1

Introduction

Issues in Water Harvesting and Water Security

CHAPTER MENU

1.1 Concept/Principles of Water Harvesting and Water Security

Rainwater harvesting (RWH) is not a new concept. The basic principle of water harvesting (WH) is to capture rainfall and high-intensity rainfall-induced surface runoff in one area and transfer it to another water-scarce area, thereby increasing the amount of water available in the latter. The concept of water security has its genesis in the need to shift focus to demand-side water management from supply-side, so that water is available in adequate quantity, during both normal and typical conditions. It became clear long ago that water systems should be considered as a whole, since water quantity and water quality issues on rainwater, surface water, and groundwater resources are linked. However, the term "water security" has taken a central position recently associated with other popular terms such as "food-water-energy nexus," "water hazard," "water risk," "water vulnerability," "water resilience," "sustainable water resources management," "integrated water resources management," and "adaptive water management."

The term "water security" is generally associated with other terms such as "integrated," "sustainable," and "adaptive." However, achieving water security, in practice, requires interinstitutional and interdisciplinary integration across the boundaries of many sectors, such as political, administrative, governance, biophysical, social, infrastructural, economic, and financial, most of which lie outside the direct realm of water, to reduce competition or even conflict over water resources. Development studies often consider the national scale, hydrological studies generally employ a catchment scale, and social scientific studies usually focus on the community scale. Therefore, water security at household, local, urban, rural, state, regional, country, or global level is likely to have very different meanings. WH and water security have been therefore defined in a number of ways, and can be grouped as *in situ* and *ex situ* types, and it is necessary to clearly assess the potential of RWH in reality, depending on the source, availability, and volume of water.

Water Harvesting for Groundwater Management: Issues, Perspectives, Scope, and Challenges,
First Edition. Partha Sarathi Datta.

1.1.1 Source of Water and Its Availability

The primary source of water is rainfall. Globally, the exposed land surfaces receive approximately 113 000 km^3 of rainfall each year. Of this, approximately 41 000 km^3 (or 36%) is surface runoff, which replenishes rivers, streams, and lakes. The balance (64%) is evaporated via vegetation, soil, and water surfaces.

Easy access to water and its adequate availability is essential for living beings, domestic, agricultural, industrial, and economic development purposes. Although, globally, enough water exists, its supply has reduced due to growing population demand for water for domestic, agriculture, energy production, manufacturing, and healthcare purposes, and via pollution. In many countries, where water supply comes mostly from surface water bodies, pollution of rivers and lakes and the non-availability of adequate quantities of good-quality water supply has lead to increased dependence on groundwater. This has resulted in indiscriminate extraction of groundwater in excess of the natural recharge in many areas, causing substantial decline in groundwater levels and yields of many dug wells and tube wells.

The increase in groundwater abstraction, associated with population growth and increasing demands for water, food, and income, began during the first half of the twentieth century in a limited number of countries such as Italy, Mexico, Spain, and the USA. However, the periods of maximum growth were not simultaneous, and varied from country to country: 1950–1970 in the United States, 1960–1990 in India, and 1975–2000 in China. The most pronounced increase in extraction has been in those countries where current groundwater withdrawals are the highest. In the 1960s, a second phase started in parts of South and East Asia, the Middle East, and northern Africa. In the 1990s, a third phase started, including some South and South-East Asian countries such as Sri Lanka and Vietnam, and also sub-Saharan Africa. In the developed countries, stabilizing/declining trends followed a strong but variable increase in abstraction of groundwater in the earlier stages.

For example, in the USA, in 30 years (1950–1980), abstraction increased by 144%, followed by a temporary decline but a stable average during 1980–2005. In Japan, in 30 years (1965–1995), abstraction increased by 60%, before declining by 13% during 1995–1999. In several European countries also, although extraction was generally at lower levels, periods of marked growth have been observed; for example, in the UK, more than 54% of growth occurred in 25 years (1950–1975); in Denmark, more than 70% in seven years (1970–1977); in Spain, more than 15% in 10 years; and in The Netherlands, more than 12% in five years (1971–1976). In Australia, groundwater abstraction almost tripled in 30 years (1970–2000). In Germany, Belgium, France, Sweden and Canada, groundwater abstraction remained relatively stable over time. Since the beginning of the twenty-first century, almost all European countries have demonstrated stabilization or slightly declining groundwater abstraction trends.

In developing countries, such as India and China, with increasing demographic and economic growth, increases in groundwater abstraction have generally been observed from the period 1970–1980 onwards, especially where irrigation has expanded significantly. Large increases have occurred in countries of the arid and semi-arid zone where oil revenues facilitated deep groundwater (including non-renewable resources) to be withdrawn for irrigation. Total groundwater withdrawal increased by a factor of 11 in Libya during 1970–2000; by 10 in Saudi Arabia during 1975–2000; by 6 in Egypt during

1972–2000; by 3.3 in Iran during 1965–1995; and by 3.2 in Tunisia during 1977–2000. During the last 50 years, easy accessibility of groundwater and its local availability have increased the number of shallow wells. On the other hand, public affordability for sinking tube wells has increased due to technological developments in construction of deep tube wells, water abstraction devices and pumping methods, provision of free or subsidized electricity for pumping in many parts, and easy credit availability from financial institutions.

