Water and Its Management: Dependence, Linkages and Challenges

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Abstract

This chapter highlights the key dependences, linkages and challenges of water resources management. (Many of these issues discussed are revisited and illustrated in the following chapters.) The first part introduces surface and groundwater management in the terrestrial part of the water cycle. Comprehensive presentations of key hydrological phenomena and processes, monitoring, assessment and control are followed by overviews of dependences, linkages and challenges. The manifold facets of intensive human/resource interaction and inherent threats to the resources base are exposed. Both sections present examples illustrating differing contexts and options for solution. The second part summarizes the main drivers and challenges of contemporary water resources management and governance. It provides a critical overview of different water discourses in recent decades. The role of benchmark and recurring water events, their declarations and intergovernmental resolutions are analyzed, and the key concepts and methods of implementation are discussed.

Keywords

Surface water • Groundwater • Availability and uses • Challenges of water resource management

3.1 Introduction

Water is more than a common, yet fascinating substance to be found in the atmosphere, on land, underground, in seas and oceans and in the mantle of Earth. It is the source and an indispensable component of all forms of life. This is true not only for the biological processes of ecosystems, including humans, but also applies for economic metabolisms. As a key factor in all human activities water is simultaneously a production resource, transport agent, cooling medium and ultimately as water body recipient of sediments, debris, byproducts and waste from human settlements, agricultural land, industrial estates, mines and infrastructure. Water resources are finite and can easily be subject to quantitative or qualitative deterioration.

This chapter aims to summarize the key challenges and opportunities water and its management faces at present and in the foreseeable future. The motto of the 2nd World Water Forum (WWF) (2000) "Water is Everybody's Business" aptly coins the complexities, but also the importance of managing and safeguarding water. What had been once conceived as a straightforward engineering approach has been becoming a rather complex, transdisciplinary, multi stakeholder, multiple level, collaborative, but also confrontational exercise. Decisions, concerning water resources are made within new, still evolving, formal and informal institutional frameworks. As a corollary of the motto of the 2nd WWF, all water stakeholders should know more about

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water, its governance and management, and about the role different stakeholder groups may play in these processes.

This chapter starts with an overview of the interdependences, linkages and challenges we face in the domains of surface- and groundwater and their respective managements. Sect. 3.4 of this chapter provides an overview of the challenges faced by the contemporary concepts and practice of water resources management. The broad international and interdisciplinary debate, what may be called the water resources management discourse and its evolution will be introduced. While it is widely acknowledged that water resources management is integrative and focusing on thematic subdivisions may narrow the scope, it has to be acknowledged that water use and management historically evolved with surface and groundwater management pursued largely in separate “silos”. Although, surface and groundwater are part of a continuum, due to the profound differences between these forms of occurrence of water and the different expertise and technologies needed to utilize surface or groundwater respectively, different professional communities have emerged. Even at present the overwhelming part of water demands are covered either from surface- or/and from groundwater bodies. While the conjunctive use of both resources (see Sect. 23.3 for more detail) is becoming more and more commonplace, proactive water resources management, especially at project scale still frequently refer either to surface or to groundwater. Hence highlighting the differences and peculiarities is not only warranted, but necessary to recognize the opportunities and constraints an integrated approach may face.

3.2 Surface Water Resources

The beginning of life on Earth has been linked to water. Modern humans (Homo sapiens) have inhabited this earth for some 300 000 years (Hublin et al. 2017; Richter et al. 2017), most of that time as hunter-gatherers. Some 10000 years ago, when people adopted an agrarian way of life, humans started establishing permanent settlements. All early civilizations were established close to large water bodies-rivers, lakes and seas. Over 70% of the surface area of our planet as well as human bodies consists of water. Therefore, water is literally life.

Water is not only a part of our constitution but plays a key role in promoting our livelihood practices by supporting agriculture, industries, energy production, recreation, domestic use such as drinking, cooking and bathing etc. The match or the mismatch between water availability and its uses leads to water scarcity issues and adds stress to human societies. In this section the availability of surface water resources and the water cycle will be discussed, followed by an overview of surface water management. Finally, we will present some future challenges and risks for water management.

