1

Renewable Resources and Environmental Quality

Sun sustains every life on Earth.

OBJECTIVES

To present renewable energy such as solar, biomass, and wind
To quantify hydrological, carbon, oxygen, nitrogen and phosphorus cycles
To provide unit data on human demand and footprints
To quantitatively describe the uncertainty of the carrying capacity of Earth by using SPSS
To calculate C, N, P, water, energy, and ecological footprints
To define nine planetary boundaries
To explain peak oil and phosphorus in terms of mineral depletion
To calculate air, water, and soil quality indexes

1.1 Renewable Resources and Energy

Free water and energy have sustained human life on Earth in the past million years because water can be harvested from the sky and energy can be produced from solar, biomass, and wind. Since the Industrial Revolution in 1781, however, nonrenewable fossil energy such as coal, oil, and natural gas has become the major power source for human economic activities. For example, environmental engineering infrastructure system (EEIS) such as centralized water treatment plant (WTP) and wastewater treatment plant (WWTP) are mostly powered by fossil fuels and have become symbols of modern life. Due to the economy of scale, centralized EEIS was designed to fit for all because unit cost of water and wastewater produced decreases with the increasing plant capacity. As EEIS ages, however, maintenance becomes more and more expensive. Under climate change and sea level rise, retrofitting existing WWTP may cost more than building new plants. For example, Miami-Dade Water and Sewer Department (MD WASD) plans spend \$6 billion dollar to increase resiliency of three WWTPs with total average flow rate of 300 MGD in next 20 years which could be much more expensive than building new plants within the same budget.

Currently, the average electricity compositions in the United States contributed by coal, natural gas, nuclear, and renewables are 33, 33, 20, and 14, respectively. Among the other renewable energy sources, wind, biomass, solar, and geothermal energy consist of 4.7, 1.6, 1.0, and 0.4% of the total energy portfolio, respectively. Oil provides almost 100% of transportation energy. Solar energy is the only primary energy continuously arriving on Earth at a rate of 1361 W/m^2. Each day, about 174 peta-watts (10^{15} W) of sunlight hits the planet Earth. Assuming Earth to be a black body, its mean temperature without the greenhouse effect can be estimated from Example 1.1.

Example 1.1 Earth's radius $R = 6.37 \times 10^6$ m, solar constant at the average radius of Earth's orbit around the sun $S_o = 1363\ \text{W/m}^2$, the global fraction of incoming solar radiation that is reflected as the albedo constant, $\alpha_p = 0.3$.
Find: The mean global temperature without global warming gas.

Solution:

If the average global ***albedo*** is α_p,

$$\text{Absorbed energy flux per m}^2 = Q_{\text{abs}} = \frac{S_o \pi R^2 \left(1 - \alpha_p\right)}{4\pi R^2}$$

$$\text{or} \quad Q_{\text{abs}} = \frac{S_o}{4}\left(1 - \alpha_p\right)$$

Sustainable Environmental Engineering, First Edition. Walter Z. Tang and Mika Sillanpää.

At the equilibrium climate, the amount of solar radiation absorbed must be balanced by the emission of terrestrial radiation by the planet at the global mean:

$$Q_{\mathrm{abs}} = Q_{\mathrm{out}}$$

where Q_{out} is the longwave radiation emitted by Earth.

Assuming that Earth is a black body, then its equilibrium emission temperature can be estimated from the Stefan–Boltzmann law:

$$Q_{\mathrm{abs}} = \sigma T_{\mathrm{E}}^4$$

where σ is the infrared energy that Earth will emit per unit area, $5.670373 \times 10^{-8}\ \mathrm{W/m^2\,K^4}$ (m = meters, K = Kelvin), which is referred as the Stefan–Boltzmann constant.

At the equilibrium, the incoming solar energy equals the energy emitted by Earth:

$$\sigma T_{\mathrm{E}}^4 = \frac{S_{\mathrm{o}}}{4}\left(1 - \alpha_{\mathrm{p}}\right)$$

Answer: $T_{\mathrm{E}} = 255\ \mathrm{K}$

Comments: 255 K is the equilibrium emission temperature of Earth and would also be the equilibrium global mean surface temperature if Earth did not have an atmosphere. In other words, the average Earth temperature should be −19.5 °C (−3.1 °F). However, because of the greenhouse effect of the atmosphere air such as CO_2, the actual Earth average global temperature is about 14 °C (57 °F).

Mankind has been working on technologies of renewable energy since the onset of the Industrial Revolution. Table 1.1 lists the history of renewable energy and the associated technologies to deliver them.

Since all the EEIS needs energy to operate, many roadmaps of renewable energy have been proposed. Table 1.2 shows that the United States, European Union, and China are targeting 20% renewable energy by 2020. By 2050, 50% of the world energy will be renewable and 100% of the world energy will come from renewables by 2090.

Regardless which route of the roadmap, EEIS design should anticipate the change of energy composition and contribute positively to decouple economic development from deteriorating environments by renewable energy to substitute fossil fuels such as coal, oil, and gas. One way to achieve this is to produce energy from WWTPs. If all the WWTPs in the United States can be retrofitted to energy-positive water resource recovery facility (WRRF), about 3% of total electricity produced in the United States could be saved. SEE is to help

Table 1.1 History of commercial renewable energy.

Year	Goal
200 BC	Vertical waterwheels powered mills to crush grain, full cloth, tan leather, smelt and shape iron, saw wood, and carry out a variety of other early industrial processes
100 AC	Vertical carousel-type mills utilized the wind to grind corn and to raise water from streams to irrigate gardens. Their use soon spread to India, other parts of the Muslim world, and China, where farmers employed them to pump water, grind grain, and crush sugarcane
1590s	The Dutch built windmills for multiple uses to their fullest scale to ground the grain produced on the rich meadows and to saw wood
1830s	In 1860, thousands of distilleries churned out at least 90 million gallons of alcohol per year for lighting in the United States
1850s	The windmill became a popular water pumping tool for home and rail builders
1860	First solar power system developed in France to produce steam to drive machinery
1876	First demonstration of generating electricity directly from sunlight in a selenium solar cell
1882	First commercial-scale hydroelectric plant went into operation in Appleton, Wisconsin
1888	First windmill to generate electricity developed in Cleveland, Ohio
1892	World's first geothermal district heating system built in Boise, Idaho
1921	World's first geothermal power plant built in California
1927	First commercial wind turbines sold to generate electricity on remote farms
1935	Hoover Dam, the world's largest hydroelectric power plant, was built
1953	First silicon solar cell developed at Bell Laboratories
1960	General Electric (GE) developed hydrogen fuel cells to generate electricity for Apollo and Gemini Space missions
1960	First commercial-scale geothermal electric plants in the United States built in California
1970s	Solar cells began to lower in price and became cost-effective for use on land
1978	World's first solar-powered village; Tohono O'Odham Reservation, Arizona
1980	World's first wind farm built in New Hampshire
1981	Solar One: first large-scale solar thermal power plant began operation in Daggett, California
2008	First commercial cellulosic ethanol plant went into production in Wyoming
2014	World's largest concentrated solar power generation plant went online in Ivanpah, California

Source: http://alternativeenergy.procon.org/view.timeline.php?timelineID=000015 (accessed 25 September 2016).

Table 1.2 Renewable energy roadmap.

Year	Goal
2018	100% of US electricity comes from solar, wind, and other renewables (Gore's prediction) $255 billion spent per year (more than four times what is currently spent) on biofuels, wind power, solar photovoltaics, and hydrogen fuel cells, according to market research firm Clean Edge $150 billion invested by this date by the US government on climate-friendly energy development (Obama's plan)
2020	All new cars are hybrids, according to an anonymous survey of car industry executives by IBM Institute for Business Value 35 miles/gal is average for the US fleet 20% of the European Union's energy comes from renewables 15% of China's energy comes from renewables
2022	36 billion gallons of biofuels sold in the United States, up from 4.7 billion gallons in 2007
2030	50% increase in world energy demand from 2005 levels, according to the US Department of Energy (DOE) All new federal buildings are carbon neutral, as stated in the 2007 Energy Act 70% of Hawaii's energy comes from renewables, thanks in part to a ban on new coal plants One-fifth of US power comes from wind, the DOE predicts One-fourth of US workers wear a green collar, according to the American Solar Energy Society 20 million new jobs created by renewable industry according to a United Nations report
2050	50% of the world's energy comes from renewables, as claimed by the Energy [R]evolution Report
2090	100% of the world's energy comes from renewables, as claimed by the Energy [R]evolution Report

Source: http://alternativeenergy.procon.org/view.timeline.php?timelineID=000015 (accessed 25 September 2016).

designers to retrofit or design WRRFs as true energy production centers.

Solar radiation also powers the Earth's natural hydrological cycle to replenish water through precipitation, evaporation, transpiration, infiltration, and runoff. Since 97% of the water is saltwater in the oceans, only 2% is bound as ice and 1% is in lakes, rivers, and groundwater. To manage flood and drought effectively for sustainable development, integrated water resources management (IWRM) is critical for sustainable development as defined by the Global Water Partnership:

> IWRM is a process which promotes the coordinated development and management of water, land and related resources, to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

When water is abundant, the water quality index (WQI) is critical in assessing water pollution problems and developing water management strategies to sustain local economic and societal needs. When water is scarce, rain harvest and the reclamation of gray and black water may hold the key to sustainable economic development of the region. For example, in the Aries region, rain harvest and the reuse of gray and black water become critical, because climate change is causing more extreme weather and altering water availability in many regions. Therefore, adaptation is crucial to ensure that sufficient water of adequate quality is available for human and the environment. One way to adapt to the climate change is to design and construct integrated and interconnected green infrastructure (GI) to build sustainable community. The reason is that GI adapts to climate change better in the hydrological cycle such as precipitation, evaporation, transpiration, runoff, and storage during flood and drought. Indeed, GI is one of the critical EEISs to ensure sustainable development within the regional hydrological boundary as average global GDP continues to rise and the human population approaches 10 billion by 2100. SEE designers should sustainably manage the water cycle so that the water footprint (WFP) is less than the regeneration rate of the regional hydrological cycle.

On a global scale, water cycle includes annually 4.25×10^{20} g of water evaporating from the oceans; this is equivalent to a water layer of 117.8 cm thickness spread over the total ocean surface. A total of 0.397×10^{20} g is transferred from the oceans to the continents (11 cm). The continents receive precipitation of 1.081×10^{20} g annually, equivalent to a layer of 74.6 cm covering the total land area. Two-thirds of this amount evaporates and one-third returns through rivers or glaciers to the sea. The global ratio between evaporation and runoff is 0.357. Water budget is one of the critical aspects in the integrated water management of a given area. For a specific area, water budget can be simplified as follows:

$$Q_{\text{storage}} = Q_{\text{prep.}} - Q_{\text{EP}} - Q_{\text{IF}} - Q_{\text{runoff}} \tag{1.1}$$

For natural cover, only 10% is runoff, while evapotranspiration, shallow infiltration, and deep infiltration are 40, 25 and 25% respectively. If a city has 75–100% impervious cover, 40% is evapotranspiration, while the runoff could be as high as 55%. For example, May to October is the rainy season in Miami when precipitation is greater than evapotranspiration and the ponds and lakes rise. From November to April, precipitation is less than evapotranspiration and the reservoirs decrease. Example 1.2 illustrates the hydrological balance of water in Miami.

Example 1.2 For Miami, the following precipitation data is given (Table 1.3):

Miami-Dade County covers 2000 miles^2, which is $5.5 \times 10^{10}\ \text{ft}^2$. If evapotranspiration is 35 in/year and infiltration is 8 in/year, what would be the total precipitation and runoff, respectively?

Find: What percentage of pavement is considered impervious?

