“CHAPTER 4”

POPULATION GROWTH ON A FINITE EARTH:

POPULATION MODELS, FOOD AND WATER

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Introduction

Making progress toward sustainable development requires efforts to satisfy the minimum needs of a growing population on a finite earth. Two of the most important basic needs are food and water; it is imperative that we understand the factors influencing our ability to provide these two essentials. Our system of food production and distribution is based on climate, soil characteristics, availability of water, and locations of population centers relative to food production regions, among other factors. In recent decades we have developed the ability to modify some of these factors as well as the food plants and animals themselves, yielding greater productivity per hectare. Our system of water treatment and distribution is based on factors such as the physical, chemical, and biological characteristics of the source water, the desired characteristics of the water for its ultimate use, and the locations of water sources and water use. We need water for domestic purposes, but much greater amounts are needed for agriculture and industry. Furthermore, the global ecosystem upon which our lifestyle is based requires ample water.

Over the years, global society has developed innovative ways of attempting to satisfy these needs. We now have the means of providing for the minimum basic needs of all people on the planet. Yet sizeable fractions of the global population are living under hardship because of the inequitable distribution of resources and the failure of governments to overcome that distribution. Furthermore, there are now so many people relying on the world’s resources that we have begun to alter regional and global systems. Examples include climate change, the ozone hole, loss of species diversity, and desertification. Thus we need to consider changing the current management of the earth’s resources, first to maximize chances that all people today have access to adequate food and water, and second to maximize chances that future generations will also have their basic needs met.

In this handout, we briefly explore such issues in three sections. First, we consider models for global population that enable us to predict possible future growth. We then use this information with data on the available land for farming to estimate changes over time in the amount of agricultural land per capita. Finally, we consider the global hydrologic cycle and consider the influence of human activities on this cycle.
Population

The various ways in which the population affects the environment are functions of many complex factors, such as the spatial distribution of the population across the globe, the age distribution at different locations, lifestyles, rates of growth, and rates of decline. Here we deal only with the very simplest of these factors, focusing on the change of total number of people in the industrialized world and in developing countries. In this section, we begin by modeling the global population using mass balance techniques. We then consider modifications of the mass balance equation to account for limited availability of food, and finally examine separate birth and death rates in industrialized and developing countries.

Application of Mass Balance Concepts to Model Global Population

We can estimate changes in population over time using a mass balance (or in this case a “number balance”) by considering the earth as a reservoir with input and output flow rates. As illustrated in Figure 1, the input flow rate to the reservoir is number of births per year, while the output flow rate is number of deaths per year. The time rate of change of the global population N is thus equal to $Q_{in} - Q_{out}$, where $Q_{in} = k_{fertility}N$ and $Q_{out} = k_{mortality}N$. The parameters $k_{fertility}$ and $k_{mortality}$ are first order rate constants (in $\text{year}^{-1}$) for births and deaths, respectively. Note that $k_{fertility}$ is defined as the annual fractional change in global population due to births, while $k_{mortality}$ is defined as the annual fractional change in global population due to deaths. We can further write $r = k_{fertility} - k_{mortality}$, where $r$ is the rate constant for overall population change, also called the intrinsic growth rate.

![Figure 1](image_url)  
Figure 1. The earth can be modeled as a reservoir containing $N(t)$ people with the number of births/year equal to $Q_{in}(t)$ and the number of deaths/year equal to $Q_{out}(t)$.

Based on these definitions, the equation for global population is:

$$\frac{dN}{dt} = Q_{in} - Q_{out} = k_{fertility}N - k_{mortality}N = rN \quad (1)$$

The solution to Equation 1 is:
where \( N_0 \) is the population at \( t = 0 \). Since \( r \) has units of year\(^{-1}\), the reciprocal of \( r \) is a measure of time and in fact has physical significance. We define \( r^{-1} \) as the residence time \( \tau \), so we can rewrite Equation 2 as:

\[
N(t) = N_0 \exp \left( \frac{t}{\tau} \right)
\]

This implies that the population increases by a factor of Euler’s constant \( e \), approximately 2.718, for every time period of \( \tau \) years. Note that the population will increase slowly at first, but will eventually reach extremely high rates of growth due to the exponential increase. This is a consequence of initially small numbers of people each having several children, and each of those children in turn has more children. By the time great-great-grandchildren have their own kids, the rate of population increase is large compared to what it was at the beginning.

