA and chromosomal damage to a number of organisms (IARC [17]). Bisphenol A (BPA), an organic compound, is also contaminant of concern in bottled water. However, limited data is available on BPA concentration in bottled water. A Japanese study found BPA concentrations of 0.24 – 3.5 µg/l in commercial bottled waters (Lim and Takeuchi [22]).

6.2 BOTTLED WATER ENERGY CONSUMPTION

Carbon dioxide emission to atmosphere resulting from various anthropogenic activities is considered a major cause of climate change and levels of CO$_2$ emission and energy (fossil fuel) consumption are closely related (NRC [25]). Energy use is a critical factor in bottled water production and distribution because of industry’s dependency on fossil fuels. Energy needs in bottled water industry include: energy for water treatment, energy for plastic bottle production, and energy to transport bottled water to markets. All other energy uses—for bottling, sealing, labeling, and refrigeration—are far smaller than those for the production of the bottled water and transportation.

6.3 ENERGY USE FOR WATER TREATMENT

Limited data is available on energy use for water treatment in bottled water industry. However, approximate energy use in bottled water industry can be estimated if it is assumed that energy use for water treatment in bottled water industry is comparable to the energy use for public water treatment because of similar water treatment process. The main component of energy use in small decentralized systems such as Portaqua water treatment process discussed earlier is attributed to pump that is installed to operate the reversed osmosis (RO) membrane (Bogle and Younos [2]). The energy usage for Portaqua system to treat water is 3.0 kWh/1.0 m$^3$ to 3.5 kWh/1.0 m$^3$. Furthermore quality of water to be treated is a major factor in energy consumption. For example, research shows that energy use to operate RO membrane for desalination of brackish and sea water is 4.0 kWh/1.0 m$^3$ to 10 kWh/1.0 m$^3$ (Younos and Tulou [42]). For large scale bottled water industry, energy needs for water treatment are comparable to energy consumption noted above. Further advances in membrane technologies, developing of new and innovative water treatment technologies, or using renewable energy sources such as solar and wind energy for water treatment are expected to reduce energy needs and increase energy use efficiency for both large scale centralized and small decentralized water treatment systems.

6.4 ENERGY USE FOR BOTTLED WATER PRODUCTION AND DISTRIBUTION

Gleick and Cooley [13] studied the energy footprint required for bottled water production and transportation, and quantified key energy inputs necessary for site-specific assessments of energy consumption. They concluded that for short transportation distances energy need is dominated by production of plastic bottle. Dettore [8] used life-cycle assessment (LCA) technique to quantify life-cycle energy use of bottled water. Dettore concluded that over 70 percent of total energy use is attributable to plastic bottle production if bottled water is used locally or distributed short distance.
However, energy use is dominated by bottle transportation if bottled water is transported long-distance, i.e., national and overseas distribution.

Limited data is available on quantification of energy use for bottled water production and its environmental consequences. According to Woods [41], worldwide, the amount of fossil fuel used for PET bottle production is about 48 million kilo-liters which results in 10.89 billion kg of CO\textsubscript{2} emission (based on 2.32 kg of CO\textsubscript{2}/liter of oil). O’Connor [27] estimated that in the U.S. about 2.4 million kilo-liters of fossil fuel is used for PET bottle production which translates to about 0.54 billion kg of CO\textsubscript{2} emission.

In general, energy use for transportation of bottled water depends on a variety of factors that include (Ferrier, [10]): 1) transportation mode: trains, boats, trucks, personal cars, airplanes; 2) the age and model of a particular transportation mode; 3) life cycle travel distance: including transportation from producer to retailer to consumer, and producer to wholesaler to retailer to consumer; and 4) driving modes: urban areas versus rural areas and highways. Weber and Matthews [35] estimated that average short distance travel distance for bottled water to deliver to retailer is 330km, and its total life cycle transportation travel distance is 1,200km. Table 1 shows estimated fossil fuel consumption for bottled water travel distances of 330km and 1,200km (Weber and Matthews [2008] and authors’ estimation of resultant CO\textsubscript{2} emissions. Calculated CO\textsubscript{2} emissions in Table 1 are based on the following assumptions: 1) CO\textsubscript{2} emissions mostly originate from trucks, the most common mode of transportation for bottled water; 2) the rate of energy consumed is 2.7 MJ/1,000kg-km; 3) the carbon content of diesel fuel is estimated at 72.71 CO\textsubscript{2} per Million-BTU (USEPA, [33]); and 4) the estimated weight of the truck is based on the U.S. Department of Transportation’s 36,288 kg (40 ton) limit for tractor trailer trucks.

