World Water Resources and Achieving Water Security

Rattan Lal*

Abstract
Water is the elixir of life and a principal indicator of sustainable development. It is important to understand the magnitude of water resources, the hydrological cycle, and the impact of land use and management. Large area of Earth’s surface is covered by water, but renewable fresh water resources are finite (~2.5% of the total), unequally distributed geographically, and prone to eutrophication and pollution. Conceptually, water resources comprise of four categories: (i) blue water is the fresh surface and ground water (e.g., water in lakes, rivers, and aquifers), (ii) green water is the precipitation on land that is stored in the soil for plant use, (iii) gray water is contaminated by human use, and (iv) virtual water is embedded in agricultural and industrial produce. Water scarcity, when demand exceeds supply, occurs wherever the per capita availability of renewable freshwater is <1700 m³/yr. In contrast, water stress occurs when the per capita availability of renewable freshwater is <1000 m³/yr. Therefore, water security exists when all people at all times have physical and economic access to sufficient, safe, and clean water that meets their basic needs for an active and healthy life. Water footprint, the amount of water required to produce goods and services for human consumption, is increasing with increase in world population and its growing affluence. Thus, sustainable management of water involves technologies to increase the green water storage in soil, purify the gray water, reduce export of virtual water, increase water use efficiency, and desalinize brackish water.

Types of Water
As is stated above, ~97.5% of Earth’s water resources comprise of saline water (Table 1). The remaining 2.5% of the water is called fresh water which falls as precipitation. Of the freshwater, 69.5% is contained in ice caps, glaciers, permanent snow, ground ice, and permafrost (Table 1). Only 1.2% of all fresh water is surface water and other fresh water, and it is this water which can be used for all living organisms (animals including human, plants etc.) (Fig. 1).

The fresh water (415 km³, Fig. 1) can be conceptually grouped under two categories, liquid water in lakes, rivers, ground water; and atmospheric water which falls as precipitation. This water is called blue water. Thus, the blue water amounts to ~85.9% of all fresh water. Soil water, which plants can use for uptake and transpiration, is estimated at ~14.1% or 15.78 km³ and is called “green water”. The strategy is to augment the green water with supplemental use of blue or gray water so that plant growth and agronomic productivity can be increased.

The water used for urban and industrial purposes and contaminated by human waste is called gray water. Thus, for safe use, gray water must be treated to denature contaminants and filtered to remove all organic and inorganic pollutants. Use of gray water to supplement blue and green water is a high priority.

The water imbedded in agricultural products (e.g., grains, meat, cheese, cloth) and industrial materials, and thus can be traded across regions or international boundaries is called virtual water. Thus, virtual water is imported and exported along with other produce.

Abbreviations: MRT, mean residence time; WF, water footprint.

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Table 1. World water resources (adapted from Speidel and Agnew, 1982; Shiklomanov, 1993; ICA, 2012).

<table>
<thead>
<tr>
<th>Reserve</th>
<th>Reserve Amount</th>
<th>Total</th>
<th>Percent of Freshwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean</td>
<td>1338.00 km³</td>
<td>96.54</td>
<td>–</td>
</tr>
<tr>
<td>Ice caps, glaciers, permanent snow</td>
<td>24.06</td>
<td>1.74</td>
<td>68.6</td>
</tr>
<tr>
<td>Ground water</td>
<td>23.40</td>
<td>1.69</td>
<td>–</td>
</tr>
<tr>
<td>i. Fresh</td>
<td>10.53</td>
<td>0.76</td>
<td>30.1</td>
</tr>
<tr>
<td>ii. Saline</td>
<td>12.87</td>
<td>0.93</td>
<td>–</td>
</tr>
<tr>
<td>Ground ice and permafrost</td>
<td>0.300</td>
<td>0.022</td>
<td>0.86</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>0.0165</td>
<td>0.001</td>
<td>0.05</td>
</tr>
<tr>
<td>Lakes</td>
<td>0.1764</td>
<td>0.013</td>
<td>–</td>
</tr>
<tr>
<td>i. Fresh</td>
<td>0.091</td>
<td>0.007</td>
<td>0.026</td>
</tr>
<tr>
<td>ii. Saline</td>
<td>0.0854</td>
<td>0.007</td>
<td>–</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.0129</td>
<td>0.001</td>
<td>0.04</td>
</tr>
<tr>
<td>Swamp water</td>
<td>0.01147</td>
<td>0.0008</td>
<td>0.03</td>
</tr>
<tr>
<td>Rivers</td>
<td>0.00212</td>
<td>0.0002</td>
<td>0.006</td>
</tr>
<tr>
<td>Biological water</td>
<td>0.00112</td>
<td>0.0001</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Fig. 1. World water resources (redrawn from data sources listed in Table 1).
Sustainable intensification of agro ecosystems, to produce more from the resources already allocated for agricultural production, implies judicious use of all types of water (blue, green, gray, and virtual), and to maximize the use efficiency of green water.