3.2.1 The Hydrological Cycle

About 71% of the Earth's surface is covered with water. The *oceans* hold about 97.5% of the earth’s water resources as saline water. Therefore, only 2.5% of all the water on earth is fresh, making it a relatively limited resource. Furthermore, of this 2.5% of fresh water, more than two-thirds (68.7%) is frozen as snow and ice, and more than one-third is stored below the surface as ground water. This means that only 0.3% of all fresh water on the planet is readily available as surface water in lakes, swamps, rivers and streams (Gleick 1996). Freshwater is millions of years old and is continually circulating in the hydrological cycle, which basically consists of flows (fluxes) of water between various stores or storages. Water is stored in the atmosphere as vapor, in liquid states in the oceans, rivers, lakes, reservoirs and wetlands as well as in the surface in soils and plants and beneath the surface in underground aquifers. Water exists in solid states in ice shields and glaciers and snow packs as well as in permafrost soils.

All this storage is temporary as water is always in flux, moving from and into the various storages. Precipitation is the process of water falling from the atmosphere to the earth surface. Precipitation can take many forms such as rain, snow and hail. When precipitation hits the land surface, some of it will be intercepted by vegetation and evaporated back into the atmosphere. Precipitation which reaches the ground will run-off if it hits impermeable surfaces such as built up areas or concrete roads. The precipitation which reaches the soil surface, infiltrates into the soil until the soil reaches saturation, then the rest flows as overland flow into streams and rivers and lakes. The water which infiltrates into the soil eventually percolates into the bedrock and underground aquifers. Groundwater is also moving laterally towards rivers and contributes to river flow as baseflow. Groundwater movement is very slow in comparison to surface water flow and could take thousands of years to reach rivers or other surface outlets (springs, oceans) as shown in Table 2.2 in Sect. 2.2.1.

Water returns to the atmosphere through evaporation caused by the heat of the sun. Water can also evaporate from humans and animals in the form of respiration and perspiration. Plants draw water from the soil and evapotranspire it back into the atmosphere. Water vapor in the air then condenses to form clouds and when oversaturated, cooled or triggered by the presence of condensation nuclei, falls back again to the earth surface through precipitation. The water cycle consisting of fluxes and stores is shown in Fig. 3.1. The total quantity of water on earth therefore does not change but is in a permanent state of flux. A water balance equation can be used to describe and quantify the flow and storage of water within the hydrological cycle.