<table>
<thead>
<tr>
<th>Travel Distance</th>
<th>Energy Use (MJ/Kg)</th>
<th>Energy Use (BTU/Kg)</th>
<th>CO\textsubscript{2} Emission (calculated) (Kg per Truck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>330 km</td>
<td>0.891</td>
<td>844.51</td>
<td>2228.24</td>
</tr>
<tr>
<td>1,200 km</td>
<td>3.240</td>
<td>3073.46</td>
<td>8108.11</td>
</tr>
</tbody>
</table>

It should be noted that total energy consumption and resultant CO\textsubscript{2} emissions depend on frequency of truck travel and delivery and it is not unique to bottled water. Other soft beverages packaged in plastic bottles also consume large amounts of energy during transportation.

### 6.5 DISPOSAL AND MANAGEMENT OF USED BOTTLED WATER

“Plastic Pollution” of surface waters and oceans due to plastic bottle trash is a major global environmental concern and threat to ecosystem (e.g., NRDC [26]). There is a worldwide need for proper disposal and management of plastic bottles. At present, practices for management of used plastic bottled water around the world include landfill disposal (underground burial), incineration, and recycling. Landfill disposal is the most common practice. For example, in the U.S. about 80 percent of used plastic water bottles are disposed in landfills (Columbia Water Center [7]; GAO [12]). However, landfill practice by itself is considered an environmental dilemma. It is estimated that it takes more than 1,000 years for a plastic bottle to decompose and be regarded environmentally safe (City of Ann Arbor [6]). In addition, land requirement for landfill is a major limitation particularly in urban areas. Significant amounts of trash and used plastic bottles to be disposed of are transported to other areas away from urban centers.

Incineration is not a common type of disposal for plastic bottles and the amount of plastic water bottles that are incinerated is unknown. Furthermore, incineration is not considered a viable option for plastic bottle disposal because of its potential contribution to air pollution and health impacts (The Story of Stuff Project [32]).
At present, recycling of plastic bottles is considered the most appropriate management option and is promoted worldwide. However, as yet globally recycling of plastic bottles is not a common practice. According to European Trade Association, in Europe about 48 percent (2010 data) of used PET bottles are collected for recycling (Wikipedia [40]) while the PET bottles recycling rate in the U.S. is about 28 percent (2009 data) (IBWA [18]). Used PET bottles can be reused as-is (for example, in case of small community water bottling projects in Mexico described earlier). The majority of used bottles are actually downcycled; a process in which a recyclable material is made into a second, non-recyclable material (The Story of Stuff Project [32]). It should be noted that recycling of plastic bottled water consumes energy as well. As shown in Table 2, recycling of PET bottles has limited impact on energy saving and reducing CO$_2$ emissions (Ferrier [10]).

<table>
<thead>
<tr>
<th>PET Recycle Rate (percent)</th>
<th>Energy Need (GJ per 1,000 liters)</th>
<th>CO$_2$ Emission (kg per 1,000 liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.9</td>
<td>7.4</td>
</tr>
<tr>
<td>50</td>
<td>5.0</td>
<td>6.4</td>
</tr>
<tr>
<td>100</td>
<td>4.1</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Energy savings due to recycling of plastic bottles appears to be not significant. However, recycling and downcycling of plastic bottled will significantly reduce global plastic pollution.

7. CONCLUSION

At present, it remains uncertain wither the bottled water is a panacea or plague of our modern civilization. Major noted disadvantages of bottled water technology relate to plastic bottles due to its high energy demand and its impact on the environment. There is some concern about the quality of bottled water but similar concerns exist about the quality of tap water delivered via public water supply systems. As a matter of fact, a major reason for popularity of bottled water is public distrust about quality of tap water and the perception that bottled water is cleaner than tap water. Major advantages of the bottled water technology include the opportunity to provide safe water to communities where extending public water distribution pipelines is cost prohibitive. With appropriate investment, there is a great opportunity to incorporate bottled water production as a decentralized water system for community development and job creation in low-income areas. Bottled water production can be a part of the solution to global lack of safe drinking water if futuristic technologies such as renewable energy use for water treatment are incorporated into infrastructure system design. Furthermore, increased public education to recycle used bottled water and developing technologies to produce biodegradable bottles will enhance the potential of integrating decentralized bottled water technology into the fabric of modern societies.

As the world population continues to climb past seven billion people, it is critical to incorporate innovative procedures that will enable policy and decision-makers make bold intellectual and financial investments that will result in providing safe drinking water to large un-served communities throughout the world. Proper implementation of small decentralized water systems including bottled water technology is expected to alleviate global scarcity of safe drinking water and improve human health and environment.
REFERENCES