**GLOBAL WATER CYCLE**

Water on Earth exists primarily in three physical forms: solid (ice), liquid, and vapor. Some water is also bound or absorbed through chemical and physical processes. Water changes from one form into another depending on the temperature, but also from one reservoir into another depending on its use. This process of change in water from one form into another, and exchange in water among principal reservoirs (e.g., land, ocean, atmosphere and plants) is called the hydrologic cycle. Simply put, hydrologic cycle refers to the movement of water in, on, and above the Earth in the form of liquid, vapor, and solid phases. Water is recharged because of continuous recycling, thus flow of water among reservoirs is important to determine the availability of water resources for human consumption. Readers are referred to other reviews (e.g., Trenberth et al., 2007) for detailed understanding of the hydrologic cycle, different pools/reservoirs and fluxes among them.

The principle mode of exchange between land, ocean, and atmosphere is precipitation and evaporation (Fig. 2). Precipitation involves condensation of water vapor as rain, snow, hail, fog etc. Cumulative annual precipitation is estimated at $486 \times 10^3$ km$^3$, of which $373 \times 10^3$ km$^3$ is over the ocean. If all the water in the atmosphere condensed and rained at once on the land, it will be ~2.5 cm (1 in.) of rain.

Evaporation involves conversion of water from liquid to vapor phase and transfer into the atmosphere. Specifically, evaporation from plant surfaces is called transpiration. Total annual evapotranspiration, equal to that of precipitation is $486 \times 10^3$ km$^3$. Of this, $73 \times 10^3$ km$^3$ occurs from land and $413 \times 10^3$ km$^3$ from ocean (Fig. 2). These values are averages, and estimates of precipitation over the land and ocean vary widely (Malinin, 1994; Klige, 1985; UNESCO, 1978). In comparison with the data on precipitation and evaporation presented in Fig. 2, Speidel and Agnew (1982) estimated annual precipitation and evaporation at $111 \times 10^3$ km$^3$ and $71 \times 10^3$ km$^3$ on land vs. $385 \times 10^3$ and $425 \times 10^3$ km$^3$ on ocean, respectively. Other sources of global data on the hydrological cycle include those by Berner and Berner (1987), and Van der Leeden et al. (1990) among others.

The mean residence time (MRT) of water, computed as pool divided by flux, varies widely among pools. From the data in Table 1 and Fig. 2, MRT of water in the atmosphere is 9.5 d ($12,900 \text{ km}^3/486 \times 10^3 \text{ km}^3/\text{yr} = 9.5 \text{ d}$). Accordingly, MRT is 1 to 2 mo for water in soil, 2 to 6 mo in rivers, 50 to 100 yr in shallow ground water and 10,000 yr in deep ground water (deep), 3200 yr in oceans and 20,000 yr in Antarctica (Physical Geography, 2006; Jouzel et al., 2007; USGS, 2008). The projected climate change will accelerate the global water cycle (Huntington, 2005) and, the MRT of different reservoirs will change. The climate system determines the upper limit on the circulation rate of renewable freshwater resources (Oki and Kanae, 2006).