Globally, this has resulted in indiscriminate extraction of groundwater in excess of the natural recharge in many areas, causing substantial decline in groundwater levels and yields of many dug wells and tube wells, particularly during the summer. It has become difficult for resource managers to co-ordinate users of the same aquifers across wide geographic spaces. Over the last few decades, increasing groundwater depletion and degradation in India and other parts of the world, and ecologically damaging, socially intrusive, capital-intensive, and unsustainable water resource development projects implemented so far have forced people to find alternative sources of water supply. These problems have forced people to consider local RWH, conservation, and reuse for agriculture, irrigation, and other purposes. Globally, from time immemorial, people were aware that groundwater augmentation by artificial recharge and WH by collecting, storing, and conserving of local rainwater surface runoff on natural catchment areas on rocky surfaces, hill slopes, rooftops, and artificially prepared impervious/semi-pervious surfaces may provide augmentation of water supply.

1.1.2 Concept and Definition of Water Harvesting

The RWH concept employs a wide range of approaches and technologies to collect and store rainwater. WH has been defined and classified in a number of ways, and can be grouped as *in situ* and *ex situ* types, depending on the source of the collected water.

a) *In situ* RWH technologies are soil management strategies that enhance rainfall infiltration and reduce surface runoff.
b) *Ex situ* RWH collects surface runoff water from areas such as rooftops, land surfaces, steep slopes, road surfaces or rock catchments for storage in tanks. Depending on the size of the storage, *ex situ* RWH systems can be further divided into passive and active systems.
    - Passive systems (e.g. rain barrels) are small-volume (50–100 gal) systems that capture rooftop runoff without treatment. The captured water is generally not used for drinking purposes. Due to their size, passive harvesting systems are commonly used in residential applications.
    - Active systems (e.g. cisterns) are of relatively larger volume (1000–100 000 gal) and capture runoff from roofs or other suitable surfaces such as terraces and road surfaces. Active harvesting systems provide water quality treatment and can be used on a community level.

Commonly, the terms WH and RWH are synonymous and used interchangeably. The main difference is with respect to breadth and scope. Most of the definitions are similar and closely related, and WH is generally defined as: “The collection and management of high intensity rainfall induced water runoff and/or floodwater to increase water availability for domestic and agricultural use as well as ecosystem sustenance.”

1.1.2.1 Why Harvest Rainwater?

Important reasons for harvesting rainwater include the following:

- For centuries, it has been the simplest indigenous technology, being practiced in India and many other parts of the world.
- To conserve surface water runoff during the monsoon.
- To reduce soil erosion.
- To arrest groundwater decline and augment the groundwater table.
- To improve water quality in aquifers.
- To inculcate a culture of water conservation.
- Self-sufficiency, less expensive, and ease of maintenance.

1.1.2.2 Aims of Water Harvesting

The aims of WH are essentially to collect surface runoff from areas of surplus and to store it in over- or underground storage, to recharge groundwater levels, deliberately reallocate water resources over time within a landscape and make it available to places where there is water shortage. This increases the availability of water by (i) impeding and trapping surface runoff, (ii) maximizing water runoff storage, and (iii) harvesting subsurface groundwater. Water harvesting makes more water available for domestic, livestock, and agricultural use by buffering and bridging drought spells and dry seasons through storage. Water harvesting captures water for domestic use, replenishes green water supplies, or increases blue water availability locally. New methods and mechanisms are being developed all over the world to conserve water as far as possible in all sectors. Our predecessors also adopted concepts of water recharge, which are still practiced today. However, with time, improvements in technology have introduced new recharge techniques to achieve better results.

1.1.2.3 Principles, Concept and Components

The basic principle of WH is to capture rainfall in one area and transfer it to another water-scarce area, thereby increasing the amount of water available in the latter. Water harvesting is seen as an integral part of sustainable land and water management. Water harvesting and runoff recycling has six basic components: a catchment or collection area, collection (harvesting) of excess rainfall, runoff conveyance system (including lifting and conveyance), water application area, efficient storage of harvested water, and optimal utilization of applied water for maximum benefits. In some cases, the components are adjacent to each other, in other cases they are connected by a conveyance system. The storage and application areas may also be the same, typically where water is concentrated in the soil for direct use by plants.

1.1.2.3.1 Catchment or Collection Area

The area where high-intensity rainfall-induced runoff is harvested. The catchment area may be a few square meters to several square kilometers. It may be a rooftop, a paved road, compacted surfaces, rocky areas or open rangelands, cultivated or uncultivated land and natural slopes.

1.1.2.3.2 Conveyance System

The system by which runoff is conveyed through gutters and pipes (in the case of rooftop WH) or overland via rills, gullies or channel flow and diverted onto cultivated fields (where water is stored in the soil) or into specifically designed storage facilities.

1.1.2.3.3 Storage Component

The place where harvested runoff water is stored until it is used by people, animals, or plants. Water may be stored in the soil profile as soil moisture, above ground (tanks, ponds or reservoirs), underground (cisterns) or as groundwater (near-surface aquifers) (Oweis et al. 2012). In places where concentrated runoff is directly diverted to fields, the application area is identical to the storage area, as plants can directly use the accumulated soil water. A great variety of storage systems hold the water until it is used either adjacent to the storage facilities or further away.

1.1.2.3.4 Application Area or Target

The area where the harvested water is put into use for domestic consumption (drinking and other household uses), livestock consumption, or agricultural use (including supplementary irrigation).

Water harvesting may occur naturally, for example in depressions, or "artificially" through human intervention. Artificial WH involves interventions to improve precipitation collection and to direct runoff to the application area. When surface runoff is very low, approaches such as smoothing or compacting the soil surface, clearing rock surfaces, surface sealing or using impermeable coverings can improve WH. Water availability by harvesting can be enhanced by the recharge of soil water and groundwater, and water storage in reservoirs, for ecosystem maintenance and industrial use, although most WH technologies are employed for domestic and agricultural use.