Equation 2 was first publicized by Thomas Malthus in 1798 in England. Malthus believed there was a fundamental mismatch between human population growth and the increase in production of food (Kormondy, 1996, pp. 388-389). The amount of food available can increase over time due to improving methods of production, according to Malthus, and this increase progresses arithmetically. In contrast, the population increases geometrically (that is, exponentially) as in Equation 2. Thus food production can never keep pace with population growth, and human numbers will have to be kept down by famine, war, and disease. In theory, Malthus’s conclusion is independent of the value of \( r \) and also independent of the arithmetic relationship describing food production. As long as one relationship is geometric and the other is arithmetic, the former will eventually overtake the latter.

In opposition to Malthus’s writings, early scientists had observed that populations of insects, although increasing exponentially at first, did not continue to increase according to Equation 2 – if they did, there would not be room for all the insects that have been produced over time. Rather, there was something that mitigated the exponential growth. In fact, Malthus stated in 1830 that there was a “density dependence” where increasing population density would prevent unlimited exponential growth (Vandermeer and Goldberg, 2000, p. 11). This concept was quantified in 1838 when P.F. Verhulst proposed the “true law of population” (Vandermeer and Goldberg, 2000, p. 11; Kormondy, 1996, p. 200-201). This is now called the “logistic equation,” and although there are inaccuracies in it, the equation has been used extensively.

The Logistic Equation

We begin by assuming that Equation 1 is valid only for small population densities. If food is a limiting factor governing population growth, then instead of Equation 1, we write:
\[ \frac{dN}{dt} = b F N \]  \hspace{1cm} (4)

where \( b \) is the number of births minus deaths per person per unit of food consumed by an individual, e.g., in kg\(^{-1}\), and \( F \) is the amount of food production capacity remaining, e.g., in kg/year, after the land has been used to produce food for the current population. Note that \( b \) is a constant which depends on the relation between food intake and health of an individual (as health affects the birth rate and death rate), while \( F \) decreases with time as an increasing number of people consume more kg/year. If \( F_T \) is the maximum possible food production from all available land in kg/year and \( c \) is the amount of food eaten by one person per unit time, e.g., kg/(person year), then we can write:

\[ F = F_T - cN \]  \hspace{1cm} (5)

so that Equation 4 becomes:

\[ \frac{dN}{dt} = b (F_T - cN) N \]  \hspace{1cm} (6)

This equation can be written in the form:

\[ \frac{dN}{dt} = b F_T N \left( \frac{F_T - N}{c} \right) \]  \hspace{1cm} (7)

The term \( F_T/c \) represents the maximum number of people that can be supported by the available food production, and it is called the “carrying capacity” of the environment. Ecologists often denote it by \( K \), so we can rewrite Equation 7 as:

\[ \frac{dN}{dt} = b F_T N \left( \frac{K - N}{K} \right) \]  \hspace{1cm} (8)

Since the intrinsic growth rate \( r \) is simply equal to \( b F_T \), we can rewrite Equation 8 as:

\[ \frac{dN}{dt} = r N \left( \frac{K - N}{K} \right) \]  \hspace{1cm} (9)

The right side of Equation 9 contains the original exponential growth term \( rN \), multiplied by a correction factor \((K-N)/K\) that accounts for the increased resistance to population growth as the carrying capacity of the environment is neared. In the limit where \( F \) approaches 0, \( N \) becomes close to \( K \) and hence \( dN/dt \) approaches 0. In Homework 3, you are asked to determine the solution to this differential equation and use it in two cases. Several authors have discussed various derivations of the logistic equation. For
examples, see Vandermeer and Goldberg (2000, pp. 16-18), and Masters (1998, pp. 93-95).