Solution:

The total precipitation in Miami by in/year is

$$\begin{aligned} Q_{\text{prep.}}(\text{in/year}) &= 1.61 + 2.24 + 2.99 + 3.15 + 5.35 + 9.69 \\ &\quad 6.50 + 8.90 + 9.84 + 6.34 + 3.27 + 2.05 \\ Q_{\text{prep.}}(\text{in/year}) &= 61.93\ \text{in/year} \end{aligned}$$

Annual volume precipitation rate in Miami in m^3/year is

$$\begin{aligned} Q_{\text{prep.}}\left(\text{m}^3/\text{year}\right) &= 61.93\ \text{in/year} \div 12\ \text{in/ft} \\ &= 5.16\ \text{ft/year} \times 5.5 \times 10^{10}\text{ft}^2 \\ &= 2.84 \times 10^{11}\text{ft}^3/\text{year} \div 35.31\ \text{ft}^3/\text{m}^3 \\ &= 8.04 \times 10^{9}\text{m}^3/\text{year} \end{aligned}$$

The total runoff in Miami by in/year is

$$Q_{\text{runoff}} = Q_{\text{prep.}} - Q_{\text{EP}} - Q_{\text{IF}} = 61.93 - 35 - 8 = 18.93\ \text{in/year}$$

The annual runoff in Miami in m^3/year is to multiply in/year by area:

$$\begin{aligned} Q_{\text{runoff}}\left(\text{m}^3/\text{year}\right) &= 18.93\ \text{in/year} \div 12\ \text{in/ft} \times 5.5 \times 10^{10}\ \text{ft}^2 \\ &= 1.58\ \text{ft/year} \times 5.5 \times 10^{10}\ \text{ft}^2 \\ &= 8.68 \times 10^{10}\ \text{ft}^3/\text{year} \div 35.31\ \text{ft}^3/\text{m}^3 \\ &= 2.46 \times 10^{9}\ \text{m}^3/\text{year} \end{aligned}$$

The runoff and precipitation ratio is

$$\text{Runoff ratio} = \frac{Q_{\text{runoff}}}{Q_{\text{prep.}}} = \frac{18.93}{61.93} = 30.56\%$$

Answer: Since the runoff to precipitation ratio is 30.56%, at least 75% area of Miami is impervious.

Comments: The conclusion on the percentage of impervious surface in Miami greatly depends upon the evapotranspiration data. There are large differences in many reported evapotranspiration data. Therefore, the better way to solve problem is to compile all the data and calculate the mean and standard deviation to quantify the uncertainty of the runoff ratio.

Powered by the sun, plants and phytoplankton fix atmospheric CO_2 into biomass through photosynthesis. CO_2 is then added to the atmosphere through cellular respiration of animals, and the burning of fossil fuels and volcanoes complete the carbon cycle. Autotrophs convert carbon dioxide to organic molecules that are used by heterotrophs. During the carbon cycle, carbon could also be stored through fossil fuels, soils, aquatic sediments, the oceans, plant and animal biomass, and the atmosphere (CO_2) (Example 1.3).

Example 1.3 Under one atmospheric pressure, the partial pressure of CO_2 (P_{CO_2}) is 0.0003 parts CO_2 in 1 part of air. According to Henry's law, the CO_2 content of rainwater is between 1 ppm at 0 °C and 0.5 ppm at 20 °C, if 1.08×10^{20} g of freshwater water falls annually as precipitation on the continents and a global mean precipitation temperature is 15 °C with 0.6 ppm CO_2 in the rainwater.

Find: What would be the annual flux of CO_2 with precipitation to the continent surface?

Solution:

Since the average global annual precipitation is 1.08×10^{20} g H_2O, the annual flux of CO_2 with precipitation to the continent surface would be

$$\begin{aligned} &0.6 \times 10^{-6}\text{CO}_2 \times 1.08 \times 10^{20}\ \text{g}\,\text{H}_2\text{O} \\ &\quad = 6.5 \times 10^{13}\ \text{g}\,\text{CO}_2\ \left(1.8 \times 10^{13}\ \text{g}\,\text{C/year}\right) \end{aligned}$$

Answer: The annual flux of CO_2 with precipitation to the continent surface is 6.5×10^{13} g CO_2.

Table 1.3 Average monthly precipitation in Miami.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Precipitation (inch)	1.61	2.24	2.99	3.15	5.35	9.69	6.50	8.90	9.84	6.34	3.27	2.05

Comments: Some CO_2 is instantaneously lost again into the atmosphere when the precipitation evaporates from rocks, soil, or vegetation. Industrial fossil-fuel burning increases the CO_2 content of air locally, and rain may contain larger CO_2 concentration compared with the global average. Therefore, actual measurements of CO_2 in rainwater may be much higher than expected from the equilibrium.

Phytoplankton contributes 50–85% of oxygen in the Earth's atmosphere through photosynthesis with oxygen as a by-product through the reduction of CO_2. Forest, grass, algae, and agriculture produce the rest. Phytoplankton has a short turnover time, which means that it has a small standing biomass compared with its production:

$$\text{Turnover time} = \frac{\text{standing crop biomass}\ \ (\text{mg/m}^2)}{\text{production}\ \ (\text{mg/m}^2/\text{day})} \tag{1.2}$$

The nitrogen cycle starts from the fixation of 80% non-bioavailable nitrogen gas (N_2) in the atmosphere. Through bacteria, nitrogen enters ecosystems. Organic matter is decomposed to ammonia, NH_4^+, in *ammonification* by bacteria. During *nitrification*, bacteria convert NH_4^+ to NO_3^-. Bacteria use NO_3^- for metabolism instead of O_2 and release N_2 back into the atmosphere in *denitrification*, which completes the nitrogen cycle.

Different from the nitrogen cycle, phosphorus can only become bioavailable to plants or animals through weathering from rock. Some phosphate is taken up by producers and incorporated into organic materials. Other phosphate leaches into groundwater or surface water and enters to the sea. Phosphorus is returned to soil or water through the decomposition of biomass or the excretion by animals.

1.2 Human Demand and Footprint

1.2.1 Human Demand

Human demand can be simply expressed as the air we breathe, the water we drink, and the food we eat. As a result, human generates waste such as feces and urine as follows:

$$\text{Food} + H_2O + O_2 = \text{feces} + \text{urine} + CO_2 + H_2O \tag{1.3}$$

On average, each person needs the following amounts of natural resources to survive. The quantity of air required is relatively constant. For example, the daily air inhalation rates (m^3/day) for adult, child, and infant are 22.8, 14.8, and 3.76, respectively. Only 2 kg water is required for drinking purposes, while 2–4 kg food is needed by an adult for a day. Water and food have large variations because food contains different amount of moisture. The US Environmental Protection Agency (EPA) Exposure Factors Handbook (US EPA, 1997) provides detailed data related to water and food variation in different categories. Table 1.4 shows that total dairy food and meats are 308.6 ± 5.3 and 172.2 ± 1.6 g/day, respectively. The average and standard deviation of grain intake is 200.0 ± 3.0 g/day.

Table 1.4 Average consumption of meat in the United States (US EPA, 1997).

Animal protein	Daily take rate (g/day)
Fresh cows' milk	253.5 ± 4.9
Eggs	26.9 ± 0.5
Beef and veal	87.6 ± 1.1
Pork	28.2 ± 0.6
Poultry	31.3 ± 0.8
Other	25.1 ± 0.4

In ecology, primary producers are organisms in an ecosystem that produce biomass from inorganic compounds (autotrophs). Gross primary production (GPP) is the amount of chemical energy as biomass that primary producers create in a given length of time. The amount of chemical energy in consumers' food that is converted to their own new biomass during a given time period is called the secondary production of an ecosystem. The efficiency of animals as energy transformers can be calculated using the following equation:

$$\eta_p = \frac{\text{net secondary production}}{\text{assimilation of primary production}} \tag{1.4}$$

where η_p is the production efficiency.

Net secondary production is the energy stored in biomass represented by growth, reproduction, and respiration. Thus, the fraction of food energy not used for respiration is the production efficiency. For example, birds and mammals generally have low production efficiencies of between 1 and 3% because they use so much energy to maintain a constant body temperature. Fishes and insects have production efficiencies of around 10 and 40%, respectively.

Trophic efficiency is the percentage of production transferred from one trophic level to the next. The energy lost through respiration, feces, and unconsumed organics at lower trophic levels causes low production efficiencies from 5 to 20%. Therefore, 80–95% of the energy available at one trophic level is not transferred to the next over a food chain. Usually, 10% of energy is transferred from primary producers to primary consumers, and 10% of that energy is transferred to secondary consumers. As a result, only 1% of net primary production (NPP) is available to the secondary consumers.

The dynamics of energy through ecosystems have important implications for healthy diet. For example, eating meat is an inefficient way of tapping photosynthetic products due to low trophic efficiency in the food chain. More importantly, vegetable protein is no less nutritious than animal protein. Indeed, worldwide agriculture could feed many more people if vegetarian diet were the dominant diet because primary consumers feeding on plants have much higher trophic efficiency. More importantly, diet containing more vegetable, fruits, and plant protein has much healthier benefit than red meats.

Although each person's demand for air, water, and food may not be huge, the total impacts of human on the environments such as air, water, and soil could be devastating. If EEIS were not designed sustainably, residential, industrial, and agricultural wastes may become a bottleneck for economic development of the future generations. In 2016, 7.2 billion people in the world may take three population trajectories to 8, 9.3, and 10.6 billion by 2050, depending upon low, medium, and high birth rates, respectively, according to the United Nations' (UN) projection as shown in Figure 1.1.

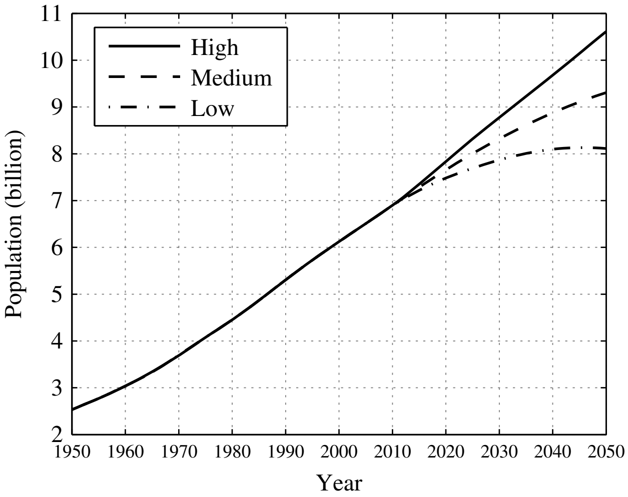

Figure 1.1 World population, 1950–2010, with projections to 2050.

In addition, life expectancy is predicted to increase from 69 to 75 between 2015 and 2050. Figure 1.2 shows that the life expectancy has also increased globally by almost 20 years. Twice as many people on the planet would live 40% longer, with each person consuming many times more animal protein than the average person did in the 1960s.

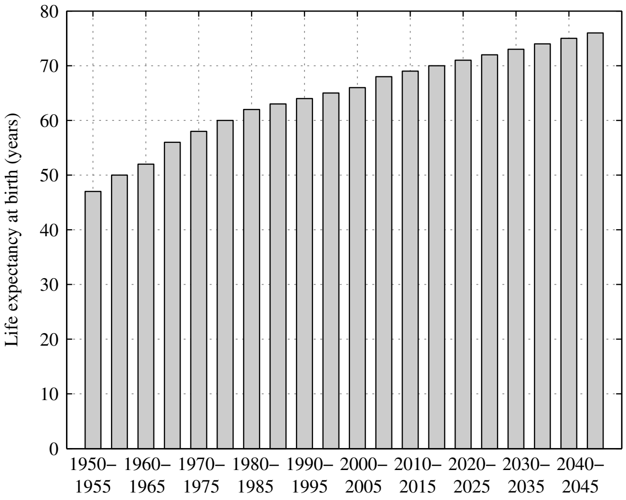

Figure 1.2 Life expectancy for the world, 1950–2005, with projection to 2050. (*Source:* esa.un.org/unpp.)

As living standards increase, animal protein consumption per person increases exponentially. From the data presented by the Earth Policy Institute, several major trends can be observed due to human protein consumption: (i) wild fish is declining due to depleting fish stocks from overfishing, (ii) beef production is also declining due to the stricter environmental regulations and change of diet, and (iii) pork and farmed fish are increasing due to insatiable demand from China. For example, the total number of pigs in China equals that of the rest of the world combined. Unfortunately, pork is rather fatty red meat, which directly correlates with the high death rate due to stroke and heart disease.

1.2.2 Human Footprints

Human footprint (FP) is measured in terms of the average land available for each person on planet Earth as ecological footprint (EF). Ewing et al. (2009) applied the EF to gauge how much land and water area a person requires to produce the resources it consumes and to absorb its carbon dioxide emissions based on current technology. Currently, the biocapacity of the Earth is 1.8 ha. In theory, the average EF of each person should not exceed 1.8 ha. Since 1 ha equals 20 000 m^2, each person on average has 40 000 m^2 land. However, the EF in the United States is 9 ha, while the global average EF is only 5 ha. Therefore, modern society such as the United States is ecologically overshooting in terms of EF. To allow nature to regenerate its stock sustainably for human consumption, about two additional planet Earths are needed if each person had EF of 9 ha. For this reason, sustainable cities have to be designed and built to reduce the ecological overshooting.

To estimate the loading factor, the unit value of the impact on the environment per capita is expressed as follows (Table 1.5).

Table 1.5 Waste production per capita per day.