**GLOBAL WATER USE**

Water is the principal indicator for sustainable development and eradication of poverty (Zalewski, 2010). Expectedly, human activities are strongly affecting the global water cycle. Directly, humans affect the water cycle by withdrawing it from different reservoirs for agricultural, urban, and industrial uses (Table 2). Globally, water withdrawal for these uses is estimated at 70% for agriculture, 11% for urban, and 19% for industrial uses (FAO, 2015). Because of the large variation among countries, some withdrawing more than others, the statistics based
on averaging the ratio of each country is 59, 23, and 18 for agriculture, urban, and industrial uses, respectively (FAO, 2015). Only ~1% of the world’s fresh water is accessible for direct human use, and need to be renewed by precipitation. Indirectly, humans also impact water through land use change and alterations in climate through fossil fuel combustion (Rost et al., 2008). Within agricultural activities, the largest withdrawal of blue water (e.g., rivers, lakes, ground water) is estimated at ~2500 km³/yr. In the United States, 40% of the freshwater withdrawal is for irrigated agriculture which contributes more than US$50 billion to the national economy (Rost et al., 2008; Kabat et al., 2002; Vörösmarty and Sahagian, 2000; L’Vovich and White, 1990). Yet, the green water (soil water) is used on the rainfed cropland producing 60 to 70% of the global food (Falkenmark and Rockström, 2004). With increase in food demand, use of both blue and green water is likely to increase (Röckstrom et al., 2008, 2007, 1999; Röckstrom and Gordon, 2001). Total consumption of blue and green water for global food production is ~5000 km³/yr. Similar estimates of global water use provided by ICA are shown in Table 2.

### Table 2. Estimates of global freshwater use withdrawn from rivers, lakes, and ground water (adapted from ICA, 2012).

<table>
<thead>
<tr>
<th>Activity</th>
<th>Percent use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>68</td>
</tr>
<tr>
<td>Domestic and other industrial</td>
<td>19</td>
</tr>
<tr>
<td>Power</td>
<td>10</td>
</tr>
<tr>
<td>Evaporation from reservoirs</td>
<td>3</td>
</tr>
</tbody>
</table>

### WATER SCARCITY

Water is essential for all life, and the demand for this essential commodity is increasing rapidly at regional and global scales. The world population is growing at the rate of ~73 million per year (UNU, 2013). The freshwater withdrawal, which has already tripled since 1965, is increasing at the rate of 64 km³/yr (FAO, 2015). In addition to the demand for food, increase in water demand is attributed to changes in dietary preferences toward animal-based diet and growing production of biofuels.

Consumptive water use refers to the water which is not returned into surface runoff or stream flow, and enters the atmospheric pool through evaporation and transpiration. In contrast, non-consumptive use involves returns to the surface runoff as contaminated water. In addition to blue and green water, the water contaminated after domestic use is called, “gray water.” The processes of water contamination by agricultural fertilizers and plant nutrients are called “eutrophication” and “nonpoint-source pollution”. Human use of grey water and contaminated water can be a serious health hazard. Indeed, 780 million people lack access to clean water (WHO, 2008; UN Water, 2008). More than 2 billion people presently live under highly water-stressed areas (Oki and Kanae, 2006). By 2050, 67% of the world population may live in regions where water is scarce (Wallace, 2000).

It is widely believed that demand of renewable freshwater may drastically exceed its supply, especially in arid and semi-arid regions with high and increasing population. Water scarcity is defined as per capita supplies of <1700 m³/yr (IPCC, 2007). In some cases, water scarcity is also defined when a country or region’s water supply is <1000 m³/capita/yr (ICA, 2012).