Separation of Birth and Death Rates

Thus far, we have considered only the net increase in population determined by the number of births minus the number of deaths. In fact, technology has changed both of these variables, and understanding human population growth requires considering them separately and comparing them.

Figure 2 shows the birth and death rates in industrialized countries for the years 1775-1990, using data from the United Nations and Population Reference Bureau (see Kormandy, 1996, p. 396). The distance between the two curves represents the net population growth in any year, expressed as a fraction of the total population. The distance is slightly decreasing throughout the time period, ranging from a maximum of 0.01 near 1800 to 0.006 in 1990, suggesting that the net increase in population over the past 200+ years has been roughly 0.6% to 1% per year in the world’s industrialized countries. This is only slightly greater than population growth worldwide prior to the industrial revolution, e.g., 0.3% per year in 1650 (Meadows et al., 1972, p. 41), when death rates were much higher due to primitive medical techniques.

Figure 3 shows the birth and death rates in developing countries for the same years as Figure 2, taken from the same data source. A very different picture is apparent: the birth rate was constant at slightly more than 0.04 births per person per year until around 1930, after which the rate decreased slowly to about 0.03 in 1990. The death rate was in the range of 0.034-0.038 deaths per person per year until 1900, when it started dropping precipitously to its 1990 value of 0.010 deaths/year, about the same as in industrialized countries. How should these Figures be interpreted?

Figure 3 shows that the rapid rate of population increase in the developing world is not due to skyrocketing birth rates. Rather, the birth rates are actually decreasing. The problem of rapid population growth occurs mainly because better medical technology around the world is reducing the death rate. Unfortunately, the birth rate is decreasing far more slowly than the death rate, and thus the distance between the two curves in Figure 3 is increasing. This also shows why population control is so difficult: in many countries, a large family is preferable to help with the work that needs to be done, especially in subsistence farming. As farming becomes less productive due to depletion of nutrients in the soil, even more work must be done to obtain enough food. In the next section, we will consider the amounts of land needed to grow this food as well as models for nonrenewable resources.

We saw above that the logistic equation produces a more realistic prediction of population versus time compared with the classic exponential curve. This is because it accounts for factors that limit the population, such as availability of food, expressed as the carrying capacity $K$. We now consider global food production as a variable in its own right.
Food Production

Although there have been several arguments against Malthus’s stated growth laws, there is nevertheless a serious concern that food production may be a limiting factor as the world population grows. In fact, one challenge is maintaining a balance between keeping the world fed today and preserving the world’s ecosystems for food production in future generations.

*Unsustainable Practices*

The world contains about 3.2 Billion hectares of arable land which can support the growth of food crops (President’s Science Advisory Panel on World Food Supply, 1967). Roughly half of that land was being cultivated in 1970, with the other half being less accessible and requiring substantial investments before farming. Several reports reached the conclusion that the less accessible land would not be economically viable to use for
food production, despite food shortages in some areas of the world (e.g., UN Food and Agricultural Organization, 1970).

![Birth and Death Rates in Developing Countries](image)

Figure 3. Birth and death rates in developing countries as a function of year for 1775-1990 (data from United Nations and Population Reference Bureau, see Kormondy, 1996, p. 396).

We can define \( A(t) \) as the land area used to produce food for the world’s population at time \( t \). If the global population is \( N(t) \), then we can define \( \alpha(t) \) as the land area per capita used to produce food for the world’s population, given by the expression \( \alpha(t) = A(t)/N(t) \).