Components	Standard	Unit
COD	180	g/capita/day
N	13	g/capita/day
P	2.1	g/capita/day
Flow rate	0.36	m^3/capita/day
COD	500	g/m^3/capita/day
N concentration	36	g N/m^3/capita/day
P concentration	5.8	g P/m^3/capita/day

1.2.2.1 Water Footprints

Water FP can be color coded as green for precipitation, blue for surface and groundwater, and gray, which refers to the volume required to assimilate pollutants to the background level. In the past, economic development is proportional to air, water, and land degradation. For example, before a forest land is developed, the percentages of precipitation by evaporation, seepage, and the runoff are 40, 50, and 10, respectively. After development, these percentages typically changed to 30, 15, and 55, respectively. The large runoff increases stormwater volume and flooding probability. In a typical year, one acre of land cleared for development may cause 10 tons of eroded sediment, while one acre of impervious cover leads to one million gallons of runoff. In addition, flooding could threaten lives and damage the habitat, ruining streams and rivers and decreasing biodiversity in water channels. Since runoff is also a major nonpoint source, pollution control is important during land development and construction to minimize its impact on the water quality. One of the effective strategies is to build green infrastructure to reduce runoff by absorbing the nutrients and increasing Earth's biomass and reduce water footprints of economic development.

1.2.2.2 Gray Water System

Gray water consists of all domestic water used except black water which is toilet wastewater. It does not contain urine, defecation, or pathogens. It is easier to treat than black water which has minute pathogens. The major treatment objectives for gray water are to (i) kill pathogens and protect public health; (ii) protect groundwater from contamination; (iii) enable safe reuse for urban agriculture, irrigation, aquifer recharge, and landscaping; and (iv) avoid damage to buildings and surrounding areas. Reusing gray water significantly reduces nutrients, energy, carbon, and water FP. The treated gray water can be used to irrigate crops and lawns (but cannot be used for drinking or cooking without advanced treatment), reduces potable water demand in urban agriculture, and increases river flows and aquifer recharge.

Gray water FP is defined as the freshwater volume required to assimilate gray water to its natural background water quality and is calculated according to the following equations:

$$\mathrm{GWF} = \frac{L}{C_{\mathrm{ambient}} - C_{\mathrm{nature}}} \tag{1.5}$$

$$\mathrm{GWF}_{\text{Nitrogen and phosphorus}} = \frac{\alpha \times Q \times \text{population}}{C_{\text{Nitrogen and phosphorus}} - 0} \tag{1.6}$$

where

$L = \alpha \times a_{\mathrm{ppl}}$ is the loading rate (g/person/day)
α is the coefficient of location
a_{ppl} is the application rate of loading = rate Q (gallons or g/person/day) × population
C_{ambient} is the standard set for the ambient concentration in g/l (when trophic state of a water body cannot be determined, it suggests using the maximal allowable concentration (MAC))
C_{nature} is the background concentration in g/l and is usually zero

Since ambient water quality standards are used in the calculation, the water FP of gray water depends upon which ambient nutrient standards are used. Many different guidelines for the different reuse policies have been established by the World Health Organization (WHO, 2012) or the US EPA (Example 1.4).

Example 1.4 Please find the average income figure from the World Bank website for Opa-locka, Miami-Dade County, the United States, China, and Nigeria through the following websites:

http://waterfootprint.org/en/resources/interactive-tools/personal-water-footprint-calculator
http://data.worldbank.org/country

Find: Water footprint (WFP) of a person with average income in Opa-locka, Miami-Dade County, the United States, China, and Nigeria.

Solution:

WFP of a person with average income in Opa-locka:

$$\text{Water footprint} = 772\ \mathrm{m^3/year} = 27\,263\ \mathrm{ft^3/year}.$$

$$\text{Average income in Opa} - \text{Locka} = \$12\ 080.00\ (\text{from miamidade.gov})$$

WFP of a person with average income in Miami-Dade County:

$$\text{Water footprint} = 3081\ \text{m}^3/\text{year} = 108\ 805\ \text{ft}^3/\text{year}.$$

$$\text{Average income in Miami} - \text{Dade} = \$49\ 900.00\ (\text{from miamidade.gov})$$

WFP of a person with average income in the United States:

$$\text{Water footprint} = 3341\ \text{m}^3/\text{year} = 117\ 986\ \text{ft}^3/\text{year}.$$

$$\text{Average income in the United States} = \$55\ 200.00$$

WFP of a person with average income in China:

$$\text{Water footprint} = 1404\ \text{m}^3/\text{year} = 49\ 582\ \text{ft}^3/\text{year}.$$

$$\text{Average income in China} = \$7400.00$$

WFP of a person with average income in Nigeria:

$$\text{Water footprint} = 727\ \text{m}^3/\text{year} = 25\ 674\ \text{ft}^3/\text{year}.$$

$$\text{Average income in Nigeria} = \$2970.00$$

The aforementioned WFP clearly shows that WFP depends upon average income. Figure 1.3 compares WFP by individual from Opa-locka, Miami-Dade County, the United States, China, and Nigeria (Example 1.5).

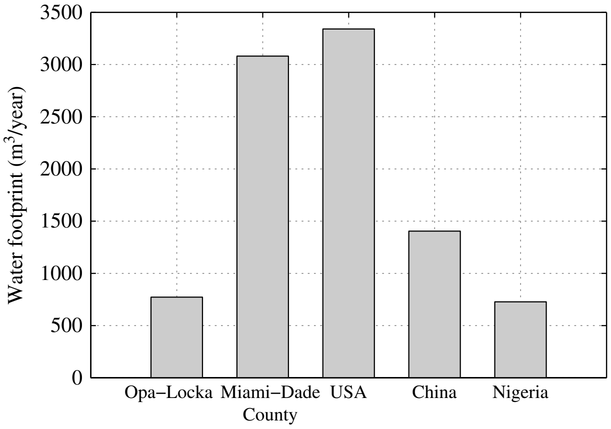

Figure 1.3 Comparison of water footprint.

Example 1.5 Please find the average N and P discharge per person per day in the United States, Japan, China, and Zimbabwe. Please calculate the gray water footprint for the aforementioned, respectively, using the following technical guideline book by Franke et al. (2013).

Find: The average N and P discharge per person per day and calculate the gray water footprint in the United States, Japan, China, and Zimbabwe. Table 1.6 lists the maximal allowable concentration of N and P for different eutrophication states.

Table 1.6 Maximal allowable concentration in μg/l.

Nutrients	Chemical formula	Maximum permitted concentration μg/l	Referenced guideline
Ammonium NH_3 (unionized as NH_3)	NH_3	19 unionized NH_3-N[a]	CCME
Nitrate as NO_3	NO_3	13 000	CCME
Nitrite as N	NO_2	60	CCME
Total phosphorus	Ultra-oligotrophic	4	CCME
	Oligotrophic	10	
	Meso-trophic	20	
	Meso-eutrophic	35	
	Eutrophic	100	

Note:
[a] The unionized ammonia guideline value is expressed as μg ammonia/l. This is equivalent to 16 μg ammonia-N/l (= 19 × 14.0067/17.35052).

Solution:

When trophic state of a water body cannot be determined, the tier 1 of gray water footprint guidelines suggests using the value of 20 μg/l (MAC) and 16 μg/l for nitrogen for meso-trophic water bodies to calculate the GWF.

For a natural/background concentration of nearly zero, Equation (1.5) can be used to calculate the GWF to be done:

$$\text{GWF} = \frac{L}{C_{\text{ambient}} - C_{\text{nature}}}$$

Average N and P discharge per person and per day and the grey water footprint in United States:

$$\text{N} : 18\ \text{g/person/day}$$

$$\text{P} : 4\ \text{g/person/day}$$

$$\text{GWF}_{\text{Nitrogen}} = \frac{18\ \text{g/person/day}}{16 \times 10^{-6}\ \text{g/l}} = 1125\ 000\ \text{l/day/person}$$

$$\text{GWF}_{\text{Phosphorus}} = \frac{4\ \text{g/person/day}}{20 \times 10^{-6}\ \text{g/l}} = 200\ 000\ \text{l/day/person}$$

Average N and P discharge per person and per day and the gray water footprint in Japan:

$$\mathrm{N}: 8.5\,\mathrm{g/person/day}$$

$$\mathrm{P}: 1\,\mathrm{g/person/day}$$

$$\mathrm{GWF}_{\mathrm{Nitrogen}} = \frac{8.5\,\mathrm{g/person/day}}{16 \times 10^{-6}\,\mathrm{g/l}} = 531\,250\ \mathrm{l/day/person}$$

$$\mathrm{GWF}_{\mathrm{Phosphorus}} = \frac{1\,\mathrm{g/person/day}}{20 \times 10^{-6}\,\mathrm{g/l}} = 50\,000\ \mathrm{l/day/person}$$

Average N and P discharge per person and per day and the gray water footprint in China:

$$\mathrm{N}: 8\,\mathrm{g/person/day}$$

$$\mathrm{P}: 1.1\,\mathrm{g/person/day}$$

$$\mathrm{GWF}_{\mathrm{Nitrogen}} = \frac{8\,\mathrm{g/person/day}}{16 \times 10^{-6}\,\mathrm{g/l}} = 500\,000\ \mathrm{l/day/person}$$

$$\mathrm{GWF}_{\mathrm{Phosphorus}} = \frac{1.1\,\mathrm{g/person/day}}{20 \times 10^{-6}\,\mathrm{g/l}} = 55\,000\ \mathrm{l/day/person}$$

Average N and P discharge per person and per day and the gray water footprint in Zimbabwe:

$$\mathrm{N}: 7.8\,\mathrm{g/person/day}$$

$$\mathrm{P}: 1.2\,\mathrm{g/person/day}$$

$$\mathrm{GWF}_{\mathrm{Nitrogen}} = \frac{7.8\,\mathrm{g/person/day}}{16 \times 10^{-6}\,\mathrm{g/l}} = 487\,500\ \mathrm{l/day/person}$$

$$\mathrm{GWF}_{\mathrm{Phosphorus}} = \frac{1.2\,\mathrm{g/person/day}}{20 \times 10^{-6}\,\mathrm{g/l}} = 60\,000\ \mathrm{l/day/person}$$

Comments: The water FP based upon N and P is different with FP due to N being much larger than P. WFP in the United States is significantly larger than other countries, which may be caused by the high animal protein diet.

Since the natural concentration of nitrogen and phosphorus would be the same for the same water body, GWF inversely proportional to the MAC. This can be clearly seen by the fact that if the nutrient status of a lake is different, the GWF will change significantly. For example, to maintain the ultra-oligotrophic status of 4 μg/l, the GWF would be 25 times greater than extra-eutrophic condition (Example 1.6).

Example 1.6 Phosphorus (P) ambient water quality standard can be defined as extra-trophic, meso-trophic, eutrophic, meso-eutrophic, and extra-eutrophic states as shown in Table 1.7.

Find: The gray water footprint if a person is discharging 1 g P/capita/day, while the background P concentration is 0.

Solution:

1) The problem can be solved using following equation:

$$\mathrm{GWF} = \frac{L}{C_{\mathrm{ambient}} - C_{\mathrm{nature}}} \tag{1.5}$$

2) By substituting all the known variables for L, C_{ambient}, and C_{natural} into Equation 1.5, the GWF is listed as Table 1.7.

For example,

$$\mathrm{GWF} = \frac{1\,\mathrm{gP/capita/day}}{4 \times 10^{-6}(\mathrm{g/l}) - 0} = 250\,\mathrm{m}^3/\mathrm{person/day}$$

Table 1.7 Footprint of phosphorus in m^3/person/day.

Ambient water quality standard	C_{ambient} in μg/l	$\mathrm{GWF} = \frac{L}{C_{\mathrm{ambient}} - C_{\mathrm{nature}}}$ in m^3/person/day
Extra-trophic	4	250
Meso-trophic	10	100
Eutrophic	20	50
Meso-eutrophic	50	20
Extra-eutrophic	100	10

Comments: If ambient water quality standards are 4 and 100 μg/l, the GWF of P discharged by each person in a day would be 250 and 10 m^3/person/day, respectively. Therefore, the freshwater volume required to assimilate the P loading to ambient standards at 4 μg/l would be 25 times more than that at 100 μg/l. This is very significant because ambient standards were established by the receiving ecosystem. In the Everglades National Park (ENP), the native plants are so sensitive to P concentration, and the discharge standards of N and P for rehydration of the ENP were 0.27 and 0.005 mg/l, respectively. For recharging groundwater aquifer, however, the discharge standard concentration of N and P could be one to two orders of magnitude higher than that required by the ENP due to different receiving ecosystems because the aquifer soil could further purify the discharged water.