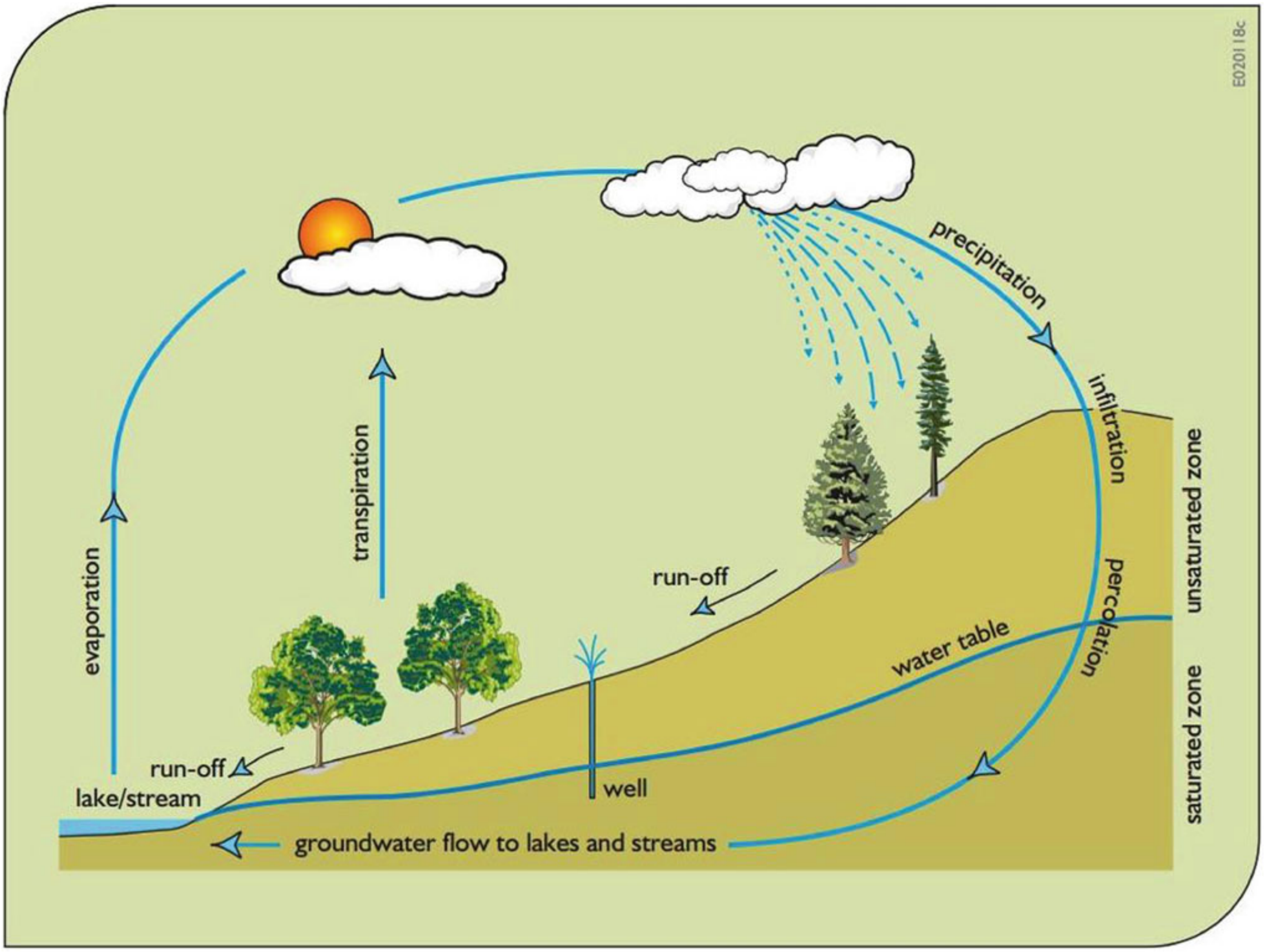


Fig. 3.1 The hydrological cycle. Reproduced from: Loucks et al. (2005)

3.2.2 Surface Water Systems: Some Essential Concepts

As Sect. 3.2 focuses on surface water hydrology, understanding runoff generation processes is very important. Hillslope hydrology is concerned with the partitioning of net precipitation passing through the vegetation coverage into several runoff components (Bogena 2001). Runoff is the total amount of water flowing into a stream/river, evaluated as the sum of direct runoff and base flow. Direct runoff is the sum of surface runoff and interflow. The surface runoff component is the sum of the so called Horton overland flow and saturation excess overland flow. In the following sections, the individual terms contributing to total runoff will be discussed. Total runoff comprises generally, of a combination of various runoff processes. One exception is during dry periods where the stream is recharged by the groundwater system (baseflow) alone (Bogena 2001). During a storm event, several runoff processes may be involved and the importance of each process depends on climate, type and state of the soil or surface cover, slope, geology, and vegetation.