The catchment to application area ratio (C/A) represents the quantity of rainfall/runoff in WH systems, and is a measure of the size of the catchment compared with the size of the application area. It is generally used where runoff is stored in the soil for plant production. In the design of WH systems, this ratio is determined by considering seasonal rainfall, crop water requirement, and physical characteristics of both the catchment and the concentration area. Ideally, the catchment area (with the exception of rooftop WH) should have clay or shallow soils with low infiltration rates, susceptible to crusting and sealing, or hard surfaces with high runoff coefficients such as roads or rocky hillsides. However, in systems where runoff is stored in the soil, deep soils with high water infiltration and storage capacity are desirable in the application area.

1.1.2.4 Water Retention, Recharge, and Reuse Concept

This concept focuses on water buffering to better manage natural recharge, and to extend the chain of water use. During very high-intensity rainfall, large quantities are usually lost through floods, surface runoff, and evaporation. The unused water can be retained through the following buffering technique/strategies.

- *Groundwater recharge and storage*: this is "closed" underground storage with smaller evaporation losses than for open water storage. Water can be accessed by wells. Examples include sand dams, infiltration ponds, and spate irrigation.
- *Soil moisture conservation in the root zone*: water is stored in the root zone of the soil. Crops can use some of the water, and the remaining part percolates deeper to recharge the groundwater. Examples include grass strips, deep plowing, and conservation agriculture.
- *Closed tank storage*: in this approach, water can be stored without pollution, close to the location where it is used as drinking water. Examples include rooftop tanks, underground cisterns, and fog shields.

- *Open surface water storage*: by this method, larger volumes of water can be stored and used for agricultural and industrial purposes. Examples include storage reservoirs (small), road WH, and trapezoidal bunds.
- *Coastal reservoirs for freshwater storage*: the excess fresh water from river runoff during the wet season can be stored in reservoirs and then pumped to the land during the dry season, to meet the water demand and supply gap in coastal regions.

Each type of buffer option has its strengths and weaknesses, and local conditions usually help to determine which option to use. In general, buffering capacity increases as one moves from small to large storage, and from surface to soil or groundwater storage. Often, different types of storage complement each other in water buffering at landscape and basin level.

1.1.2.5 Water Harvesting for Groundwater Recharge

Water harvesting for groundwater recharge is most generally used for collecting and managing high-intensity rainfall-induced floodwaters and runoff to recharge groundwater artificially. The term “artificial recharge” has different connotations for different practitioners. Whether the groundwater recharge occurs under natural or artificial conditions, the same physical laws govern the recharge process. However, in artificial recharge, human effort involves adopting procedures and approaches to accelerate the natural process of recharging the aquifers through percolation of stored or flowing surface water which otherwise would not easily reach the aquifers.

In the broadest sense, artificial recharge of groundwater refers to the addition and/or infiltration of surface water to the aquifer to ensure the availability of water at a particular location at a particular time. Therefore, any man-made facility that adds water to an aquifer may be considered as artificial recharge. Artificial recharge also aims at augmenting groundwater storage at a rate exceeding that of natural conditions of replenishment, by some method of construction, spreading of water, or by artificially changing natural conditions. The process may be either planned, such as storing water in pits, tanks, etc. for deliberately feeding the aquifer, or unplanned and incidental to human activities, such as applied irrigation, leakages from pipes, etc. This is useful for reducing overdraft, conserving surface runoff, and increasing available groundwater supplies.

Rainwater in rural areas is considered fairly clean except for some dissolved gases it may pick up from the atmosphere. However, rainwater in urban areas is not free of pollution and contains atmospheric gases in dissolved form, sediments, dust, aerosols, particulates, anthropogenic gases from industrial discharge, biomass and fossil fuel burning, metallurgical processes, and other anthropogenic activities, and also biochemical processes in soil and water. The carbonates, nitrates, and sulfates in the atmosphere react with water vapor and form carbonic, nitric, and sulfuric acids, which create acid rain, which is detrimental to ecosystem and water quality. Therefore, both in rural and urban areas, surface runoff may carry pollutants from non-point sources (fertilizers, pesticides, chicken and cow manure), dissolved minerals, sediments, sewage, decaying plants, algae, bacteria, etc. Building elevated banks around ponds can reduce surface runoff, but water may be lost to evaporation if the ponds are not completely covered. Moreover, ponds may be connected to groundwater flow and may be subject to contamination by dissolved chemicals.

In RWH harvesting, high-intensity rainfall-induced floodwater and surface runoff can be harvested to recharge and replenish groundwater, depending on catchment type. Water is conserved and stored for reuse to extend crop-growing periods and/or for supplementary irrigation during dry periods in semi-arid rural areas. Groundwater extraction is done in traditional as well as unconventional ways (e.g. qanat systems, horizontal wells, etc.). The major advantages of RWH are that it is simple, efficient, cheap, replicable, and easily adaptable at small scale, and it improves water use efficiency and soil fertility, reduces soil erosion, and improves agricultural productivity (Li et al. 2000). However, the quantity of water that can be harvested depends on the frequency and intensity of rainfall, catchment characteristics, runoff amount, water infiltration rate and percolation rate to recharge the aquifers.