1.3 Challenges and Opportunities

In the developing world, about 1 billion people do not have access to modern sanitary facilities, 1.3 billion people lack electricity, and 2.7 billion people still rely on local biomass for food preparation, which results in deforestation, soil erosion, and human health deterioration (IEA, 2011). One way to reduce the health hazard of incomplete combustion is to increase application of high efficient stover with wood pellets. To improve sanitary facilities, composite toilets may serve as a transition for better environments. In the developed countries such as the United States, there is a trend to decentralize wastewater treatment infrastructure so that the treated wastewater could be close to irrigation sites for resue. In addition, aging water infrastructures such as WTP and WWTPs were assessed as grade D due to lack of retrofitting or improvement capital. For example, aging infrastructure caused lead poisoning in Wisconsin. There were many cases of sewage overflow during the wet season all over the major US cities. In Miami-Dade, thousands of gallons of sewer were discharged to the Biscayne Canal because a 64-inch sewer pipe broke at 840 NW 155 Lane on 30 June 2017. Since the leaked sewer could enter the Biscayne Canal and flowed into the interacoastal communities, a precautionary advisory to avoid recreational water activities including swimming was issued by the Miami-Dade County. As the WWTPs and sewer pipe system approach their design life, sewer leaks due to pipe breaks and the reduced performance of WWTPs suggest that design paradigm shift from fit-for-all to fit-for-purpose is the main challenge for the next-generation SEE designers. Indeed, some of the traditional design philosophy should be revisited as new knowledge and technologies are created and commercialized. For example, chlorine is used as a post-disinfectant in more than 70% of WWTPs in the United States, while almost 90% of WTPs in the United States use chlorine. The major health concern of chlorination is the disinfection by-products (DBPs) which are heavily regulated by the US EPA.

Table 1.8 History industrial productions of nitrogen fertilizers.

Year	Author	Contribution	References
1840	Justus von Liebig	Global biospheric cycles and of nitrogen in crop production	von Liebig (1840)
1860	Jean-Baptiste Boussingault	Nutritional value of fertilizers	Smil (2001)
1877	Théophile Schloesing	Bacterial origins of nitrification	Smil (2001)
1885	Ulysse Gayon	Denitrifying bacteria that can reduce nitrates and, via NO and N_2O, return N_2 to the atmosphere	Smil (2001)
1886	Hermann Hellriegel	Leguminous nodules as the sites of biofixation	Smil (2001)
1909	Fritz Haber	Synthesizing ammonia using iron-based catalyst	Smil (2001) and Stoltzenberg and Haber (2004)
1920	Carl Bosch	Mass production of ammonia inexpensive nitrogenous fertilizers	Smil (2001)

1.3.1 Excessive Nitrogen Runoff

Due to the exponentially increasing human population, the Haber–Bosch (HB) process is used in the industrial production of nitrogen fertilizers for agriculture. Without the HB process, nearly four times more land would be needed to produce the food needed for 7.2 billion people. Table 1.8 shows the major milestones of this process. Due to excessive application of fertilizer and nutrient runoff, however, the planetary boundary (PB) of nitrogen loading to the ecosystem is considered as being trespassed by human economic activities.

1.3.2 Phosphorus Depletion

Phosphorus is an essential component in adenosine triphosphate (ATP), an energy-bearing compound that drives biochemical processes in plants and animals. It is also a critical element in DNA, RNA, and phospholipids that are essential for the function of cellular membranes. Phosphorus, present as phosphate minerals in the soil, is a nonrenewable resource. Phosphate rock, or calcium phosphate, $Ca_3(PO_4)_2$, is the only important commercial source of phosphorus. The United States is the largest producer of phosphate rock in the world (USGS, 1997). In 1996, 13 300 000 metric tons of phosphate rock was mined in the United States, which counted to about one-third of the world's total. About 86% of phosphate rock comes from North Carolina and Florida. Ninety-one percentage of all the phosphate rock mined in the United States was used to make fertilizer. To meet the insatiable agricultural demand for phosphorus, the mining of phosphorus is depleting the reserve. With 7000 million tons of P reserve, it would be completely used up by 2061 and 2070 with annual consumption growth rates of 3 and 2.5%, respectively. If consumption growth rates were 2 and 1% annually (Wetzel, 1983; Steen, 1998), it would be depleted by 80 and 60% by the end of 2071, respectively. Detergents contain sodium tripolyphosphate (STPP) ($Na_5P_3O_{10}$). Over two million tons of phosphorus was used annually in detergents in the United States in 1983 alone (Wetzel, 1983). About 50% of the wastewater phosphorus nationwide came from detergents (Hammond, 1971). If excessive phosphorus is discharged to the natural water body, one pound of phosphorus could grow 700 lb of algae (Beeton, 1971) and leads to significant eutrophication in surface waters.

1.3.3 Carbon Pollution

Carbon dioxide concentration has been closely correlated with the global temperature. If current trends continue and no international collective efforts were implemented, even the best scenario on carbon reduction could barely stop the Earth from warming by less than 2 °C, which is considered as a tipping point by the end of this century although it has only increased by 0.83 °C currently. If international agreement developed in the Paris Conference in 2015 could be implemented, the deterioration trajectory might be reversed. China burns almost as much coal as the rest of the world combined and is the world's leading greenhouse gas emitter because its annual GDP had grown more than 10% in the past three decades. The major environmental issue rooted in China is its energy structure by using coal as the major energy source as shown in Figure 1.4.

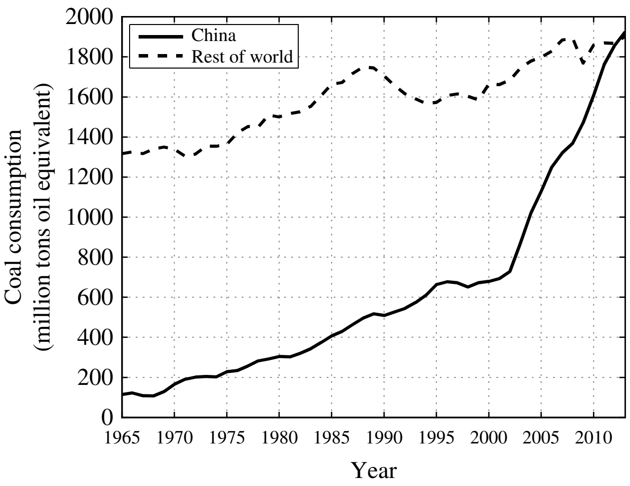

Figure 1.4 Coal consumption in China and the rest of the world in 1965–2013. (*Source:* Data from Statistical Review of World Energy June 2014, London.)

1.3.4 Peak Oil

Peak oil is the time when the rate of oil production worldwide is forecasted to decline. The International Energy Agency (IEA) released the results of a unique comprehensive analysis of 800 oilfields, including all 54 supergiant reserves (>5 Gbbl) in production (World Energy Outlook (WEO) of November 2008). As oil production peaks, liquid fuel prices and price volatility could increase dramatically, and, without timely mitigation, the economic, social, and political costs would be unprecedented (World Bank, 2012). For these reasons, leading countries such as Germany is planning to ban all the fossil fuels by 2030.

1.3.5 Climate Change

Extreme weather could be expected in the next decades due to combining factors such as greenhouse gas emission as well as solar minimum. Figure 1.5 shows that the observed global average temperature varied from −9 to +3 °C in the past 400 000 years (Petit et al., 1999). The mean temperature is less than 0 °C during 85% of the time with global average temperature greater than 0 degree, while only 15% of the interglacial represents warm holiday in this period of time. The major warning sign for climate is that the Earth should have been cooling much faster than it does now. Therefore, global warming due to CO_2 would be a major concern if CO_2 emission is out of control. Regardless of global warming or cooling, extreme weather will bring more intensive drought, flooding, and hurricanes. For these reasons, EEIS should be designed to be resilient and adaptive to both warm and cold climates in the next 100 years.

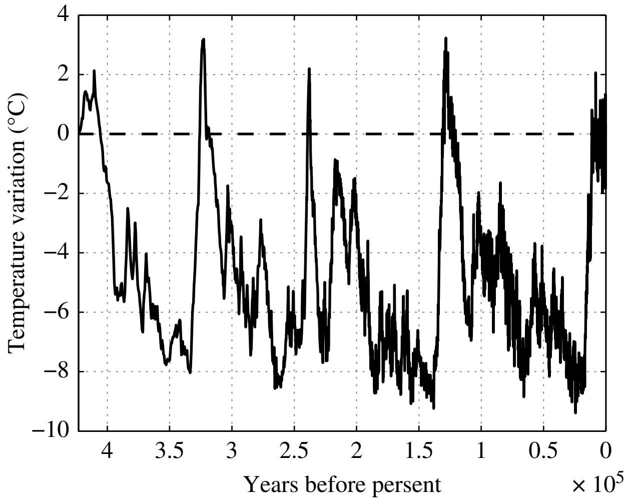

Figure 1.5 Historical isotopic temperature record from the Vostok Ice Core. (*Source:* Data from Petit et al. (1999).)

1.4 Carrying Capacity

Carrying capacity is the maximum number of organisms that can be supported in a given habitat. This pale blue dot planet Earth is home to 7.2 billion people in 2018. It is expected that 10 billion people will live on this planet by 2100. The question that begs an accurate answer is, how many people that the planet Earth can support without irreversible damage to its ecological system due to great pressure that human exerted on the Earth? What are the safe operating boundaries for humans to thrive without triggering the tipping point, at which Earth shifts from its Holocene to Anthropocene? To answer this question, the human EF were compared with Earth's carrying capacity by Ree and Wackernagel (2013). Another way to answer this question is through the primary biomass production of the Earth divided by the primary biomass to support a person. For example, Miller (1971) estimated that 1000 tons of grass as primary biomass would be needed to support a man for 1 year if he was fed on 300 trout, which must consume 90 000 frogs, which must consume 27 million grasshoppers. Net Primary Production (NPPP) is the amount of plant material produced on Earth and the net amount of solar energy converted to plant organic matter through photosynthesis. Carbon can be measured by the photosynthesis process (i.e. CO_2 exchange between atmosphere and biosphere). Twenty-four to thirty-two percentage of NPP is consumed by 7.2 billion people globally. If all the global NPP had been used, it could support 22–29 billion people. However, the global ecosystem would collapse as there would not be enough grass and other vegetation at the bottom of the food chain to regenerate the needed resource for humans to survive. In addition, it would also change the composition of the atmosphere and the level of biodiversity. For this reason, the carrying capacity was estimated around from 22 to 29 billion people.

Since the Earth carrying capacity is limited, planetary boundaries (PBs) must be set so that a safe operating zone for Earth can be defined so that human activity will not change Earth's Holocene state in the next 10 000 years. Humans on this planet are part of an ecological system shared with millions of other species. Before 1840, mankind was in harmony with nature by farming and hunting despite the logistic growth of human population. Many factors such as average GDP, sustainable technologies, and green consumption will determine Earth's carrying capacity. *World Dynamics* (Boyd, 1972) and *The Limits to Growth* (Meadows et al., 1972) concluded that Earth's economic system will tend to stop growing and collapse from reduced availability of resources, overpopulation, and pollution at some point. Technological innovation, population control, and resource availability could delay the collapse with the right policy of stabilizing material consumption.

Under the current technology and consumption pattern, about 10 billion people could be sustained at $10 000 GDP, respectively. If incomes in middle- and low-income countries were to catch up with incomes of the high-income countries (roughly $41 000 per capita), there would be a roughly 3.4-fold increase in global income further from $87 trillion to $290 trillion, which could increase if the high-income countries grow with the world population. If Brazil, Russia, India, China, and Southern Africa (BRICS) countries catch up with the developed countries and Africa catches up BRICS, there would be no new lands, fossil-fuel reserves, and groundwater. Even worse, Earth's ecosystems could not absorb the corresponding carbon dioxide from fossil fuels, nitrogen runoff from fertilizers, and toxic pollutants dissipated in the oceans and rivers. For these reasons, to ensure the world stays within PBs, sustainability has become a prerequisite for human development at all levels, from the local community to nations and the world. The world annual economy would double every two decades at the current growth rate of 4%. As a result, economic activities would break the PBs unless technological innovation could be much faster than economic development on a global scale. More importantly, all the EEIS could be designed, built, and operated sustainably. Table 1.9 lists the dramatically different estimates for the carrying capacity of Earth by 65 research projects.

Table 1.9 Different estimated carrying capacity of Earth.

Carrying capacity ≤ billions	Number of estimates
2	6
4	7
8	20
16	14
32	32
64	7
128	2
256	1
512	1
1024	1

Figure 1.6 shows that there are 32 studies estimating that the Earth's carrying capacity is less than 32 billion. The carrying capacities of two and four billion people appear not to be good estimates because the current population is 7.2 billion. Earth apparently supports us fairly well. At the other extreme, there is only one estimate that the carrying capacity is less than 256, 512, and 1024 billion, respectively. The different estimating methods with different assumptions are the major factors contributing to the widely different carrying capacity estimates. Food, water, and energy could be the limited constraining factors. The interaction between these factors could further complicates the estimates. For example, the natural reserves of fossil fuel could limit the fertilizer production, the pumping of irrigation water, and the use of farming machines. Therefore, the human population that could be supported by planet Earth is limited.