3.2.2.1 Surface Runoff—Overland Flow

When rainfall reaches the land surface it can infiltrate into the soil. Most of this infiltrated water percolate vertically. However, soil has a finite capacity to absorb water. The maximum rate at which infiltration can occur under specific conditions of soil moisture is referred to as infiltration capacity (Fetter 1994). The infiltration capacity varies not only from soil to soil but is also different for dry versus moist conditions even for the same soil (Fetter 1994). As the capillary forces diminish with increased soil-moisture content, the infiltration capacity drops. Eventually, the infiltration capacity reaches a more or less constant, or equilibrium value. If the precipitation rate is lower than the equilibrium infiltration capacity, then all the precipitation reaching the land surface will infiltrate, but when the precipitation rate is greater than the initial infiltration capacity, the overland flow process, sometimes called Horton overland flow after Robert Horton (1933, 1940) occurs (Fetter 1994; Bharati et al. 2002). Therefore, Horton overland flow is the portion of rain, or snowmelt that moves laterally across the land surface and enters a wetland, stream, or other body of water. Horton overland flow is rarely observed in the field, except after very heavy precipitation events or where the soils are very fine textured, hydrophobic, heavily compacted, bare or frozen. A further mechanism producing overland flow is called return flow (Dunne and Black 1970). Return flow occurs when subsurface flow emerges as seepage at the foot of the slope and enters the stream or other water body as surface flow.

3.2.2.2 Interflow

If the unsaturated zone is uniformly permeable, most of the infiltrated water percolates vertically. However, if layers of soil with a lower vertical hydraulic conductivity occur beneath the surface, then infiltrated water may move horizontally or laterally in the unsaturated zone without reaching the water table and discharge directly into a stream or other body of water. This is referred to as interflow and can have a significant contribution to total stream flow (Fetter 1994).

During the 1960’s and 1970’s, increasing evidence of the complexity of flow generation and the impact of subsurface flow on storm hydrographs began to appear (e.g. Whipkey 1965; Hewlett and Hibbert 1966; Kirkby and Chorley 1967; Betson and Marius 1969; Dunne and Black 1970; Bryan and Jones 1997). This coincided with increasing reports of subsurface erosion features in many different materials and climatic zones (Bryan and Jones 1997). The field hydrologists then realized that stormflows could take place where overland flow was completely missing e.g. in forest catchments (Tani 2011). Many observational studies studying this problem have emphasized role of macropores (Mosley 1979; Tani 2011). Tani (1998) has observed that major stormflows are produced by a system of fast lateral saturated flow within macropores receiving vertical quick propagations of rainwater within unsaturated soil matrix. This effect can occur at rainfall intensities below those required for a Hortonian overland flow (Bogena 2001).

3.2.2.3 Baseflow

Baseflow is the sustained flow in a stream that comes from groundwater discharge or seepage. Days, weeks or even years may pass before water that seeps to the water table eventually reaches a stream. Some groundwater can, however, reach a stream during or shortly after an input event via translatory flow i.e. when a belt of antecedent water is forced by new seeping water or when there is a perched groundwater below the slope (Lawrence 1994). In humid regions, streams receive much of their volume from the groundwater system. These streams are gaining or effluent streams. In arid regions the groundwater table is very low and most streams lose volume to the groundwater system. These streams are then referred to as losing or influent streams (Fetter 1994). Baseflow will be further discussed in Sect. 3.3.2 in a groundwater perspective.

3.2.3 The Water Balance

The main water balance components are Precipitation, Runoff, Evapotranspiration, and Water Storage in various forms. A general water balance equation can be written as:

$$P = R + E + \Delta S$$

where, P is precipitation
E is evapotranspiration
R is runoff
ΔS is the change in storage (eg. in soil or groundwater).

Water balances can be calculated for land areas such as watersheds, river basins and countries as well as for surface and subsurface water bodies such as lakes and reservoirs, swamps, groundwater bodies, glaciers, ice sheets and inland seas. The water balance may be computed for any time interval such as a year, season, month or number of days (UNESCO 1974).

At the global scales, there are already several international initiatives that aim at developing water resources assessments and water balances, such as the activities of the UNESCO- International Hydrological Programme (IHP). Under the UNESCO-IHP Programme, an Atlas of World Water Resources was developed already in the 1970s, followed by guidelines for conducting water resources assessments (Godwin et al. 1990; UNESCO-IHP 1999; United Nations 2014). A compilation of water balances have also been produced by FAO/AQUASTAT (Food and Agriculture Organization of the United Nations 2016). The World Meteorological Organization (WMO), Commission for Hydrology has also worked on hydrology and water resources assessment (World Meteorological Organization 2008). These form the core of water balances thinking, as we know it today (European Commission 2015). New methods to improve water balance calculations continue to be developed. Use of satellite data, remote sensing tools and hydrological modeling are developing novel methods to calculate water balances (Sood and Smakhtin 2015, Daniel et al. 2011, Singh and Frevert 2002a, b).