Let us consider two scenarios for food production as the population grows. In the first scenario, we assume that the land area per capita for food production \( \alpha \) remains constant as the population rises. Thus the total land area \( A(t) \) increases in exact proportion to \( N(t) \) until all arable land is used. This situation is illustrated in Figure 4, which shows an exponential increase in \( A(t) \). This estimate does not account for the decrease in arable land as population increases, since more land is needed for expanding cities. Figure 4 indicates the results of one calculation suggesting that the loss can reach nearly half of the total arable land by the middle of the 21st century. The food problem thus becomes a
“double edged sword” as a growing population needs more food from a decreasing amount of land. In the second scenario, we assume that the area of land used for food production cannot expand above 1.6 Billion ha. This implies A is a constant while $\alpha(t)$ decreases with time due to improvements in the technology related to food production. Both of these scenarios have been considered in class.

![The World's Total Arable Land](image)

Figure 4. The amount of arable land in the world as a function of time (redrawn from Meadows et al., 1972, p. 60).

Another major requirement for food production, in short supply second only to arable land, is fresh water (Meadows et al., 1972, p. 62-63). In many areas of the world where food production is dominant, water is the limiting factor ahead of availability of land. The world’s largest water irrigation project at the time it was developed, the Central Valley Project in California, brought huge amounts of water to agricultural lands in the state, producing over a fourth of the fruits and vegetables consumed in the country for many years. This was done after farms had used most of the groundwater in the region, destroying wetlands and drying up lakes and streams (Reisner, 1993).

Related to the amount of land available for farming is the use of chemicals to boost productivity. Farmers in the U.S. used roughly 20 million tons of fertilizer per year in the early 1990’s, roughly triple the amount used in 1960 (Environmental Alamanc, 1994, p. 173). The increase has been attributed in part to poor soil management that allows the topsoil to erode, as well as to farming policies that provide greater subsidies when
farmers continue growing one type of crop rather than rotating crops to replenish the soil. Subsidies are also related to the crop yield, which encourages growers to use fertilizer for higher production rather than to adopt techniques that conserve the soil nutrients (p.172).

The Food and Agricultural Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) conducted a study in the 1980s of global food production using land characteristics and climatic data. Three types of agriculture were assumed: (1) low technology with traditional crops, no soil conservation, and no fertilizer or chemicals, (2) intermediate technology in crop selection, soil conservation methods, and fertilizers/chemicals, and (3) high technology in all of these topics. Based on projected populations in the year 2000 and no food imports or exports, results show that low technology agriculture results in food shortages in 64 developing countries with a combined population of 1.1 Billion. If high technology food production is assumed, 19 countries with a population totaling 100 Million cannot produce enough food for their population, but these are mainly small West Asian countries and Pacific Island nations that have sufficient foreign exchange to purchase their food. Taken as a group with imports and exports allowed, the 117 developing countries in the study are able to produce enough food for 1.5 times their overall population even with low technology; the inequities result from considering the countries separately. The study notes that current global average consumption of plant energy for food, seed, and animal feed is about 6000 calories/day. This implies a global carrying capacity of 11 Billion people with the current number of malnourished people around the world. If plant energy consumption is assumed to be 9000 calories/day, resulting in better nourishment for the world’s population, the global carrying capacity is only 7.5 Billion people (WCED, 1987, pp. 98-99).

Application of other chemicals is also increasing: herbicide and pesticide use increased by 64% between 1964 and 1991 in this country (p. 173), in part due to increasing resistance to the chemicals. According to the Environmental Almanac (1994, p. 182), nearly 275 species of weeds and 500 species of insects had become resistant to chemicals by the early 1990’s. Despite the increase in chemical use, farmers lost more crops to pests at that time than in the 1940’s. Pimentel (1989) reports that insect damage to crops has risen from 7% to 13% since 1945 despite a ten-fold increase in pesticide use. Furthermore, data collected by the U.S. EPA show that a large fraction of fruits and vegetables contain pesticide residues. Figure 5 indicates the fraction of food crop samples analyzed by EPA that contain traces of pesticides during 1990-1992.