1.1.3 Factors Governing Selection of Suitable Structures for Artificial Recharge of Groundwater

- Quantity of non-committed surface runoff available
- Rainfall pattern
- Land use and vegetation
- Topography and terrain profile
- Soil type and soil depth
- Thickness of weathered/granular zones
- Hydrological and hydrogeological characteristics
- Socioeconomic conditions and infrastructural facilities available
- Environmental and ecological impacts of artificial recharge scheme

From time immemorial, people have been aware that traditional RWH technologies with simple, highly efficient structures for collecting and conserving local rainwater that runs off natural/man-made catchment areas can provide water for the local society and meet their needs for future use. Therefore, rainwater collection through artificial storage has been practiced in semi-arid areas. Due to its many benefits, RWH has received increased attention in recent decades and both governments and NGOs have started promoting RWH as a solution to water scarcity and water access. Consequently, a rapid expansion of rainwater catchment systems has occurred, especially in Asian and African countries facing water scarcity. RWH is mostly a local intervention and a decentralized method of gaining access to drinking water. However, due to very limited and sketchy knowledge about actual field-level performance in specific locations for augmentation of groundwater resources, debates have been ongoing for or against the large-scale acceptance of these technologies.

For instance, in India, despite over two decades of publicized activities and critical acclaim for these practices, with investments by international agencies for bringing "traditional knowledge" into development practice and encouragement from those sympathetic to grassroots environmentalism, concern about their vulnerability still exists. These technologies have also faced wide-ranging criticisms for ignoring scientific knowledge (and thus effectiveness) and power relations (linked to issues of equity) (Mosse 2003; Chhotray 2007). Funding agencies experience limitations in implementation at local scale, due to minimum scientific quantitative analysis of real-time data about the status of aquifer water quality and quantity, in order to understand the balances between water budget zones, yields of various crops grown, etc. in order to predict the impact of decisions on aquifer water quality and quantity – a common decision support system for all stakeholders.

Moreover, due to heterogeneity and the interconnectivity of groundwater aquifers across space and with surface water sources, recharge by one group or community may impact water availability for other neighboring or downstream groups. So far, impacts have been reported mostly with respect to changes in water availability, increased groundwater table, revival of flow of rivulets, and yields of crops, relying mainly on qualitative analysis based on secondary information collected from farmers/beneficiaries. However, limited/no scientific quantitative analysis has been done based on baseline data and chronological documentation to actually quantify the extent of soil erosion prevented, rise in the water table, increase in the time of water flow, or yields of the various crops grown at basin/watershed level.

In many countries, due to pollution of surface water bodies and non-availability of adequate quantities of good-quality water, there has been increasing dependence on groundwater. Unplanned and indiscriminate extraction of groundwater has also risen due to an increase in the sinking of tube wells driven by affordable technological developments in construction of deep tube wells, water abstraction devices and pumping methods, provision of subsidized or free electricity for pumping in many areas, and easy credit from financial institutions. This has resulted in imbalance between water withdrawal and natural recharge in many areas, causing substantial decline in groundwater levels and yields of many dug wells and tube wells. Therefore, it is necessary to determine the strengths, weaknesses, opportunities, and threats of these WH technologies, as well as benefits and gaps in knowledge, implementation and funding strategies, public participation, etc., and to assess the ability of these technologies to overcome the water stress situation in any meaningful sense.

Against this background of RWH and groundwater issues, an analysis of the food-water-energy nexus is discussed in the next section.

1.2 Food-Water-Energy Nexus

Water is essential for agricultural production, and energy and food security. Water, energy, and food create an interrelated nexus of resources. Food production is the largest consumer of water globally, accounting for 30% of global energy demand, as petroleum-based fertilizers and transportation are critical to the food production supply chain. Water is used to generate 8% of world energy. Energy production creates pollution from fossil fuels, damaging agricultural land and water. The nexus is context/regional specific, with variations in water resources due to geography, population, economic growth, demand, energy mix, and climate. It is therefore important to understand the regional challenges and devise context-specific solutions to address the nexus. The regional variability of water supply and the associated costs of water supply infrastructure for energy needs can significantly affect energy planning, especially in a water-scarce country. For policy makers, the food-water-energy nexus is a balancing act between competing issues of human security.

In the "nexus" approach, efforts are made to use new policies and tools to improve resource values in order to achieve higher resource use efficiency, which cannot be achieved in isolation. The nexus is a conceptual framework that considers the interconnectedness of water, food and energy securities, and seeks to integrate and develop collective solutions and strategies that promote positive synergies among these sectors, mitigating the tradeoffs and focusing on the interlinkages among the three resources. According to UN reports, effective institutional arrangements, which can facilitate policy integration in developed and developing countries, still suffer from considerable uncertainty due to differences in environments. Low- and middle-income countries tend to use most of their water for meeting basic needs such as food production, whereas the share of water used for domestic and industrial consumption increases exponentially in high-income countries.

Worldwide, over 80% of available water (particularly groundwater) is used for agricultural activities and food crop production. In combination with water, other factors such as high-yielding hybrid seeds and availability of supplement nutrients like fertilizers, etc. are responsible for increasing food production. Water consumed daily through food intake is much higher than water used for drinking. The food consumed by one person daily needs 2000–5000 L water to produce. Hence, growing water scarcity is now one of the most significant challenges for food security. Therefore, along with rapid population growth, the interconnection of land, water, and energy use for water supply, agriculture and food production, and associated water pollution is also increasing. The complexity and interdependency of water, energy, and food systems are growing with increasing human, social, and economic development. Projections on climate change are making it imperative that in order to manage water and energy availability, allocation, production, consumption, and security, the food-water-energy nexus is integrated into all development plans.

One problem is that most people have limited concern about higher consumption of water, energy, and food, or the wasteful use of water and energy, and little knowledge about balancing water-for-food, water-for-energy, energy-for-food, and energy-for-water. Little is known about people’s attitude and behavior patterns on consumption and use of water, energy, and food. In reality, policy makers often ignore the food-water-energy nexus, despite the fact that water and energy are needed to grow food, energy is needed to pump groundwater, and water is needed to generate energy, even in solar farms. For example, pumping groundwater provides over 50% of irrigation in South Asia, and the aspirations of the growing South Asian population increase demands on energy and food. But in the current global situation, when droughts, floods, and storms are more frequent and severe, organizations should be increasing consultation with other sectors, within and between different countries, and examining all the implications.