3.2.3.1 Overview of Hydrological Modeling

Modeling is the process of organizing, synthesizing, and integrating component parts into a realistic representation of the prototype (Bouraoui 1994). The reliance on models in carrying out water balance assessments is increasing because models enable us to study very complex problems and to synthesize different kinds of information (Sorooshian and Gupta 1995; Singh and Frevert 2002a, b). Due to the increasing capability and widespread availability of computers, the development, acceptance and use of computer models has increased. However, model results are only as reliable as the model assumptions, inputs and parameter estimates (Sorooshian and Gupta 1995). Therefore, before being able to move any further, there are three major hurdles. The first is to select a suitable model to simulate the processes and management goals of the study area. The second is to select values for the model parameters so that the model closely simulates the behavior of the study site (Sorooshian and Gupta 1995). The third is the fundamental need of reliable data to run the model.

3.2.3.2 General Categorization

Since the development of the Stanford Watershed model (Crawford and Linsley 1966), there has been a proliferation of watershed models (Renard et al. 1982; Singh 1995; Singh and Frevert 2002a, b; Sood and Smakhtin 2015). At present, a large number of models of different types and developed for different purposes exist. In general, these models can be categorized into three classes (Bouraoui 1994): 1. Empirical models 2. Conceptual models 3. Physical models.

Empirical models or black box models contain non-physically based transfer functions to transform input data to output data. These models are often referred to as cause and effect models where the physical processes taking place are not simulated (Bouraoui 1994). This type of model is relatively simple, requires little data and can be used for statistical extrapolation. However, extrapolating beyond the range of available information especially for an outlier, or extreme events, may lead to highly erroneous results. Examples include simple regression models or water-balance/water-quality spreadsheet models. Conceptual models can be defined as semi-physical models since they simulate physical processes using major simplifications. This approach is used when information or general knowledge of the processes taking place is lacking (Bouraoui 1994). Examples of conceptual models are Hydrologiska Byråns Vattenbalansavdelning—HBV (Bergström 1976, 1992) and QUAL-2 K (Chapra and Pelletier 2003). Alternatively, physically based models simulate the internal mechanisms of the system using a theoretical approach. These models use physical parameters that can be either measured or determined using appropriate equations. Examples of such models are: the MIKE- Système Hydrologique Européen (SHE) model (Jayatilaka et al. 1998), the Precipitation Runoff Modeling System/Modular Modeling System—PRMS/MMS model (Leavesley et al. 1983), the Soil and Water Assessment Tool—SWAT (Arnold et al. 2012), and the Hydrological Simulation Program-FORTRAN—HSPF (Bicknell et al. 1997).

3.2.3.3 Lumped and Distributed Models

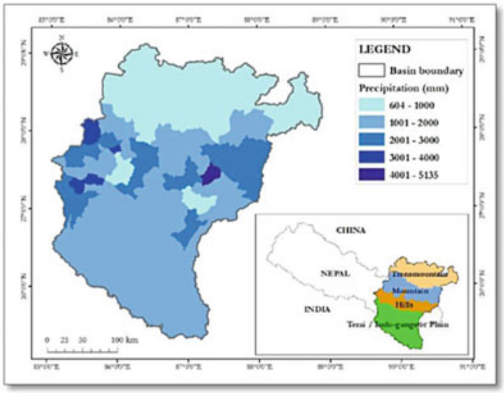
Hydrologic assessment models can also be divided into lumped and distributed models. A lumped model, is in general, expressed by ordinary differential equations taking no account of spatial variability of processes, input, boundary conditions and system (watershed) characteristics (Singh 1995). The whole catchment is assumed to be homogenous, and all the potential variations are lumped (averaged) together. Thus, the degree of accuracy of the model is expected to vary with the degree of non-homogeneity of the catchment. Lumped models provide a unique output for the whole watershed, however, they do not provide any information regarding the spatial behavior of the outputs (Bouraoui 1994).