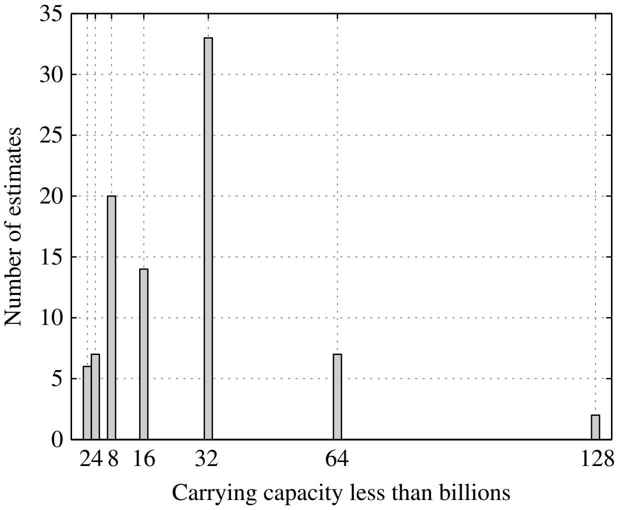

Figure 1.6 Carrying capacity estimates. (*Source:* Data from the UNEP (2012).)

The major difference arises from the constraint factors as well as the speed of technological advance and adoption. Innovation, leadership, entrepreneurship, finance, and policy will answer the challenges that climate change imposes upon us. At the same time, abundant opportunities are also presented to the next generation of EEIS designers.

Global environmental constraints have been quantified as carrying capacity and human FP to define safe operating space within specific PBs to avoid human impact cross tipping points (Rockström et al., 2009). To achieve this, innovation is the key in economic growth and human development. According to the sustainable development trajectory from 2015 to 2030, the world should cooperate within the PBs by adopting sustainable technologies, stabilizing the world's population, and protecting threatened species and ecosystems. The new global rules of the UN 2030 ensure an orderly and cooperative process, improving outcomes to achieve the sustainable development goals (SDGs) for 193 countries of the world. To achieve these sustainable targets, SEE designers would play a critical role in building new cities or villages. Smart cities, regenerative design, zero water, energy, and waste communities are all the new challenges and tasks for EEIS designers to decouple the economic development from environmental degradation.

For humans to thrive and coexist with nature, PB is defined as a safe operating space for humanity with respect to the functioning of Earth's system. Nine PBs are grouped in four categories: (i) the global biogeochemical cycles of nitrogen, phosphorus, carbon, and water; (ii) the major physical circulation systems of the planet such as the climate, stratosphere, and ocean system; (iii) biophysical features of Earth that contribute to the underlying resilience of its self-regulatory capacity such as marine and terrestrial biodiversity and land systems; and (iv) two critical features associated with anthropogenic global change such as aerosol loading and chemical pollution. The aims of the nine PBs are to quantify a safe global level of depleting nonrenewable fossil resources such as energy (coal, oil, gas) and fossil; use the living biosphere such as ecosystems, biodiversity, and land use; and absorb and dissipate human waste flows including carbon, nitrogen, phosphorus, and toxic chemicals. Currently, climate change, change rates of the global nitrogen cycle, and rate of biodiversity loss have apparently been transgressed by mankind. According to human FP, Rockström et al. (2009) determined seven quantitative PBs: "1) climate change (CO_2 concentration in the atmosphere <350 ppm and/or a maximum change of +1 W m^{-2} in radiative forcing); 2) ocean acidification (mean surface seawater saturation state with respect to aragonite ≥80% of pre-industrial levels); 3) stratospheric ozone (<5% reduction in O_3 concentration from pre-industrial level of 290 Dobson Units); 4) biogeochemical nitrogen (N) cycle (limit industrial and agricultural fixation of N_2 to 35 Tg N yr^{-1}) and phosphorus (P) cycle (annual P inflow to oceans not to exceed 10 times the natural background weathering of P); 5) global freshwater use (<4000 km^3 yr^{-1} of consumptive use of runoff resources); 6) land system change (<15% of the ice-free land surface under cropland); and 7) the rate at which biological diversity is lost (annual rate of <10 extinctions per million species)."

1.5 Air, Water, and Soil Quality Index

With the global picture in mind, an SEE designer should act locally by quantifying air, water, and solid indexes first. Once these indexes are quantified, environmental issues can be prioritized according to the relative scale of these indexes compared with local environmental standards.

1.5.1 Air Quality Standards

The US EPA established the following primary National Ambient Air Quality Standards (NAAQS) in Table 1.10 to protect human health.

1.5.2 Air Quality Index

The US EPA developed an air pollutant standard index (PSI) for introducing consistency in providing information on air quality throughout the United States. The system is based on a scale of 0–500. The computed index below 100 indicates that the air quality is within acceptable range. A value over 100 implies potential health

Table 1.10 National ambient air quality standards.

Air pollutants	Primary standards	Averaging times
Carbon monoxide	9 ppm (or 10 mg/m^3)	8 h
	35 ppm (or 40 mg/m^3)	1 h
Lead	1.5 μg/m^3	Quarterly average
Nitrogen dioxide	0.053 ppm (or 100 μg/m^3)	Annual (arithmetic mean)
Particulate matter (PM_{10})	50 μg/m^3	Annual (arithmetic mean)
	150 μg/m^3	24 h
Particulate matter ($PM_{2.5}$)	15.0 μg/m^3	Annual (arithmetic mean)
	65 μg/m^3	24 h
Ozone	0.08 ppm	8 h
	0.12 ppm	1 h
Sulfur oxides	0.03 ppm	Annual (arithmetic mean)
	0.14 ppm	24 h

problems. The alerts are issued at 200, 300, and 400 levels. Five pollutants (carbon monoxide, sulfur dioxide, total suspended particulate, ozone, and nitrogen dioxide) are included in the index. The index is based on the highest index value of any of the five pollutants. Table 1.11 presents the concentration and the corresponding index value.

Table 1.12 lists the likely health effects at different PSI levels as well as health advisory for different population with different vulnerabilities.

Similar to the US EPA approach, the China Department of Environmental Protection (DEP) developed Table 1.13 by using the concentration of the particulate matter with diameter less than 2.5 μm ($PM_{2.5}$) to count particles' contribution to the air quality index (AQI).

1.5.3 Water Quality Index

In addition to drinking water quality standards, the US EPA established ambient water quality standards such as N and P concentration according to different classes of water bodies. These standards were developed by using human health risk assessment and ecological risk assessment as described in the US EPA website (https://www.epa.gov/wqs-tech). Due to different environmental capacities of different states, the EPA authorized each state to establish its state standards of N and P concentration. In Florida, for example, Florida Department of Environmental Protection (FDEP) classifies water bodies in Florida Statute 62-302.400 according to its intended use, according to Table 1.14.

Since there are standards of many water quality parameters, a unified single index such as WQI could be used to assess ambient water quality under general conditions with the *Q*-values listed in Table 1.15 to convert water quality data to *Q*-values for each water body. Once converted, a weighting factor is used to quantify the WQI, which could be used to show the relative degree of water pollution of a water body (Example 1.7).

Table 1.11 US pollutant standard index.

Index value	Air quality level	TSP (24 h) 10^{-6} g/m^3	SO_2 (24 h) 10^{-6} g/m^3	CO (8 h) 10^{-3} g/m^3	O_3 (24 h) 10^{-6} g/m^3	NO_2 (24 h) 10^{-6} g/m^3
400–500	Significant harm	1000	2620	57.5	1200	3750
300–400	Emergency	875	2100	46	1000	3000
200–300	Alert	625	1600	34	800	2260
100–200	NAAQS	375	800	17	400[c]	1130
50–100	50% of NAAQS	260	365	10	235	[a]
0–50		75[b]	80[b]	5	80	[a]
0		0	0	0	0	[a]

Source: US EPA (2014).

Note:

[a] No index values reported at concentration levels below those specified by "alert level" criteria.

[b] Annual primary NAAQS.

[c] 400×10^{-6} gm/m^3 was used instead of the O_3 alert level of 200×10^{-6} g/m^3.

Table 1.12 Associated health effects with US pollutant standard index.

Index value	Health effect descriptor	General health effects	Cautionary statements
400–500	Hazardous	Premature death of ill and elderly. Healthy people will experience adverse symptoms that affect their normal activity	All persons should remain indoors, keeping windows and doors closed All persons should minimize physical exertion and avoid automobile traffic
300–400	Hazardous	Premature onset of certain diseases in addition to significant aggravation of symptoms and decreased exercise tolerance in healthy persons	Elderly and persons with existing diseases should stay indoors and avoid physical exertion General population should avoid outdoor activity
200–300	Very unhealthy	Significant aggravation of symptoms and decreased exercise tolerance in persons with heart or lung disease with widespread symptoms in the healthy population	Elderly and persons with existing heart or lung disease should stay indoors and reduce physical activity
100–200	Unhealthy	Mild aggravation of symptoms with susceptible persons, with irritation symptoms in the healthy population	Persons with existing heart or respiratory ailments should reduce physical exertion and outdoor activity
50–100	Moderate		
0–50	Good		

Source: US EPA (2014).

Table 1.13 Air quality sub-index levels and their corresponding air pollutant concentrations (Ministry of Environmental Protection of The People's Republic of China, 2012).

	Air pollutant concentration (μg/m^3)									
Air quality sub-index	SO_2 24 h	SO_2 1 h[a]	NO_2 24 h	NO_2 1 h	PM_{10} 24 h	CO 24 h	CO 1 h	O_3 1 h	O_3 8 h	$PM_{2.5}$ 24 h
50	50	150	40	100	50	2 000	5 000	160	100	35
100	150	500	80	200	150	4 000	10 000	200	160	75
150	475	650	180	700	250	14 000	35 000	300	215	115
200	800	800	280	1200	350	24 000	60 000	400	265	150
300	1600	[b]	565	2340	420	36 000	90 000	800	800	250
400	2100	[b]	750	3090	500	48 000	120 000	1000	[c]	350
500	2620	[b]	940	3840	600	60 000	150 000	1200	[c]	500

Note:

[a] The 1-h average concentrations of SO_2, NO_2, and CO are just used for real-time reports; the daily concentrations are acquired by 24-h average.

[b] The 1-h average concentration of SO_2 will not be included in the calculation of air quality sub-index if it is greater than 800 μg/m^3, and air quality sub-index of SO_2 is reported as 24-h average.

[c] The 8-h average concentration of O_2 will not be included in the calculation of air quality sub-index if it is greater than 800 μg/m^3, and air quality sub-index of O_2 is reported as 1-h average.

Table 1.14 Classification of surface waters.

Water body class	Description
I	Potable water supplies
II	Shellfish propagation or harvesting
III	Fish consumption; recreation, propagation, and maintenance of a healthy, well-balanced population of fish and wildlife
	Fish consumption; recreation or limited recreation; and/or propagation and maintenance of a limited population of fish and wildlife
IV	Agricultural water supplies
V	Navigation, utility, and industrial use

Table 1.15 *Q*-value tables for calculating water quality index.

DO (% saturation)	*Q*-value	Nitrate-N (mg/l NO_3-N)	*Q*-value	Total phosphate (mg/l P)	*Q*-value	pH (units)	*Q*-value
0	0	0	98	0	99	<2	0
10	8	0.25	97	0.05	98	2	2
20	13	0.5	96	0.1	97	3	4
30	20	0.75	95	0.2	95	4	8
40	30	1	94	0.3	90	5	24
50	43	1.5	92	0.4	78	6	55
60	56	2	90	0.5	60	7	90
70	77	3	85	0.75	50	7.2	92
80	88	4	70	1	39	7.5	93 (max)
85	92	5	65	1.5	30	7.7	90
90	95	10	51	2	26	8	82
95	97.5	15	43	3	21	8.5	67
100	99	20	37	4	16	9	47
105	98	30	24	5	12	10	19
110	95	40	17	6	10	11	7
120	90	50	7	7	8	12	2
130	85	60	5	8	7	>12	0
140	78	70	4	9	6		
>140	50	80	3	10	5		
		90	2	>10	2		
		100	1				
		>100	1				

Example 1.7 Lake A with a temperature of 21 °C has the following water quality data with the weighting factors given in Table 1.16.

Table 1.16 Measured data of lake A.

Parameter	Tested value	*Q*-value	Weighting factor	Calculation
Dissolved oxygen	80		0.3	
Nitrate	1.93		0.2	
Phosphate	0.4		0.2	
pH	6.5		0.3	
Totals				

Find: What is the water quality index of the lake?

Solution:

Dissolved oxygen: % saturation = 80

In the DO column, find the value equal to 80.

Write down the *Q*-value to the right of that number (*Q*-value = 88).