For those working across sectors, scope exists for more rigorous research and advocacy to bridge key knowledge gaps, share knowledge, and explore more efficient approaches to addressing the interdependencies of the water, energy, and food sectors. Water, energy, and food exist in a complex web of vulnerability to each other, due to the following reasons.

- Water is required throughout the energy and food sector, in power generation of most forms of turbine-generated electricity, either directly (hydropower, geothermal) or indirectly (steam to turn turbines, cooling). Fresh water is required for food production, energy extraction and production, refining and processing, transportation and storage.

- Energy, primarily mechanical or electrical energy, and sometimes in the form of human/animal power, is required to extract, move, treat, deliver, use and dispose of water, and produce food. Energy supplies are harnessed to pump water from deeper groundwater reserves and to divert rivers over large distances.

1.2.1 Water Use Per Unit of Energy

Water use per unit of energy is generally determined in terms of "withdrawal" and "consumption." Withdrawal is the volume of water removed from a source and consumption is the volume of water that is not returned to the source after withdrawal; that is, it is evaporated or transported to another location. "Discharge" is the volume of withdrawn water that is often degraded (physically or chemically) by use, and is returned to the source, affecting its water quality. Since all types of energy and food production require large amounts of water, and water withdrawals are always greater than or equal to consumption, hence, when water availability declines and there is not enough to satisfy demands, it is important to first limit/reduce consumption of water at energy and food production facilities.

Therefore, as populations increase and droughts occur, amount of water usage is of great concern for electricity-generating systems. Oil presently accounts for only 10% of water consumption in primary energy production. Energy from coal production is currently less than oil but is likely to rise over the next 30–40 years. The mining and refining of coal requires water at various stages. Overall, the production of coal accounts for about 1% of total water consumption in energy production. Almost 90% of fresh water is used for the production of biomass, which accounts for hardly 10% of total primary energy production. In 40 years, the share of fresh water used to produce biomass will decrease to less than 80%, while the share of biomass in total primary energy production will reduce to <5%.

1.2.2 Water Consumption to Generate Electricity

Water consumption to generate electricity is projected to more than double over the next four decades. The current annual electricity generation per capita average of 2.9 MWh (ranging from 0.6 MWh in Africa to 12.0 MWh in North America) may almost double in 2050 to an average of 5.7 MWh, ranging from 2.0 MWh in Africa to 17.3 MWh in North America. The highest increases may occur in Latin America, where per capita electricity generation is likely to be four times higher than currently, followed by Africa and Asia, where it may be almost triple. In Europe, per capita electricity generation may double while in North America, it may increase by only 50%. Although worldwide electricity generation per capita may almost double, the amount of water consumed to generate electricity is likely to stay at the same level due to technology advancements, or increase only slightly on a per capita basis in Africa, Europe and North America, whereas in Asia and Latin America, per capita water consumption to generate electricity will almost double.

As traditional energy resources decrease, the attraction of unconventional sources (e.g. oil sands, oil shales, deep gas shales) increases. However, many of these require large amounts of water, further stressing current and projected systems. For energy production, policy makers must consider available water supplies, understand the driving forces, relationships and water and energy cycles for efficient and sustainable use of these technologies, and search for ways to maximize the supply of one while minimizing the use of the other. The efficiency of power plants can result in decreased water use to generate the same amounts of electricity.

The increasingly integrated trade in water for energy production and conversion requires a new paradigm of co-operation among regional and national governments, and businesses. The water-energy nexus can become a vicious cycle, as lack of technology and poor management or inefficiencies in use in one region can affect the sustainability of another. A more plausible approach may be to preserve the present level in developed nations while reducing primary energy needs and continuously improving energy intensity, possibly with present technology and large investments.

1.2.2.1 Minimizing Water Use in Energy Production

According to the US National Renewable Energy Laboratory, electricity production from fossil fuels and nuclear energy requires 190 000 million gallons of water per day, accounting for 39% of all freshwater withdrawals in the nation. In many regions of the country, as much water is used for turning on lights and running electrical appliances in homes as in taking showers and watering lawns. Of this, 72% is used for fossil fuel-related energy production, and coal accounts for 52% of US energy generation. Each kWh of energy generated by coal requires 25 gal water. According to the United States Geological Survey, thermoelectric power generation consumes only 3.3% of fresh water, with over 80% for irrigation. According the US Department of Energy, average freshwater usage (gal/MW-h) of different power sources is: nuclear (400–720); coal (390); natural gas (140); hydroelectric (1430); solar thermal (1060); geothermal (2900); biomass (390); photovoltaic (30); wind (1). All thermal cycle plants (nuclear, coal, natural gas, solar thermal) require large amounts of water for steam, cooling, and condensing. The amount of water needed reduces with increase in boiler temperatures so coal, which burns at very high temperatures, is more efficient and requires less water use.

Both water quantity and quality issues are also important. For instance, electricity companies prefer to use cooling water from a lake or river or a cooling pond, instead of a cooling tower, if environmental feasibility and cost are acceptable. Pumping cooling water through the heat exchangers of the plant can reduce the energy costs of cooling towers. However, discharge of the waste heat may increase the temperature of the water source. Power plants using natural water bodies for cooling purposes have to be designed to prevent intake of organisms into the cooling cycle. Complications may arise if organisms adaptable to the warmer plant water are injured when the plant shuts down in cold weather. Thermal cycle plants require water for cooling, but it need not be fresh water. A power plant located on the coast can use sea water without using cooling towers. Moreover, discharge water temperatures would have less effect on the environment. If dry cooling systems are used, significant water from the water table need not be used.