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**Fig. 3.** The 3 Is of water security as proposed by Hall et al. (2014).
Table 3. Key aspects of water security.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Access:</td>
<td>To safe and sufficient drinking water at an affordable cost to meet all basic needs.</td>
</tr>
<tr>
<td>2. Protection:</td>
<td>Of livelihoods, human rights, and cultural and recreational.</td>
</tr>
<tr>
<td>3. Preservation and protection:</td>
<td>Of ecosystems in water allocation and values management systems to maintain and enhance ecosystems goods and services.</td>
</tr>
<tr>
<td>4. Water supplies:</td>
<td>For socioeconomic development and activities (e.g., energy, transport, industry, tourism).</td>
</tr>
<tr>
<td>5. Collection and treatment:</td>
<td>Of gray, contaminated and other types of used water to protect human life and the environment, and recycle it for safe reuse.</td>
</tr>
<tr>
<td>6. Collaborative approaches:</td>
<td>National and international levels for equitable and just use of trans-boundary water resources.</td>
</tr>
<tr>
<td>7. Ability:</td>
<td>To cope with risks and uncertainties of water-related hazards (e.g., floods, drought, pollution).</td>
</tr>
<tr>
<td>8. Effective governance and accountability:</td>
<td>With due consideration of interests of all stakeholders.</td>
</tr>
</tbody>
</table>

About 1 billion people live in areas of physical scarcity and other 1.6 billion live in developing countries that lack the basic infrastructure to withdraw blue water from rivers and aquifers (Climate Institute, 2006). Several regions characterized by agricultural intensification are prone to rapid groundwater depletion (Konikow and Kendy, 2005). The vulnerability to climate change may aggravate the water supply (Arnell, 1999; Frederick and Major, 1997; Vörösmarty, 2009; Vörösmarty et al., 2000; Loáiciga, 2003).

Rather than the supply per se, it is also the question of proper management of existing water resources. For example, the region receiving the highest rainfall in the world, Mawsynram in Assam province of India with annual rainfall of ~1150 cm, suffers from drought during the months of low or no rainfall. Similarly, if all the freshwater resources on Earth are equally divided among the world population, the per capita supply of 5000 to 6000 m³/yr (Vörösmarty et al., 2000) is more than three times the required amount of 1700 m³/person/year. The water scarcity is caused by an uneven distribution of renewable freshwater in time and space. Climate change may accelerate the water cycle, and increase the available renewable freshwater supply (Oki and Kanae, 2006). Thus, judicious or sustainable management of water by reducing the current vulnerability is crucial to achieving water security.

**WATER SECURITY**

The variable and unpredictable climate is strongly impacting the hydrologic cycle. Thus, components of the hydrologic cycle (rainfall, runoff, soil moisture, snowmelt) are highly variable and difficult to predict (Hall et al., 2014). Extreme floods and drought, heat waves and cold air are the obvious ramifications of changing climate. Thus, water security is an increasingly growing issue regionally and globally, and is likely to be exacerbated by climate change.

In view of the water scarcity and health concerns in a changing climate, there is also a growing emphasis on ensuring water security. It is defined as “the capacity of a population to safeguard sustainable access to adequate quantities and acceptable quality of water for sustaining livelihoods, human wellbeing, and socioeconomic development, for sustaining protection against water-borne pollution and water-related disasters, and for persevering ecosystems in a climate of peace and political stability” (UNU, 2013). Simply put, water security implies management of the risks associated with extreme variability, and to minimize the stress on the society and the economy (Grey et al., 2013; Hall et al., 2014; IPCC, 2012). Economic (and agronomic) productivity is strongly affected by the hydrologic cycle (Brown and Lall, 2006). Rather than a focus on military risks and conflicts, the term “security” now also encompasses human wellbeing in the context of environmental quality. It is in this context that the terms water security and food security are closely intertwined. Therefore, access to safe and adequate amount of water is important to all inhabitants of planet Earth.