Nitrate: 1.93 mg/l

In the nitrate-N column, find the values closest to 1.93. This number falls between 1.5 and 2 in this column.

Since there is no value matching exactly to 1.93, estimate the *Q*-value between 92 and 90 (*Q*-value = 90.28).

Phosphate: 0.4 mg/l

In the total phosphate column, find the value equal to 0.4.

The *Q*-value corresponding to this concentration is 78.

pH: 6.5

In the pH column, find the values closest to 6.50. This number falls between 6 and 7.

Since there is no value matching exactly to 6.50, estimate the *Q*-value between 55 and 90 (*Q*-value = 72.5) (Table 1.17).

Answer: The water quality index of this lake is 81.8.

Table 1.17 Water quality index of lake A.

Parameter	Tested value	*Q*-value	Weighting factor	Calculation
Dissolved oxygen	80	88	0.3	88 × 0.3 = 26.4
Nitrate	1.93	90.28	0.2	90.28 × 0.2 = 18.056
Phosphate	0.4	78	0.2	78 × 0.2 = 15.6
pH	6.5	72.5	0.3	72.5 × 0.3 = 21.75
Totals				26.4 + 18.056 + 15.6 + 21.75 = 81.8

Comments: The WQI depends upon weighting factors, which could be adjusted according to the ecosystem of different intended use of the water resource. For surface water bodies such as a lake, it depends upon the eutrophication stage of the lake and whether it serves as a local drinking water resource or merely for recreational purposes. Many local and state environmental protection agencies provide local air, water, and soil quality data that can be used to quantify the WQI.

1.5.4 Soil Quality Index

The US EPA developed soil quality guidelines/standards for over 200 chemicals using environmental risk assessment. For example, the soil quality guidelines developed by Michigan Department of Environmental Quality (2004) are available at its website (http://www.deq.state.mi.us/documents/deq-rrd-part201-rules-Rule746Table.pdf). These soil quality standards can be used for calculating the soil quality index (SQI). Three factors are (i) scope (% of contaminants that do not meet their respective guidelines), (ii) frequency (% of individual tests of contaminants that do not meet their respective guidelines), and (iii) amplitude (the amount by which the contaminants do not meet their respective guidelines). The SQI can be used to compare different contaminated sites with similar types of contamination as well as to see if remediation of a particular site meets the required contaminate guidelines. A brief description of these factors and formulas for calculating the SQI is given as follows.

1.5.4.1 F_1 (Scope)

The factor F_1 (as calculated in Equation 1.7) represents the percentage of contaminants that do not meet their respective guidelines (failed contaminants) relative to the total number of contaminants that were measured (and selected for inclusion in the SQI calculation) at the site:

$$F_1 = \frac{\text{Number of failed contaminants}}{\text{Total number of contaminants}} \times 100 \qquad (1.7)$$

1.5.4.2 F_2 (Frequency)

The factor F_2 (Equation 1.8) represents the percentage of individual tests that do not meet their respective guidelines (failed tests):

$$F_2 = \frac{\text{Number of failed tests}}{\text{Total number of tests}} \times 100 \qquad (1.8)$$

1.5.4.3 F_3 (Amplitude)

The factor F_3 (Equation 1.12) represents the amount by which failed test values do not meet their respective guidelines (excursion from the guideline value). The relationship between F_3 and the amount by which the concentrations of contaminants depart from their guidelines could be calculated with the following three steps:

Step 1: Calculate the excursion of all tests in the dataset.

When the concentration of a contaminant is greater than (or less than, when the guideline is a minimum) the soil quality guideline, it is called an excursion. The magnitude of excursion of each test is calculated as follows.

When the test value must not exceed the guideline,

$$\text{Excursion}_\text{i} = \frac{\text{Failed test value}_\text{i}}{\text{Guideline}_\text{i}} - 1 \qquad (1.9)$$

For cases in which the test value must not fall below the guideline,

$$\text{Excursion}_\text{i} = \frac{\text{Guideline}_\text{i}}{\text{Failed test value}_\text{i}} - 1 \qquad (1.10)$$

Step 2: Calculate the average sum.

This refers to the average sum of excursion (ASE) by which individual tests are out of compliance and is calculated by adding together the excursion of all individual tests from their guidelines and dividing by the total number of tests that do not meet their guidelines as follows:

$$\text{ASE} = \frac{\sum_{i=1}^{n} \text{Excursion}_\text{i}}{\text{no. of failed tests}} \qquad (1.11)$$

In the SQI (CCME, 2001), the "normalized sum of excursions" (NSE) was calculated by dividing the sum of excursions by the total number of tests (tests that meet as well as those that do not meet the guidelines). By using "NSE" instead of "ASE," factor F_3 becomes smaller and increases the value of the SQI. The impact of using "NSE" is that both F_3 and the final value of the SQI increase with an increase in the total number of tests. Therefore, for the purposes of the SQI, F_3 is modified to use "ASE," where the sum of excursions is divided by only the total number of tests that are not in compliance (Equation 1.11). The main reasons for this change are as follows:

As the quality of a contaminated site is primarily judged by the amount of excursions of various contaminants from their guidelines, the value of F_3 should appropriately reflect that in comparison with F_1 and F_2.

The effect of contaminants gets diluted by dividing the excursions by the total number of tests.

Any one of the contaminants that is not in compliance can cause severe limitations for the ecosystem or public health. Therefore, the impact of any contaminant should not be minimized in rating the contaminated site.

Step 3: F_3 is then calculated by an asymptotic function that scales the ASE to yield a range between 0 and 100 as follows:

$$F_3 = \frac{\text{ASE}}{0.01\,\text{ASE} + 0.01} \tag{1.12}$$

1.5.4.4 Soil Quality Index (SQI)

Once the factors are quantified, the SQI can be calculated by adding together all the factors as if they were vectors as shown in Equation (1.13). This approach treats the index as a three-dimensional space defined by each factor along one axis. With this model, the index changes in direct proportion to changes in all three factors:

$$\text{SQI} = 100 - \sqrt{F_1^2 + \frac{F_2^2 + F_3^2}{1.732}} \tag{1.13}$$

The divisor (1.732) normalizes the resultant values to a range between 0 and 100, where 0 represents a very high level of contamination or public concern and 100 represents a negligible amount of contamination or public concern. The value of the divisor is calculated as follows:

$$\frac{\sqrt{100^2 + 100^2 + 100^2}}{100} = 1.732 \tag{1.14}$$

If a site is not tested more than once over time or space, the factor F_2 (frequency) will not be applicable and the divisor for the Equation (1.13) for calculating the SQI will be 1.414. Based on the final value of the index, contaminated sites can be divided into five different classes. Each class of contaminated site needs to be interpreted based on the level of concern for public and ecosystem health and the need for remediation. Sites with a high SQI score (e.g. 90–100) are of high quality, have a very low level of concern, and have low priorities for remediation. At the other end of the scale, a low SQI score (0–30) would indicate a very high level of concern due to contamination and therefore a great need for remediation (Table 1.18).

Table 1.18 Site classes or level of concern and soil ranking categories of the SQI.

Site classes or level of concern	Soil ranking categories of the SQI
Very low	90–100
Low	70–90
Medium	50–70
High	30–50
Very high	0–30

When reporting SQI scores for contaminated sites, users should also provide a list of major contaminants of public concern and a statement describing the need for soil remediation or soil management options where possible (Example 1.8).

Example 1.8 The US EPA provided a case study in Saskatchewan, which was contaminated with petroleum hydrocarbons and later remediated using a tier 1 approach. The soil samples were taken from four different locations and analyzed for benzene; ethylbenzene; toluene; xylenes; petroleum hydrocarbons (PHC) such as F1 (C6–C10), F2 (C10–C16), F3 (C16–C34), and F4 (C34–C50); and lead. The analytical data and applicable soil quality guidelines are presented in Table 1.19.

Find: The SQI for this site.

Solution:

$$F_1 = \frac{5}{9} \times 100 = 55.6$$

$$F_2 = \frac{6}{36} \times 100 = 16.7$$

F_3:

$$\text{Excursion}_{\text{i}} = \frac{40}{5} - 1 = 7$$

$$\text{Excursion}_{\text{ii}} = \frac{82}{50} - 1 = 0.64$$

$$\text{Excursion}_{\text{iii}} = \frac{220}{50} - 1 = 3.4$$

$$\text{Excursion}_{\text{iv}} = \frac{2840}{1000} - 1 = 1.84$$

Table 1.19 Soil sample analysis of a commercial site contaminated with petroleum hydrocarbons.

Parameter	West wall (mg/kg)	Bottom (mg/kg)	North wall (mg/kg)	South wall (mg/kg)	Saskatchewan subsoil guidelines[a]
Depth (m)	2.4	5.3	2.4	3.0	—
Benzene	0.8	1.1	0.5	*40*	5.0
Ethylbenzene	27	0.8	4.7	*82*	50
Toluene	*100*	2.0	0.8	14	30
Xylenes	*180*	4.5	7.8	*220*	50
PHC F1	820	96	140	*2840*	1 000
PHC F2	130	8.9	21	180	3 000
PHC F3	5[b]	5[b]	5[b]	5[b]	5 000
PHC F4	5[b]	5[b]	5[b]	5[b]	10 000
Lead	10	8	8	16	1 000[c]

Note:
[a] Saskatchewan's interim criteria of BTEX and PHC fractions of soils for the year 2003.
[b] Not detected at level stated.
[c] Saskatchewan's "Risk Based Corrective Actions for petroleum contaminated sites," November 1995.

$$\text{Excursion}_{\text{v}} = \frac{100}{30} - 1 = 2.3$$

$$\text{Excursion}_{\text{vi}} = \frac{180}{50} - 1 = 2.6$$

$$\text{ASE} = \frac{17.78}{6} = 2.96$$

$$F_3 = \frac{2.96}{(2.96 \times 0.01 + 0.01)}$$

$$F_3 = \frac{2.96}{0.0396} = 74.8$$

$$\text{SoQI} = 100 - \frac{\sqrt{55.6^2 + 16.7^2 + 74.8^2}}{1.732}$$

$$\text{SoQI} = 100 - 56 = 45$$

Answer: SQI = 45

Comment: The level of concern is high because the soil is contaminated with benzene, ethylbenzene, toluene, xylenes, and PHC fraction F1 (C6–C10). It is recommended that the soil be remediated.

1.6 Air, Water, and Soil Pollution

Since the severe smog environmental disasters in London and Los Angeles in the 1950s and 1960s, respectively, China is now suffering the same fate as industrialized countries after 38 years of rapid economic growth since 1980.

1.6.1 Air Pollution

Figure 1.7 shows that the primary and secondary NAAQS in the United States are 12 and 15 μg/m^3 (annual average), respectively. The corresponding standards in China are 15 and 35 μg/m^3 (annual average), respectively. Yet, none of the top 10 provinces or cities in China meet the secondary Chinese standards of 35 μg/m^3, in fact, the minimum annual average of PM$_{2.5}$ is 55 μg/m^3, which is 57% higher than the Chinese secondary standards.

For 74 major cities in China with population greater than one million, the number of days when air quality parameters were above the Chinese secondary standards was also alarmingly high as shown in Figure 1.8. It suggests that about 44% of the days could meet the Chinese secondary (NAQQS) of 35 μg/m^3, while for the rest of 56% days, the air was mildly to severely polluted.

1.6.2 Water Pollution

Water pollution in China is even worse than its air pollution, especially in urban areas. In 2015 China has almost 110 cities with over one million people and will grow to more than 220 cities by 2025. China consumes four times more water for one US dollar gross domestic production (GDP) created than water required in the U.S. Two-thirds of China's 660 cities suffer from water shortages with the situation termed "severe" in 110 cities. About 700 million people drink water that is contaminated with animal and human waste. Water pollution poisons 190 million Chinese and causes an estimated 60 000 premature deaths every year. In 2005, the Chinese water supply system leaked an estimated 10 billion m^3, more than 20% of the total produced drinking water. China classifies water resource into (i) drinkable (Cat I–III), (ii) industry use only (Cat IV), and (iii) agricultural use only (Cat V). However, only a fraction of water resources satisfy Cat I–III.

China accounts for approximately 19.5% of the world population but has only 7% of the globe's freshwater resources. In northern China, 90% of the aquifers located in under Chinese cities are polluted. Over 75% of river water flowing through urban areas is considered unsuitable for drinking or fishing. Thirty percent of river water in China is regarded as unfit for agricultural or industrial use (Figures 1.9 and 1.10).

Figure 1.11 shows that only 12 and 28% of the groundwater in the country are excellent and good, respectively.