A large amount of energy is also needed to extract, treat, and supply potable water, and further to collect, treat, and dispose of waste water. Technological advances can help to reduce energy requirements for water processing in water treatment, specifically in the desalination of salt water, and in the treatment of contaminated water and waste water for reuse. The key technologies for water treatment are reverse osmosis, ion exchange, and ultrafiltration. New approaches to reduce the energy footprint of water treatment systems involve using waste energy throughout the treatment process.

Innovative desalination technologies that use low-grade or waste heat instead of electricity have the potential to substantially reduce energy inputs, leading to an environmentally benign process and lower operation costs.

These water treatment technologies help power plants utilize available water supplies efficiently. Specialized ion exchange resins also help uranium mining operations use less water and generate less waste and enable the production of high-purity uranium used in nuclear power applications, helping to meet the increasing global demand for energy. However, demands for water and energy are increasing faster than technology can advance. The demand for water in highly populated parts of the world is high, and the resources needed to provide it are not always adequate. For instance, in China, both economic growth and physical scarcity drive water scarcity. China's annual water deficit is ~40 bcm in normal years, and 50% of its cities are facing some degree of water shortage.

Water shortages are a challenge for India as well. With 85% of the available water currently being used for agriculture, a further depletion in water supply could jeopardize agriculture and food security. Canal water and groundwater are the major sources of irrigation. Groundwater irrigation has expanded rapidly in recent decades, and forms a major part of the water withdrawals in many river basins. At present, the groundwater-irrigated area constitutes more than 60% of the total irrigated area. During recent decades, there has been practically no scope to further increase the canal water-irrigated area, and in the last 10 years or so, there has been a decline in the canal water-irrigated area.

In India, the near self-sufficiency in food production allows export of some of it with hard-to-estimate externalities including groundwater depletion and salinization, as well as degradation of soil health and the environment. India is the world's third largest exporter of groundwater through its grains export. Going by per capita availability, the parts of India from which most grains are exported are seriously water scarce. Average groundwater consumption to grow 1 kg wheat is 812 L, 1 kg rice takes 200 L (because it is far more dependent on surface water) and maize 72 L. In the 2016–2017 financial year, India is estimated to have exported 3 00 000 tonnes of wheat, 10.7 million tonnes of rice, and 700 000 tonnes of maize. India is also the world's largest extractor of groundwater; around 75 km^3 groundwater was extracted in India in 2010.

Water is usually inefficiently used in the food production chain. Decisions on site selection, technology, and suppliers are frequently made without considering the impacts of the operation on the availability and quality of water resources, especially when water is not a limiting factor by either quantity or price. When considering grain exports, it should be kept in mind that water embedded in the grains is the actual water exported, and this is much smaller than the total water used to grow crops because a small fraction of the total amount of water used in growing crops is recoverable, and the rest seeps down to the groundwater. A much larger amount of water is lost due to evaporation, and this is key to understanding how water-intensive crops affect groundwater in a region. An additional related factor for India is state-level disparities in groundwater depletion; dry regions of Gujarat and Karnataka are exporting water to wet regions of the country to satiate the thirst of those who can afford bottled water and soft drinks.

Within the power sector in India, coal-fired plants account for around 95% of total water withdrawals, the rest being split between gas-fired and nuclear power stations.

The cooling technology used, together with the overall efficiency of the power4plants, determines the amount of freshwater withdrawal from local sources, and the amount withdrawn but not returned to the local water basin (water consumption). Hence, for future industrial growth in India, availability of water has to be ensured, with water requirements for manufacturing and power generation competing with safe drinking water supply and agricultural purposes. In India, along the coast, new coal-fired power plants primarily rely on imported coal and use sea water as a cooling medium, giving them a cost advantage for transport and limiting their water stress.

A mismatch between water supply and water demand is also common in the developed world. Under an average economic growth scenario and without efficiency gains, global water requirements will grow from 4500 billion cubic meters today to nearly 7000 billion cubic meters – a 50% increase in only 20 years. By 2030, some analysts predict that available water supplies will satisfy only 60% of demand. There is no doubt that, for the survival of humanity, water and energy are and will always be inextricably linked in virtually everything from growing and processing food to industrial processes that require energy.

1.3 Climate Forcing Environmental Impacts (Floods and Droughts)

Several studies have reported increases over recent decades in the frequency of heavy to extreme hydrological events. Climate change is expected to accelerate global hydrological cycles, resulting in increased precipitation and reduced evapotranspiration, thereby increasing river discharge on a global scale. Several regions were projected to have increases in both flood frequency and drought frequency. Such regions show a decrease in the number of precipitation days, but an increase in days with heavy rain. Several regions show shifts in the flood season from springtime snowmelt to the summer period of heavy precipitation. Temperature and precipitation data have been used to estimate the Palmer Drought Severity Index for the USA, for projecting future drought (mainly as a shortage of precipitation). However, low river flows (droughts) must also be considered and measured, because many regions are irrigated with river water. The low river flows may not be estimated simply from soil moisture, rainfall or precipitation minus evapotranspiration. Drought frequency has been projected to increase globally, with a decrease or no significant changes in regions such as northern high latitudes, eastern Australia, and eastern Eurasia.