Agriculture in some developing countries is even less sustainable than in the U.S., mainly due to poor soil management that promotes erosion of topsoil and loss of nutrients. At some locations, land is being deforested to provide for agriculture. Unfortunately, many of the soils are of such poor quality that productivity will be low, and in fact deforestation in these areas can lead to desertification. Because the populace is so short of food, individuals cannot consider the effects of their actions on future generations – recall the argument of the World Commission on Environment and Development that poverty is one of the principal causes of unsustainable lifestyles.
Figure 5. Pesticide residues in several types of fruits and vegetables for samples obtained in 1990-1992 (EPA data, cited in *Environmental Almanac*, 1994, p. 175).

The current practice of shipping food around the world is expensive in terms of energy and materials, and transportation of refrigerated or frozen foods adds to the energy penalty. Furthermore, food packaging uses substantial amounts of non-biodegradable materials made from nonrenewable sources. In the face of statistics showing a bleak future, are there ways to change food production and distribution to enable more sustainable practices?

**Sustainable Agriculture**

Within the past few years, the U.S. Department of Agriculture has established the National Organic Program. This program regulates food production so that consumers can choose between food produced with unsustainable practices and that produced using established standards promoting sustainability. Examples of the standards for food to be labeled as “Organic” include the following (U.S. Department of Agriculture, 2003):

- The soil must be managed using tilling methods, crop rotations, application of plant and animal materials (e.g., compost), and cultivation practices that maintain
or improve soil conditions. This includes physical, chemical, and biological conditions.

- There must not be any prohibited substances used on the land within three years of planting new crops. These substances include most synthetic chemicals and a variety of toxic natural substances.
- Insect pests can be controlled only through practices such as introduction of predators of the pest species, development of habitats for natural enemies of the pests, or nonsynthetic controls such as lures, traps, and repellents.
- Weeds can be controlled only through practices such as mowing, livestock grazing, hand weeding, and certain synthetic mulches as long as they are removed from the field at the end of the season.
- Livestock must be managed by organic methods, such as using only organically produced feed and avoiding use of drugs such as hormones to promote growth. Livestock living conditions also must follow prescribed standards.

Additional practices to make agriculture more sustainable have been discussed by the National Research Council (1989), where it is claimed that use of natural methods to control weeds and insect pests can be profitable even in the absence of government subsidies.

David Orr (1992, p. 178) argues that the entire system of farming must be transformed to promote sustainable principles. He points out that making the transition is likely to be extremely difficult: there are questions about whether there will be enough farmers willing to go to great lengths to ensure sustainable practices. Orr also argues that it will be difficult to make changes in farming if the rest of society continues living unsustainably, and that such changes will be especially problematic at a time when ecosystems are changing due to species loss, climate change, and other factors. Nevertheless, the transition is vital and taking steps now can be the best preparation for later challenges.

**Water**

Kofi Annan, Secretary-General of the United Nations, notes that if present water consumption patterns continue, two out of every three people on Earth will live in water-stressed conditions by 2025. In a similar vein, Mikhail Gorbachev writes that the world contains 261 international water basins, all of which require a system of conscious, effective interdependence to solve their transboundary water problems. Madeleine Albright, former U.S. Secretary of State, discusses her report “An Alliance for Global Water Security for the 21st Century,” which stresses impending water shortages and calls for a new strategy for managing the world’s water resources (Gorbachev, 2000).