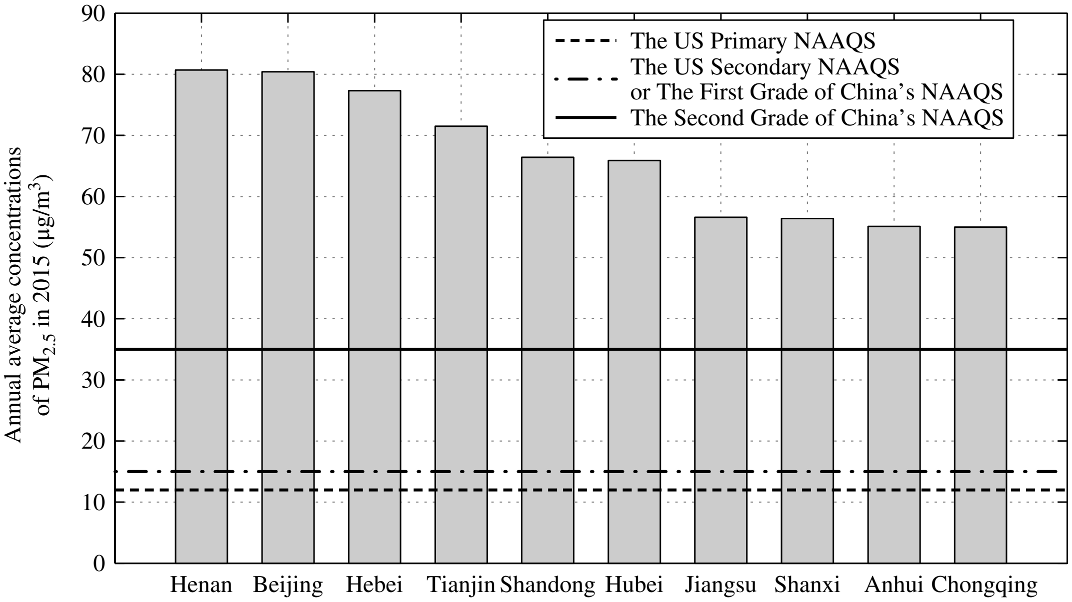

Figure 1.7 China's 10 most polluted provinces in 2015. Note: (1) US primary and secondary standards were from https://www.epa.gov/criteria-air-pollutants/naaqs-table. (2) The primary and secondary Chinese National Ambient Air Quality Standard (NAAQS) is 15 μ g/m^3 (Annual average). Available from http://transportpolicy.net/index.php?title=China:_Air_Quality_Standards. (3) Chinese Ministry of Environmental Protection (MEP). *Ambient Air Quality Standards (GB 3095-2012).* (2012) (accessed 5 August 2015). Available at http://kjs.mep.gov.cn/hjbhbz/bzwb/dqhjbh/dqhjzlbz/201203/W020120410330232398521.pdf.

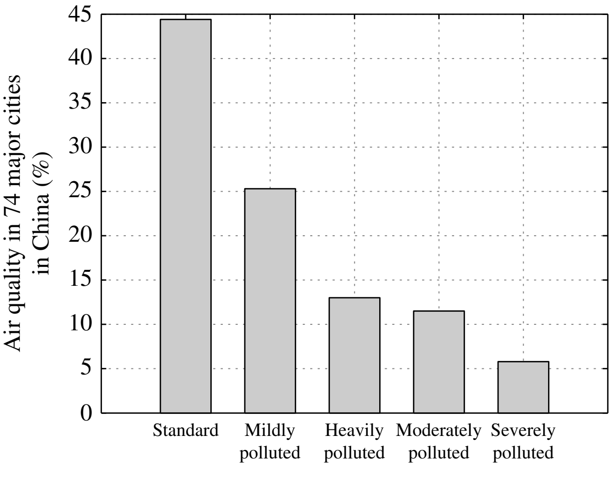

Figure 1.8 Air quality in 74 major cities in China in the first quarter of 2013. (*Source:* Department of Environmental Protection of the People's Republic of China, "Air quality in 74 major cities in China in the first quarter of 2013.")

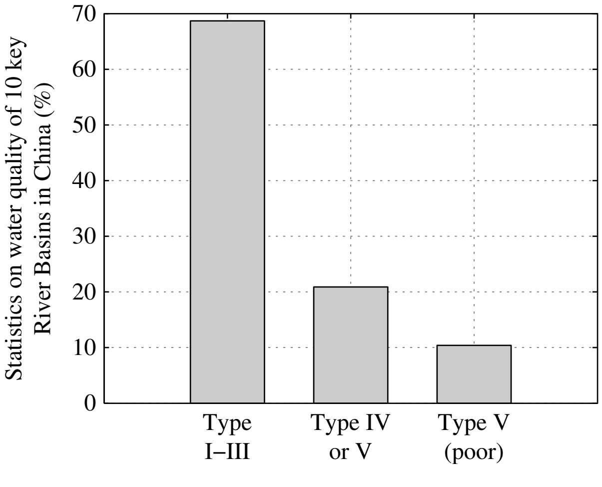

Figure 1.9 Statistics on water quality of 10 key river basins in China. (*Source:* "Communique on Land and Resources of China 2012," Bulletin of China's Environmental Conditions 2012, Ministry of Environmental Protection.)

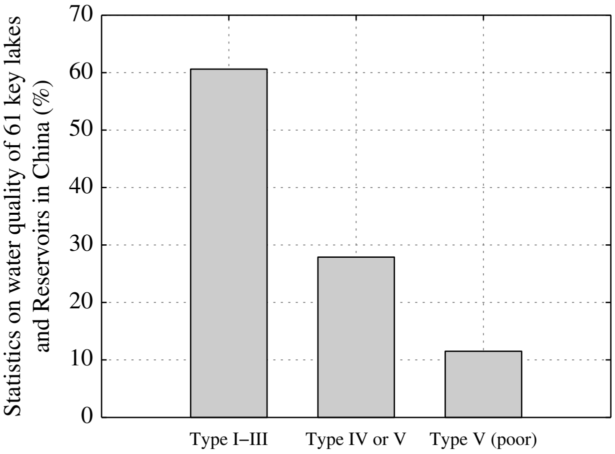

Figure 1.10 Statistics on water quality of 61 key lakes and reservoirs in China. (*Source:* "Communique on Land and Resources of China 2012," Bulletin of China's Environmental Conditions 2012, Ministry of Environmental Protection.)

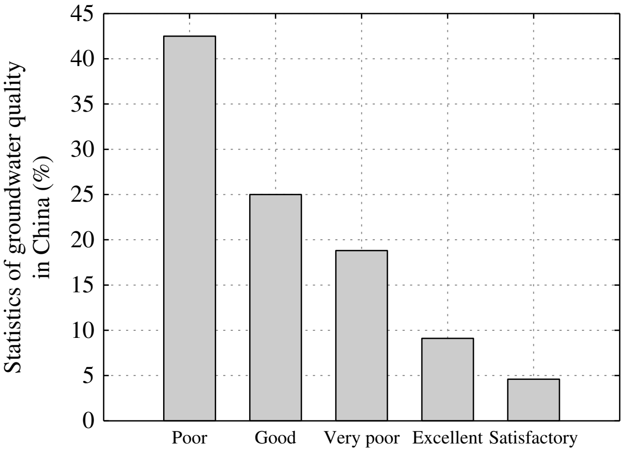

Figure 1.11 Statistics of groundwater quality in China. (*Source:* "Communique on Land and Resources of China 2012," Bulletin of China's Environmental Conditions 2012, Ministry of Environmental Protection.)

1.7 Life Cycle Assessment

One of the ways to quantify footprint of an EEIS is to conduct life cycle assessment (LCA). LCA is an evaluation method used to assess environmental impact associated with all the stages of a product's life cycle. LCA could be conducted from raw materials to finished goods, or cradle to grave, i.e. from raw materials to disposal of finished goods. LCAs are becoming a standardized protocol referred to by the International Organization for Standardization (ISO) (2006) with codes 14040–14048. Direct application of the ISO refers to product development and improvement, strategic planning, public policy making, marketing, and other processes through technique, economic, and social tools. The system should be isolated from the surroundings using system boundaries to define a specific area in the ISO process. LCA is the process of identifying the future consequences of a current or proposed action. The standardized categories of impact assessment include (i) global warming, (ii) smog formation, (iii) ozone depletion, (iv) acid rain, (v) human inhalation, (vi) ingestion toxicity, (vii) human carcinogenic inhalation, (viii) carcinogenic ingestion toxicity, and (ix) fish toxicity. Data quality is judged based upon its precision, completeness, representativeness, consistency, and reproducibility and should satisfy the assumptions and uncertainties made under the ISO. ISO has different orders to categorize the immediate impact by considering input and output methods usually used in LCA as shown in Figure 1.12.

A generic procedure of LCA according to the ISO 14040/14044 has the following five steps (ISO, 2006):

Step 1: Goal and scope definition

Goals of LCA should state the intended application, use, and audience as well as the reason for the study. The scope should define system boundaries to determine data collection. In the LCA of WWTPs, for example, following data should be collected: (i) concentration of each pollutant, (ii) flow rate, (iii) treatment and unit processing, and (iv) discharge standards and ambient water quality. The definition of goal and scope relates mainly to the identification of study type according to its intended application and audience as follows:

The objectives of the LCA assessment
Definition of a functional process

1) System boundaries defining the life cycle phases to be included
2) Procedure for coproduction or reuse and recycling in terms of mass, energy, or environmental significance
3) Choice of environmental impact categories, indicators, and characterization models
4) Data requirements, quality, uncertainty, type, and sources
5) Assumptions and limitations

Step 2: Inventory analysis and product model

The method of data collection and the quantification of input and output flows (e.g. materials or energy) depend on the assessed life cycle stages. Data collection, calculation, validation, and relation of the information to life cycle stages or objectives of assessment must be conducted for life cycle inventory analysis.

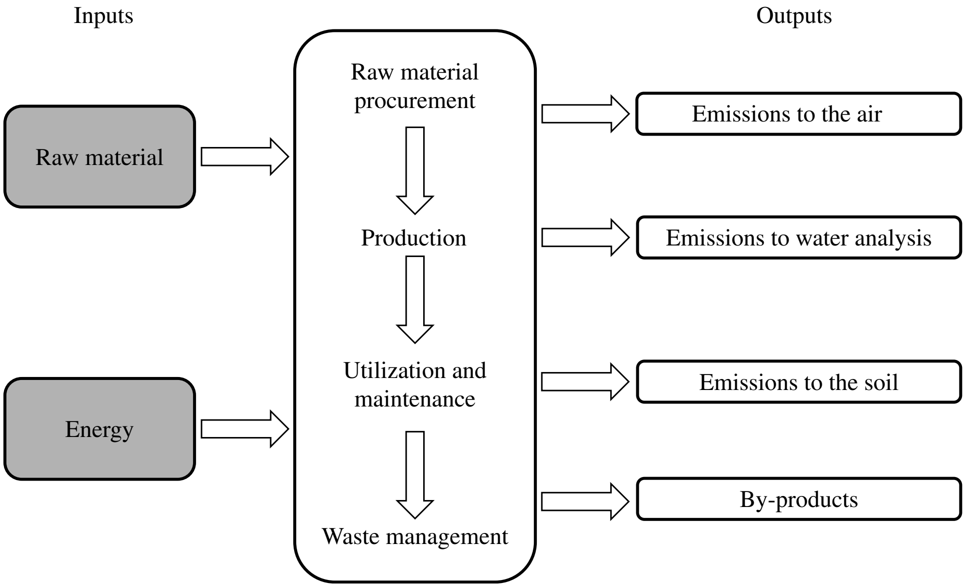

Figure 1.12 Input and output in life cycle assessment process.

Step 3: Impact assessment

Environmentally, technically, and scientifically valid models and indicators should be selected for impact assessment. Typical impact categories are water consumption, land-use change, human toxicity, ecotoxicity or carbon sequestration, etc.

Step 4: Interpretation and documentation

Hot spots contributing to environmental impacts should be identified with quantified uncertainty and sensitivity. Guidance on the normalization, grouping, or weighting should be established.

Step 5: Review

LCA helps satisfy government regulations, helps decrease the environmental impact of a given product or process, and identifies ways to improve sustainability. Therefore, an external critical review is necessary for all comparative LCA studies. LCA modeling has following five elements:

1) Data collection (quality control)
2) Model development (empirical and physical)
3) Calibration (establishment of standards)
4) Verification (confirmation that assumptions are correctly made)
5) Validation (accuracy of the calibrated equation)

One of the major uncertainties in LCA is to quantify the weights of different environmental impacts. Weighting factors are measured in a certain amount of units and can be assessed through expert opinion. Uncertainty can be quantified by standard deviation and sensitivity is the change rate of impact with respect to independent variables. Uncertainty and sensitivity analysis are two very important aspects in LCA. Robustness describes how big a range a system can work under, while reliability reflects how long it will take for a system to break down. All of these should be discussed and agreed by experts in quantifying the weighting factors so that alternatives can be compared based upon the environmental impact indexes for an EEIS.