Distributed models take into account the spatial variability of processes, input, boundary conditions, and/or system (watershed) characteristics (Singh 1995). Distributed models discretize the watershed into subunits (cells), which are assumed to be homogenous. All the hydrologic climatic and management parameters are then assumed homogenous within each cell, but may vary from cell to cell. The dynamics of the simulated processes are then described at each point within the watershed, and the outputs from each cell are routed to the watershed outlet (Beven 1985; Bouraoui 1994). Distributed models can either be conceptual in their model structure or physically based. For example, a GIS-supported and grid-based calculation of soil erosion with the simple regression equations (e.g. Universal Soil Loss Equation—USLE) can, in principle, be described as a distributed model (Bogena 2001). Box 3.1 presents an example of water balance assessment for Koshi basin in Nepal (Bharati et al. 2012) using SWAT (Arnold et al. 2012), a semi-distributed physically based model.

3.2.3.4 Time-scale Based Classification

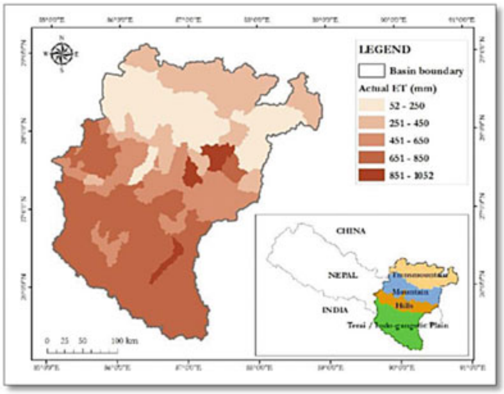
The hydrological models can also be classified based on the time scale of models (Singh 1995). Based on this description, the models can be distinguished as (a) continuous-time or event based, (b) daily, (c) monthly, and (d) annual models (Singh 1995). This classification depends on the interval of computation and the input data. The choice of a time interval is also often a function of the models intended use.

Box 3.1 Spatial Distribution of Precipitation, Actual ET and Water Yield in the Koshi Basin, Nepal using SWAT



Precipitation

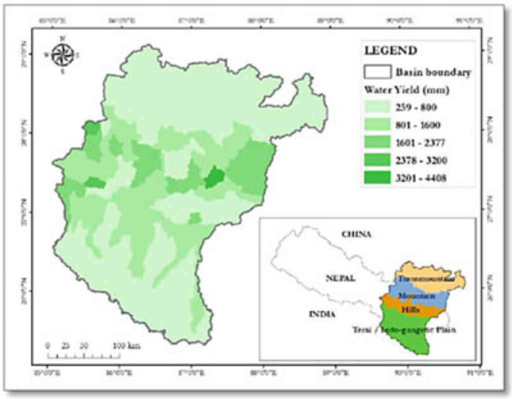
- The precipitation is lowest in the trans mountain region in the Tibetan plateau and highest in the mountains followed by hills in Nepal.
- Maximum precipitation (5,135 mm) occurred in a sub-basin in the mountain region and minimum precipitation (604 mm) in the trans mountain region in the Tibetan plateau.



Evapotranspiration (ET)

- As ET depends largely on precipitation, land cover and temperature, it was found to be high in forested areas in the hill regions of the basin and agricultural areas in the plains of Nepal and India.

- The maximum ET (1052 mm) occurred in a sub-basin, in the Indo-gangetic Plains of India, while the minimum (52 mm) occurred in a sub-basin in the Trans-mountain region.



Water Yield

- Similar to precipitation, the net water yield is lowest in the trans mountain region and highest in the mountains followed by hills in the Nepal part of the basin.

- Water yield is maximum (4,408 mm) in a sub-basin in the mountain region of Nepal and minimum (259 mm) in a sub-basin of the trans-mountain region.