Indeed, access to water is considered by some leaders to be the world’s most pressing problem (Gorbachev, 2000). One-sixth of the world’s population lacked access to improved water supplies in the year 2000, and 40% lacked access to sanitation facilities. In this same year, the Second World Water Forum in the Hague, Netherlands, set a target of reducing the fraction of the world’s population without access to safe water by 50% by
2015, and reducing the fraction of the population without sanitation facilities by 50% by 2015. This would require providing water supply services to 280,000 people and sanitation services to 384,000 people each day over the fifteen-year period (GWSSA, 2000). Much of the need for these services is in urban areas, where water use is greater than in rural locations. Sheehan (2003, p. 131, footnote 4) writes that about 60% of the global water use by people supports urban populations; about half of this is for irrigation of food crops for urban residents, a third is used by city industries, and a sixth is for urban residential use such as drinking and sanitation. Meeting the goals of the 2000 World Water Forum will require unprecedented cooperation between the private and public sectors, as noted by the World Business Council on Sustainable Development (2002). Nevertheless, work is underway to improve access to safe water in poor areas of Africa and Asia, and progress is being made.

In this section, we focus on research by Postel et al. (1996) who have studied the influence of human activities on the global hydrologic cycle. Such work can lend insight into reasons for the current water problems and how to solve them. The goal of this effort is to estimate the fraction of fresh water available to people that is already being used for human activities. All values below pertain to the year 1990 and are taken from Postel et al.

Figure 6 shows the basic flows in the hydrologic cycle. ET is “evapotranspiration”, which is a combination of evaporation and transpiration. The latter refers to the uptake of water by plants and its subsequent release into the air. Runoff includes all streams, rivers, lakes, and groundwater flow, which is where people usually obtain water.

![Hydrologic Cycle Diagram](Image)

Figure 6. Approximate water flows for the earth’s hydrologic cycle (after Postel et al., 1996). All values are in km³/year. We use more precise values in the calculations below.

To determine the impact of human activities on this cycle, we examine a method for estimating the fraction f:
To estimate the numerator, we examine water use in several categories. The first is water withdrawn from runoff for a number of purposes, including irrigation for agriculture, industrial water use, municipal water, and evaporation from reservoirs. Then we consider instream use, where runoff is used but not withdrawn. Examples include waterways used for navigation, recreation, and fishing. Finally, we examine the natural precipitation-evapotranspiration cycle for human activities focusing on non-irrigated agriculture, grazing land, managed forest land, and lawns.

To estimate the denominator, we note that not all freshwater on the planet is readily available due to a highly uneven distribution, both spatially and temporally. Some of the largest rivers are located in areas of relatively small population, while precipitation at times is so great that it causes flooding, resulting in damage rather than utility. We now consider each category in the numerator of Equation 10, and then estimate the value of the denominator.

**Water Withdrawn from Runoff**

1. The total amount of irrigated farmland is 0.24 Billion hectares, with an average of 12,000 m$^3$ water needed per hectare. Thus the total worldwide irrigation needs are 2880 km$^3$.
2. Global industrial water use is 975 km$^3$.
3. Global municipal water for domestic and civic use is 300 km$^3$.
4. Evaporation from reservoirs is assumed to be 5% of the total worldwide storage capacity of 5500 km$^3$, or 275 km$^3$.

Thus the total water withdrawn from runoff for human use is 4430 km$^3$.

**Instream Water Use**

Water used in navigation channels and for recreation is assumed to have certain standards for cleanliness. Postel et al. used dilution of polluted water as a proxy for the amount of water needed for instream use, based on the widely accepted dilution flow rule-of-thumb. That rule states that the municipal and industrial waste from each 1000 people must be diluted by 28.3 liters/sec of fresh water to reach acceptable cleanliness. Using the global population of 5.26 Billion in 1990, the total amount of dilution water needed is 4700 km$^3$ per year. It is assumed that one half of the world’s population has at least secondary treatment for its sewage and industrial wastewater, so the final value is 2350 km$^3$.