However, changes in flood and drought are not explained simply by changes in annual precipitation, heavy precipitation, or differences between precipitation and evapotranspiration ($P - E$). In contrast, river basins characterized by decreases in $P - E$ in the twenty-first century show increases in drought, but an increase in drought does not necessarily result in a decrease in $P - E$. The changes in precipitation patterns may cause an increase in the number of drought days even though precipitation, discharge, and $P - E$ increase. Comparison of flood and drought frequencies estimated from daily discharge is therefore important in predicting future discharge extremes.

According to the UN Millennium Development Goals 2007 Report, the primary contributor to climate change is the increasing level of atmospheric CO_2 from burning of fossil fuels. Carbon dioxide emissions continue to rise, as evidenced by increasing concentrations in the atmosphere. In South-East Asia and northern Africa, emissions more than doubled during 1990–2004. On a per capita basis, developed regions continue to emit far more CO_2 than developing regions. Among developing regions, western Asia is the highest per capita emitter. Sub-Saharan Africa accounts for per capita less than 10% of the CO_2 produced by an average person in the developed world. The depleting groundwater tables may force users to lower the depth of pumps in the wells, increasing the energy requirement and fossil fuel use for pumping water and thereby increasing the emission of CO_2 to the atmosphere.

Changes in flood extremes using monthly averaged river discharge data for both gauge observations and global climate model (GCM) simulations over 29 river basins larger than 200 000 km^2 in area suggest that the risk of great floods increased during the twentieth century, mainly over the northern high latitudes, and that this increase may continue. Future extreme daily precipitation projections have also been estimated based on various climate change simulations. The frequency of floods was projected to increase over many regions, except North America and central to western Eurasia. However, these studies are insufficient for future projections of extremes in global river discharge in GCM simulations, because extremes in river discharge are strongly affected by the spatial distribution of the precipitation intensity within a basin, and due to the limitation of spatial resolution in GCMs for the accurate estimation of extremes.

The intensification in extremes is therefore not easily determined from observations or current GCMs without considering anthropogenic water usage. Future global warming projections using other GCMs, regional climate models (RCMs), and ensemble models with higher spatial resolution are therefore expected to provide multimodel projection of discharge extremes.

One type of flood problem or risk is runoff which exceeds the capacity of the drainage channels – rivers and creeks in the rural environment, and storm water channels in the urban environment. Sudden floods can cause sudden morphing of existing streams into torrents, totally altering the landscape, rocks, foothills, channels, and stream heights. Water pollution and food security can ensue, due to difficulty in delivering safe water and food supplies to flood-affected areas. Risk mitigation plans often involve emergency resources, where groundwater is readily accessible locally. Groundwater from deep aquifers or even non-renewable “fossil” water bodies needs to be tested for adequate yields.

Flood risk mitigation for safe water supply requires a search for groundwater resources, with long residence times, proven safe and protected by the physical environment, along with the necessary infrastructure for exploitation, with timely replacement of vulnerable water supply systems. For identification of low-vulnerability aquifers, sustainable management of groundwater resources, groundwater renewability and rock–water interactions must be considered based on systematic hydrogeological investigations including monitoring and mapping of groundwater, integrated with geochemical and other methods. Identification of such aquifers requires risk analysis with respect to their occurrence, accessibility, quality, vulnerability, and resistance to the impact of disasters.

Shallow uppermost unconfined aquifers mainly occur in unconsolidated fluvial and glacial deposits overlain by permeable unsaturated zones of low thickness (<10 m), characterized by young groundwater and single flow system and interface with surface water. Deeper unconfined aquifers in consolidated rocks (particularly sandstones) of regional extent, overlain by permeable unsaturated zones of variable thickness, consist usually of a number of laterally and vertically interconnected groundwater flow systems of dual porosity and permeability. Karstic aquifers occur in carbonate rocks with groundwater flow in conduits, large open fissures, and openings along bedding plates, typically with high groundwater flow velocities (100 m day^{-1}) and secondary permeability; springs are important phenomena of groundwater karstic regimes. Coastal aquifers under natural conditions consist of sea water intrusion, controlled by tidal fluctuations, stream flow changes, gradient and volume of groundwater flow towards the seashore, and geological environment. Groundwater pumping significantly influences the groundwater–sea water interface. Recharge areas of all type of aquifers need to be reliably identified/delineated.

Some controversial questions always remain. Will there be no risk if there is no vulnerability? What risk is negligible? What risk is tolerable? What risk is intolerable? In view of the aforementioned uncertainties, since an extreme flood- or drought-induced disaster can dramatically affect the impact and recovery time before, during, and immediately thereafter, in the context of RWH for groundwater management, the behavioral adaptation dynamics of society, individuals, groups, and government agencies need to be seriously taken into consideration for more reliable risk characterization and assessment of the effectiveness of risk management strategies, policies, and investments. However, existing risk assessment methods rarely include this.

As global energy consumption continues to expand (20% increase since 1990), there has been progress in the development and use of renewable resources, such as hydropower and biofuels. The development of more modern renewable resources, which have no negative impact on people's health or the environment, has increased 10-fold over recent decades. However, these newer technologies, including those relying on wind, solar, wave, and geothermal energy, still account for only 0.5% of total energy consumption.

Large regions are at risk from the effects of both climate change and acidification. All major cities in the world suffer multifaceted pervasive problems. In Eastern Europe, air quality is considered the most serious environmental problem. Acid rain and transboundary air pollution, once problems only in Europe and parts of North America, are now becoming apparent in parts of the Asia-Pacific region as well as Latin America. Despite co-ordinated action worldwide, non-compliance and growth in illegal trade in ozone-depleting substances are emerging problems, with continued damage to the ozone layer occurring faster than expected. The coming decade is predicted to be the most vulnerable. All regions express concern over global warming, but special emphasis is placed by developing countries on the need for adaptive mechanisms to cope with accompanying climate variability and sea level change. The rapidly rising demand for energy for economic development can only aggravate these problems.