1.7.1 LCA Tools

The complicated procedure in the LCA process as well as a vast amount of data makes manual calculation laborious, even impossible. Fortunately, many software packages have been developed for different assessment processes as shown in Table 1.20.

1.8 Environmental Laws

To achieve sustainable development without breaking the PBs, many environmental laws have been developed according to the concept of LCA. Many laws have different goals from different angles of human, social, and

Table 1.20 LCA and LCI software tools.

Tool	Vendor	URL
BEES 3.0	NIST Building and Fire Research Laboratory	http://www.bfrl.nist.gov/oae/software/bees.html
Boustead Model 5.0	Boustead Consulting	http://www.boustead-consulting.co.uk/products.htm
CMLCA 4.2	Centre of Environmental Science	http://www.leidenuniv.nl/cml/ssp/software/cmlca/index.html
DuboCalc	Netherlands Ministry of Transport, Public Works and Water Management	http://www.rws.nl/rws/bwd/home/www/cgi-bin/index.cgi?site=1&doc=1785
Ecoinvent 1.2	Swiss Centre for Life Cycle Inventories	http://www.ecoinvent.ch
Eco-Quantum	IVAM	http://www.ivam.uva.nl/uk/producten/product7.htm
EDIP PC-Tool	Danish LCA Center	http://www.lca-center.dk
eiolca.net	Carnegie Mellon University	http://www.eiolca.net
Environmental Impact Indicator	ATHENA™ Sustainable Materials Institute	http://www.athenaSMI.ca
EPS 2000 Design System	Assess Ecostrategy Scandinavia AB	http://www.assess.se/
GaBi 4	PE Europe GmbH and IKP University of Stuttgart	http://www.gabi-software.com/software.html
GEMIS	Öko-Institut	http://www.oeko.de/service/gemis/en/index.htm
GREET 1.7	DOE's Office of Transportation	http://www.transportation.anl.gov/software/GREET/index.html
IDEMAT 2005	Delft University of Technology	http://www.io.tudelft.nl/research/dfs/idemat/index.htm
KCL-ECO 4.0	KCL	http://www1.kcl.fi/eco/softw.html
LCAIT 4.1	CIT Ekologik	http://www.lcait.com/01_1.html
LCAPIX v1.1	KM Limited	http://www.kmlmtd.com/pas/index.html
MIET 3.0	Centre of Environmental Science	http://www.leidenuniv.nl/cml/ssp/software/miet/index.html
REGIS	Sinum AG	http://www.sinum.com/htdocs/e_software_regis.shtml
SimaPro 6.0	PRé Consultants	http://www.pre.nl/simapro.html
SPINE@CPM	Chalmers	http://www.globalspine.com
SPOLD	The Society for Promotion of Life-Cycle Assessment	http://lca-net.com/spold/
TEAM™ 4.0	Ecobalance	http://www.ecobalance.com/uk_lcatool.php
Umberto	ifu Hamburg GmbH	http://www.ifu.com/en/products/umberto
US LCI Data	National Renewable Energy Lab	http://www.nrel.gov/lci

economic development. From the LCA perspective, environmental laws governing petroleum-based fuel are categorized in Table 1.21.

In terms of LCA, environmental laws are categorized as in Table 1.22.

As regulations are becoming more and more stringent, water utilities must react to the new requirements in a relatively short time frame. Retrofits to reduce emissions or comply with new design criteria are costly. If SEE designers look beyond compliance to achieving the greatest energy efficiency, WWTP should be designed as energy positive using anaerobic ammonia oxidation (Anammox) and anaerobic membrane biological reactor (AnMBR). As a result, WWTP could produce energy and yet comply with environmental laws. Indeed, regenerative design saves money in materials and in energy, reduces the financial burden on consumers, and even increases cash flow of a WWTP.

Table 1.21 Environmental laws on onshore petroleum.

Purposes of laws	Environmental laws
Where to extract	National Park System Mining Regulation Act
	Federal Land Policy and Management Act
	National Forest Management Act
	Federal Onshore Oil and Gas Leasing Reform Act
	Clean Water Act
	Wild and Scenic Rivers Act
	National Wildlife Refuge System Act
How to extract	Clean Water Act
	Federal Onshore Oil and Gas Leasing Reform Act
	Resource Conservation and Recovery Act (RCRA)
	Endangered Species Act
	Safe Drinking Water Act
	National Environmental Policy Act
Transportation of petroleum	Federal Onshore Oil and Gas Leasing Reform Act
	Federal Land Planning and Management Act
	Department of Transportation Regulations
	CERCLA
	RCRA
Transportation and storage of petroleum	Mineral Management Service Regulations
	International Convention for the Prevention of Pollution from Ships
	National Environmental Policy Act
	1990 Oil Pollution Act
	Deepwater Port Act
	Shore Protection Act
Locate the refinery	Deepwater Port Act
	National Environmental Policy Act
	Endangered Species Act
	Wild and Scenic Rivers Act
	Migratory Bird Treaty Act
	Historic Preservation Act
	Clean Air Act
Refining process emissions	Clean Air Act
	Clean Water Act
	Occupational Safety and Health Act
Refining process	Toxic Substances Control Act
	Emergency Planning and Community Right-to-Know Act
	CERCLA
Use of gasoline	Petroleum Marketing Practices Act
	Occupational Safety and Health Act
	Clean Air Act
	Power Plant and Industrial Fuel Use Act
	Environmental taxes
	Transportation controls

Table 1.22 Environmental laws on onshore petroleum.

LCA	Purposes	Environmental laws
Resource extraction	How and where resource can be extracted	Clean Water Act
Production	How to refine the cruel oil	EPCRA
Emission	What are pollutants	Clean Air Act
Use	How products can be used	TCA, FIFRA
Disposal	Disposal and damage to the environments	CERCLA or RCRA

1.9 Exercise

1.9.1 Questions

What is an ecological footprint of a person, and what is the carrying capacity of the Earth?

How much larger is your ecological footprint in comparison with the rate the Earth can regenerate?

What does an "overshoot" of an ecological footprint mean?

What is the measurement unit of the ecological footprint?

What assumptions are made in order to calculate an ecological footprint?

How would be footprint on water change if people's diet reduce from red meat to vegetable protein?

What are the risks we face as humanity's demand for ecological resources of the Earth exceeds nature's supply?

Which carrying capacity do you think is the most probable estimate?

How technology advances would impact Earth's future carrying capacity?

What role of SEE designers can play to contribute to the UN SDGs?

1.9.2 Assignment

1) Go to http://www.myfootprint.org and read the intro. Most of it will cover what you just read in the aforementioned website. Enter the quiz and work through the questions.
2) Do the quiz and compare your average ecological footprint with the average footprint of 24 acres in the United States.
3) Go to http://www.rprogress.org/ecological_footprint/footprint_FAQs.htm and answer these questions.
4) Study SPSS tutorial manual.
5) On any specific day that you are working on this assignment, please select 20 cities in the United States, Europe, and China by real-time air quality index. Please go to http://aqicn.org/map/northamerica/ for major cities in America, http://aqicn.org/map/europe/ for major cities in the European Union, and http://aqicn.org/map/china/ for major cities in China. Please conduct the following analysis using SPSS and answer following questions:
   a) What are the mean and standard deviations of the AQI for the top 20 most polluted cities in these three regions?
   b) What does the mean and standard deviation tell you about the real-time AQI in these three regions?
   c) Please rank the three regions according to the mean of their AQIs on that day.
   d) According to the standard deviation, please quantify your rank in terms of confidence intervals using Monte Carlo simulations.
   e) Do you expect any seasonal change of this rank? Why?
6) From the real-time AQI that you get for that day, please estimate the total amount of pollutants that an adult will breathe in a lifetime of SO_2, NO_2, CO, and $PM_{2.5}$ by assuming that an adult lives 70 years and half of his/her life is spent outdoors. Please answer the following questions:
   a) Will this exposure data be representative data for your exposure assessment?
   b) How can you improve the exposure assessment?

1.9.3 Problems

1) For Example 1.1, if T_a and T_s are temperatures for the atmosphere and top of atmosphere and the atmosphere and surface are in equilibrium, the following equilibrium would be true:
   i) Surface:

$$\sigma T_s^4 = \sigma T_a^4 + \frac{S_o}{4}\left(1-\alpha_p\right)$$

   ii) Atmosphere:

$$2\sigma T_a^4 = \sigma T_s^4$$

   iii) Top of atmosphere:

$$\frac{S_o}{4}\left(1-\alpha_p\right) = \sigma T_a^4$$

   What are the temperatures for the atmosphere and top of atmosphere, T_a and T_s, respectively?
2) If a watershed of 2000 m^2 in Miami-Dade County has precipitation of 65 in/year, ET is 55 in/year, runoff from the canals is 1.023×10^6 acre-ft/year, groundwater withdrawal is 331 million gallons per day (MGD), wastewater discharge back to aquifer in the form of septic systems is 1 MGD, wastewater outfall to the ocean is 216.5 MGD, and wastewater injected into the Florida aquifer (deep well injection) is 97 MGD, please answer the following:
   a) What would be the difference between the inputs and outputs?
   b) Is the water budget in a steady state?
   c) What parameters are missing from this water budget?
3) A lake has water quality as follows: dissolved oxygen, 60; nitrate, 6.10 (mg/l); phosphate, 0.8 (mg/l); and pH, 5.5. Please answer the following:
   a) What is the WQI of this water if the weighting factors of the corresponding water quality parameter are 0.3, 0.2, 0.2, and 0.3, respectively?
   b) What is the WQI of this water if the weighting factors of the corresponding water quality parameter are 0.5, 0.2, 0.2, and 0.1, respectively?
   c) Why are they different? How would one determine the weighting factors of each water quality parameter?
4) A residential house in Miami receives precipitation as in Example 1.2, which has 1 acre of land with a 4356 ft^2 roof. If a rain harvest system is to be installed by collecting the rainwater from the roof, is the rainwater sufficient for a family of four people if water consumption is 200 gal/person/day?
5) Please determine whether the hydrologic budget is in deficit, in surplus, or in a steady state as change in storage by developing a hydrologic budget equation, if precipitation is 72 in/year, evapotranspiration is 59 in/year, surface water runoff is 9.6 in/year, groundwater inflow is 8 in/year, and groundwater pumping is 3.4 in/year.

1.9.4 Projects

1.9.4.1 Xiongan Project

China proposed to build an eco-friendly megacity, Xiongan New District, as a new special economic zone of China. The zone will cover Xiongxian, Rongcheng, and Anxin counties in Hebei province. Current population is 100 000. The city will be developed through ecological protection, clustered urban layout, and coordinated development. Within the new city, Baiyangdian is one of the largest freshwater wetlands in north China, which has more than 140 lakes and covers 366 km^2. The city will cover 100, 200, and 2000 km^2 to accommodate 1, 1.5, and 2.5 million people in the next 5, 10, and 50 years, respectively. As much as $348 billion of investment will be attracted to the new city over the next decade. To support the development of Xiongan, China Development Bank would loan $18.9 billion in infrastructure. As a smart city and a tech hub, it is planned to power the city with 100% renewable energy.

Please answer the following:

1) What are the air, water, and soil quality in the city?
2) What are the major remediation projects indexes of air, water, and soil that have to be carried out before the ambitious development?
3) According to the ecological footprint, what would be the average ecological footprint in the next 5, 10, and 20 years?
4) If the ecological footprint is greater than the biocapacity, what are the major strategies that could be employed to prevent ecological overshoot in the next 5, 10, and 20 years?
5) If all the WWTPs of the city were to be designed and built as energy positive WRRFs, how much energy have to be produced annually in WRRFs in the next 5, 10, and 20 years?

1.9.4.2 Community Project

1) Please collect raw data from the hometown where you originally came from:
   a) Land areas
   b) Current population
   c) GDP in the last twenty years
   d) Predict future population and GDP in the next 5, 10, 20, 50, and 100 years
   e) According to the predicted GDP, what are the ecological footprints of people in your hometown?
   f) What would be the ecological capacity of your hometown in the next 5, 10, 20, 50, and 100 years?
   g) Is the ecological FP of your hometown greater, equal, or less than the natural biological carrying capacity in the next 5, 10, 20, 50, and 100 years?
2) Please collect following relevant raw data from the hometown where you originally came from in the last 10 years:
   a) Industrial production
   b) Agricultural production
   c) Residential houses
   d) Unit emission factors from the US EPA manual
   e) Inventory of air, water, and soil pollution
3) Please calculate the following indexes of your city:
   a) Water quality index
   b) Air quality index
   c) Soil quality index
4) According to the calculated indexes, please rank which pollution is the most urgent environmental issue in your hometown and identify the major pollution sources in your hometown.

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