**Evapotranspiration**

The fraction of land-based precipitation that is appropriated for human activities can be estimated by considering the portion going to evapotranspiration by plants, and then identifying the fraction of total global plant biomass used by people. The worldwide
growth of plant biomass, termed Net Primary Productivity by ecologists, amounts to 132 Billion mt (metric tons) per year. From Figure 6 we see that approximately 70,000 km$^3$ of precipitation is evapotranspirated each year; a more precise figure is 69,600 km$^3$, equivalent to 69,600 x 10$^9$ mt of water. Thus we can estimate the amount of water needed to produce each unit of biomass as:

$$\frac{\text{Water used for plant biomass growth}}{\text{Plant biomass}} = \frac{69,600 \times 10^9 \text{ mt}}{132 \times 10^9 \text{ mt}} \approx 500 \frac{\text{mt water}}{\text{mt biomass}} \quad (11)$$

Thus growing one unit mass of plants requires 500 times that mass in fresh water.

The amount of global biomass produced by agriculture is about 15 x 10$^9$ mt, which requires 7500 x 10$^9$ mt of water according to Equation 11. But we learned above that 2880 km$^3$ water, or 2880 x 10$^9$ mt, are used for irrigation. We assume that 880 x 10$^9$ mt are recycled, leaving 2000 x 10$^9$ mt that must be subtracted from the total agricultural water use to obtain the amount of natural precipitation appropriated by agriculture. Thus the final value is 7500 x 10$^9$ mt – 2000 x 10$^9$ mt = 5500 x 10$^9$ mt of natural precipitation which is evapotranspired by the world’s agricultural plants.

A total of 11.6 x 10$^9$ mt of biomass is produced on land for grazing cattle and other domesticated animals, requiring 5800 x 10$^9$ mt of water. Similarly, a total of 13.6 x 10$^9$ mt of biomass is produced in forests managed for human use, requiring 6800 x 10$^9$ mt of water. Finally, there are 0.4 x 10$^9$ mt of biomass in lawns, which also includes grass in parks, golf courses, and other landscaped areas. If we assume half of this biomass is irrigated, we obtain 100 x 10$^9$ mt of natural precipitation needed for lawns worldwide. The amount of natural precipitation evapotranspired by plants for human use is therefore the sum of precipitation for nonirrigated agriculture, grazing plants, managed forests, and lawns for a total of 18,200 x 10$^9$ mt, or 18,200 km$^3$ of water.

Water Available

The denominator of Equation 10 is derived from the sum of two components. The first component is called accessible runoff or AR. This component is determined as follows. We know that only part of the total runoff is in the base flow of rivers and groundwater and thus sufficiently well controlled so it can be used by people. The rest is mainly floodwater, some of which is behind dams. Besides the base flow of rivers and groundwater, a portion of the floodwater regulated by dams can also be used by people. We use the term temporally accessible water to describe the total global base flow of rivers and groundwater as well as that portion of the dammed floodwater used by people. The total amount of temporally accessible water is illustrated as a dark gray rectangle in Figure 7. Furthermore, we know that only part of the total runoff is close enough to populated areas so it can be used by people, and we term this spatially accessible water. This is shown as a light gray rectangle in Figure 7. Water that is both temporally accessible and spatially accessible is termed AR, pictured as the intersection of the two
rectangles in Figure 7. Note that AR includes the area above the dotted line (dammed floodwater) and below the dotted line (base flow of rivers and groundwater).

The second component in the denominator of Equation 10 is the evapotranspirated water, or ET. We assume that all ET for land biomass is accessible to people as an upper limit to the amount of water we could actually co-opt, since data of sufficient accuracy are not available to calculate biomass in populated versus remote areas. This will provide a conservative estimate of the fraction designated by Equation 10, giving a lower limit for the fraction of available water used by people in 1990.