In accord with the concept of food security (FAO, 2006), “water security exists when all people, at all times, have physical and economic access to sufficient, safe, and clean water that meets their basic needs for an active and healthy life.” Thus, four basic tenants of water security are:

i. Water availability: The availability of sufficient quantities of water of appropriate quality.

ii. Water access: Access by individuals and communities to sufficient water (surface and aquifer) through legal, political, economic and social arrangements at local, regional, national and international level.

iii. Utilization and Retention: Utilization of clean water for personal consumption, sanitation, healthcare, food production and processing, and recreational uses.

iv. Stability: To be water secure, a community, household or individual must have access to sufficient and clean water at all times, and not be vulnerable to losing access to water as a consequence of sudden shocks (e.g., an economic, political or climatic crisis) or cyclical events (dry season). The stability encompasses both the availability and access.

Hall et al. (2014) proposed the 3 I’s of water security (e.g., institutions, infrastructure, and information) and suggested that achieving security involves addressing these 3 I’s simultaneously rather than in isolation (Fig. 3). Thus, water security is now an important component of the U.N. Sustainable Development Goals (UNU, 2013). In this context, key aspects of water security are shown in Table 3.

Effective governance and accountability for attaining water security also involves protection and enhancement of natural infrastructure and ecosystems on the basis of a conceptual framework as outlined by UNU (2013). Among three components of water security (Fig. 4), the first and foremost involves fulfilling the physiological needs for drinking and sanitation. The second component is the risk management such as that
against drought, floods, and contamination or eutrophication (i.e., the problem of algal bloom experienced in Toledo, OH, in summer of 2014). The third aspect of water security involves fulfilling all basic needs such as for production of food, energy, recreation etc. (Fig. 4).

VIRTUAL WATER

As discussed above, virtual water is also known as the embedded or embodied water in the produce (e.g., food, biofuel). Thus, virtual water trade refers to the hidden flow of water along with the trade of other commodities from one place (region, country) to another. On average, for example, it takes $1.6 \times 10^6$ L of water to produce 1 Mg of wheat ($Triticum aestivum$ L.). Thus, trade of wheat, rice ($Oryza sativa$ L.), soybean [$Glycine max$ (L.) Merr.], biofuel, and industrial products involves trade in virtual water which must be accounted for. Water-scarce countries import virtual water to meet their basic needs of food, feed, and industrial raw materials.

WATER FOOTPRINT

Water footprint (WF) refers to the amount of water required to produce the goods and services for human consumption. It can be computed at person, community, state, country, or global scale. Hoekstra and Mekonnen (2012) assessed global WF (total of green, blue, and gray water) for the decade between 1960 and 2005 at 7404 Gm$^3$/yr for crop production, 913 Gm$^3$/yr for pasture, 46 Gm$^3$/yr for animal raising, 400 Gm$^3$/yr for industrial production, and 324 Gm$^3$ for domestic supply. Total WF of all production was estimated at 9087 Gm$^3$/yr. Similarly, Hoekstra and Mekonnen (2012) also computed the gross international virtual water flow. Of the total virtual water flow for the decade between 1996 and 2005 at 2320 Gm$^3$/yr, 2038 Gm$^3$/yr was related to trade in agricultural products and 282 Gm$^3$/yr in industrial products. On average, about one-fifth of the global WF in the period from 1996 to 2005 was for export rather than domestic consumption. Evidently, increase in population and the standard of living will increase the WF of all produce and also that of the virtual water. Increase in the trade of virtual water is indicative of the water scarcity at global scale.

CONCLUSIONS

Water scarcity and insecurity are likely to be exacerbated by the climate change, growth in population and affluent lifestyle, and competing uses (e.g., agriculture, urbanization, industry, recreation). Trade in virtual water, involving food and biofuel along with industrial produce, can also adversely impact water security of the exporting countries.

Thus, there are important researchable priorities to address issues pertaining to water security during the 21st century. Important among researchable topics can be grouped under the following categories: (i) food and agriculture, (ii) energy and biofuel, (iii) innovative and non-conventional sources, including the wastewater, (iv) climate change adaptation and management, (v) risk management and governance including water quality, and (vi) measurement, monitoring, and modeling.

Similar to soils, Earth’s water resources are adequate to meet the present and future demands. However, water resources must also be never taken for granted. They must be used, recycled, purified, and restored through science-based policy interventions and governance.

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