All regions experience problems related to groundwater or surface water or both. With the global population forecast to grow over the next 40 years, especially in Africa and Asia, water demand will increase, making it even scarcer than it already is in many regions of the world. The efficient development and management of water resources is a priority concern in West Asia, Africa, and Asia and the Pacific. In the Middle East, China, and India also, which already suffer from water stress or water scarcity, water stress will increase further, making the whole region very vulnerable. With these trends, it is important to understand the impact an increased use of renewable energy and improved energy efficiency could have in terms of water savings. Increased competition for water calls for more integrated approaches to the use of natural resources.

In Europe and North America, the protection of water resources from contamination, acidification, and eutrophication is highest on the agenda. Other global priorities are the equitable distribution of water among riparian countries sharing international river basins, non-point sources of pollution, and the impacts of major dams and diversion projects. More than 60% of all water is withdrawn in Asia, more than 10% by Europe and North America, around 5% by Latin America and the Caribbean, and even less in Africa. The proportion of the population using safe sources of drinking water in the developing world increased from 71% in 1990 to 79% in 2002. The most impressive gains were made in southern Asia. However, at present, billions of people are still using water from unsafe sources, and water-borne diseases represent the single largest cause of human sickness and death worldwide. More than one-third of the world's population is without a safe water supply.

About 60% of the world population lives within 100 km of the coast, and more than 3 billion people rely in some manner on coastal and marine habitats for food, building sites, transportation, recreation, and waste disposal. Around 33% of the world's coastal regions are at high risk of degradation, particularly pollution and infrastructure development from land-based sources. European coasts are most affected, with some 80% at risk, followed by Asia and the Pacific, with 70% of the coast at risk. In Latin America, some 50% of the mangroves are affected by forestry and aquaculture activities. Oil spills are threats in West Asia and the Caribbean, while tourism industry infrastructure development puts stress on natural coastal areas around the world.

1.4 Water Security

The definition of water security proposed by UN Water to serve as a starting point for dialogue in the UN system is: "The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability." According to Wikipedia, water security has been defined as "the reliable availability of an acceptable quantity and quality of water for health, livelihoods and production, coupled with an acceptable level of water-related risks." Water security also means addressing environmental protection and the negative effects of poor management. It is also concerned with ending fragmented responsibility for water and integrating water resources management across all sectors: finance, planning, agriculture, energy, tourism, industry, education, and health. A water-secure world reduces poverty, advances education, and increases living standards.

However, stakeholders from different disciplinary backgrounds seem to have different perceptions of the term "water security." For instance, engineering studies generally focus on water supply and demand, protection against floods, droughts, and contamination. Water resources studies focus on water scarcity, water supply, and demand management. Environmental studies usually focus on environment, water availability in terms of quality and quantity, and on impacts of hydrological variability. Policy studies focus on linkages of food, climate, energy, economy and human security, protection against water-related hazards, and sustainable development of water resources. Public health studies focus on water supply security and access to safe water, and prevention of water pollution in distribution systems. Political and governance perspectives focus on institutional division of responsibilities, power structures, equity issues, and water planning conflicts. Legal perspectives focus on water rights and ownership. Economic perspectives focus on the efficiency of water resource use, the economics of water demand and supply, water pricing and market mechanisms, cost–benefit analysis of flood risk protection, and water quality conservation.

It is therefore important that in framing policies to make water available for food, governances in different countries ensure that water is also available for energy production and conversion. Without energy to supply the water needed for all uses, there can be no production of food or the economies of modern food processing. Asia, with large geographical area and population, faces the largest challenge for water supply in general and for water use in energy production. While designing multiple resource management frameworks, the increasingly integrated shared resources and trade mechanisms require a new paradigm for the sustainable global availability and use of resources in the coming decades and beyond, instead of each country or region looking out only for itself. To effectively address these complexities, policies and frameworks need to integrate knowledge, understanding, specialization, and cross-disciplinary approaches to managing natural resources simultaneously.

References

Chhotray, V. (2007). The anti-politics machine in India: depoliticisation through local institution building for participatory watershed development. *Journal of Development Studies* 43 (6): 1037–1056.

Li, F., Cook, S., Geballe, G.T., and Burch, W.R. Jr. (2000). Rainwater harvesting agriculture: an integrated system for water management on rain-fed land in China's semi-arid areas. *Ambio: A Journal of the Human Environment* 29: 477–483.

Mosse, D. (2003). *The Rule of Water*. New Delhi: Oxford University Press.

Oweis, T.Y., Prinz, D., and Hachum, A.Y. (2012). *Water Harvesting for Agriculture in the Dry Areas*. London: CRC Press.

Further Reading

Asano, T. (1985). *Artificial Recharge of Groundwater*. Boston: Butterworth.

Bhalge, P. and Bhavsar, C. (2007). Water management in arid and semi arid zone: traditional wisdom. International History Seminar on Irrigation and Drainage, Tehran, pp. 423–428.

Borthakur, S. (2008). Traditional rainwater harvesting techniques and its applicability. *Indian Journal of Traditional Knowledge* 8 (4): 525–530.

Dhiman, S.C. and Gupta, S. (2011). *Rainwater Harvesting and Artificial Recharge*. New Delhi: Central Ground Water Board, Ministry of Water Resources.

Huisman, L. and Olsthoorn, T.N. (1983). *Artificial Groundwater Recharge*. Massachusetts: Pitman Publishing.