Figure 7. Diagram illustrating the components of total runoff. The full white rectangle \((x_3 \text{ by } y_3)\) represents the total global runoff. The light gray rectangle \((x_2 \text{ by } y_2)\) represents the spatially accessible runoff, excluding the spatially inaccessible water. The dark gray rectangle \((x_3 - x_1 \text{ by } y_1)\) represents the temporally accessible runoff, excluding floodwater. The portion of total runoff that is not within the light gray or dark gray rectangles is runoff that is neither spatially accessible nor temporally accessible. The intersection of the light gray and dark gray rectangles \((x_2 - x_1 \text{ by } y_1)\), which includes runoff that is spatially as well as temporally accessible, is known as accessible runoff, or AR. Spatially accessible runoff outside of the dark gray rectangle is floodwater near populated areas. Temporally accessible runoff outside of the light gray rectangle is base flow of rivers and groundwater far from populated areas.
We now compute the value of Accessible Runoff AR, beginning with a more precise figure for total runoff of 40,700 km$^3$/year. Of this amount, 27% of the total, or 11,100 km$^3$, is the base flow in rivers and groundwater. The remaining 29,600 km$^3$ is floodwater.

To estimate the amount of temporally accessible water, we first look at the fraction of the 29,600 km$^3$ of floodwater that is captured. The total storage capacity of the world’s dams is 5,500 km$^3$, out of which 3,500 km$^3$ is regulated for human use. The value of 3,500 km$^3$, represented by the dark gray area above the dotted line in Figure 7 (x2 – x1 by y1-y0), is added to the 11,100 km$^3$ of base flow to arrive at 14,600 km$^3$ for the total temporally accessible water.

To estimate the spatially accessible water, we consider the largest river systems. The system with the greatest flow is the Amazon Basin, which contains 5,670 km$^3$ of water or roughly 14% of the world’s runoff. But only 0.5% of the global population lives in the Amazon Basin. Even with future development, the amount of water there is so massive that the quantity used for human needs will not be greater than 5% of the total, according to Postel et al. We thus assume that 95% of this water, or 5,387 km$^3$, is spatially inaccessible.

The second largest river system is the Zaire-Congo in Africa, with a total flow of 1,324 km$^3$. Only 1.3% of the world’s population lives in that watershed, which contains 3.3% of the global runoff, so we assume that roughly one-half of this water is spatially inaccessible, or 662 km$^3$.

There are a total of 1,815 km$^3$ of river water in remote areas of North America and Eurasia. This water is assumed to be 95% spatially inaccessible, for a value of 1,725 km$^3$. All other water in the world’s river systems is considered to be spatially accessible. The total spatially inaccessible runoff is thus the sum of 5,387, 662, and 1,725 km$^3$, or 7,774 km$^3$. This value includes both base flow and floodwater.

Some of the 11,100 km$^3$ is in remote areas, so not all of it is accessible. We assume that the ratio of base water flow to total runoff is the same in remote areas as in populated areas. Thus we apply the value of 27% to the remote water flow of 7,774 km$^3$ above, and obtain 2,100 km$^3$ of base flow in remote areas. We see that 11,100 km$^3$ – 2,100 km$^3$, or 9,000 km$^3$ of the base flow is spatially accessible. When added to the 3,500 km$^3$ of spatially accessible floodwater, we obtain the total accessible runoff as AR = 12,500 km$^3$.

Computing the fraction of global water used for human consumption

The values in each category above can now be used to estimate the fraction of total available water flow f that is used by people worldwide:

\[
f = \frac{\text{Water used by people}}{\text{Water available to people}} = \frac{4430 \text{ mt} + 2350 \text{ mt} + 18,200 \text{ mt}}{12,500 \text{ mt} + 69,600 \text{ mt}} = 0.304
\]

(12)
Thus 30.4% of the available water flow in the global hydrologic cycle is being used for human needs as of 1990. As noted earlier, this figure is conservative in that all evapotranspirated water is assumed to be available; the true fraction may be greater than 0.304 but is difficult to calculate. The remaining 69.6% is used by the land ecosystems of the world for their nourishment. Postel et al. (1996) note that by 2025, it is possible that over 70% of the accessible runoff may be co-opted by human activities, resulting in significant stresses to ecological functioning. It is clear that efforts are needed now to safeguard the limited amount of fresh water available for human and ecosystem use.

References