Source: Bharati et al., 2019

Bharati L., Bhattarai U., Khadka A., Gurung P., Neumann L. E., Penton D. J., Dhaubanjar S. & Nepal S. (2019). From the mountains to the plains: impact of climate change on water resources in the Koshi River Basin. IWMI Working Paper. 187, 49

Understanding of the hydrology has traditionally been established through measurements of climate and various water balance components at point locations. Such direct measurements are often gathered and protected by national authorities, with limited public access. Point measurements are also hard to upscale rapidly over time and space. Remote sensing, the indirect measurement of physical parameters based on electromagnetism and signal processing theory, has emerged as a promising alternative, overcoming these limitations. Sensors deployed onboard unmanned-aerial vehicles (UAVs), airplanes or satellites, are used to remotely measure parameters affecting the water cycle based on signal responses over a grid (for observations and hydrological data management, see also Chap. 13).

For instance, satellite based global precipitation is estimated using radar and microwave imaging by Tropical Rainfall Measuring Mission (TRMM), Integrated Multi-satellitE Retrievals for Global precipitation measurement (IMERG) and Global Satellite Mapping of Precipitation (GSMaP). Advanced SCATterometer (ASCAT) and European Remote Sensing—2 (ERS-2) satellites remotely monitor soil moisture based on radar measurement of emissivity and reflectivity. Radar interferometry (e.g. Shuttle Radar Topography Mission—SRTM, TerraSAR-X add-on for Digital Elevation Measurement—TanDEM-X) is used to developing elevation models while radar altimetry (e.g. CyroSAT, Synthetic Apeture Radar—SAR, Altimeter Corrected Elevations, Version 2—ACE2) is being explored to measure water levels. Thermal and multi-spectral imagery can be used to distinguish different surface land covers (e.g. LandSat) and snow cover (e.g. Moderate Resolution Imaging Spectroradiometer—MODIS). Multi-spectral imagery can also be used to measure evapotranspiration. Gravimetry can provide estimates for total water storage, including sub-surface water (e.g. Gravity Recovery and Climate Experiment—GRACE). These examples present satellite-based products, but the sensors can be installed on ground-based or air-borne carriers for localized measurements. The rapid adoption of remote sensing techniques has also fueled the development of models and data assimilation methods that combine traditional point based measurements with gridded remote sensing datasets (Liu et al. 2012).

Remote sensing provides an opportunity to develop globally standardized data sets (among them also the so-called reanalysis data, see also Sect. 2.2), often accessible publicly. However, their application in sub-continental and local scale analysis is debatable (McCabe and Wood 2006; van Dijk and Renzullo 2011). The spatial resolution of satellite-based products and their performance is inherently poor in areas with complex topography. Interference in data due to cloud cover is another major issue for satellite-based products. Use of ground-based or air-borne carriers, such as Unmanned Aerial Vehicles (UAVs), gliders, helicopters etc., can overcome the issue of clouds and provide data with finer resolutions; but the cost of such endeavors can be high. On-the ground validation of remote sensing products is also challenging, requiring comparisons of grid-based and point measurement. Processing of geophysical signals actually measured by these sensors to physical hydrological and climatic parameters requires rigorous processing algorithms that can be computationally intensive. Nonetheless, remote sensing is already revolutionizing the measurement and modeling of the hydrological cycle as the technology becomes more reliable, efficient and cost effective. For more detail see Chap. 13.

3.2.4 Water Availability and Uses

Flows and storages described in the previous section are due to natural phenomena. Human activities also influence components of the water balance equation. This can be through building large artificial storages such as reservoirs, abstractions for water supply or water transfers to other areas and by transferring return flows from various uses such as irrigation areas back into the hydrological (or water) cycle. Land use changes, such as increase in agricultural area, deforestation, or imperviousness on urbanized areas can also influence the processes of evapotranspiration, infiltration, soils storage, and runoff. Therefore, water balances can also be calculated to capture the equilibrium in the physical system between inputs and outputs modified by the human intervention (European Commission 2015).

Once water balances have been established for a certain land area such as a river basin or even country, water availability can then be estimated. Water availability calculations are usually done to manage current water resources against the various anthropogenic demand/uses and for designing future water resources development through infrastructure projects such as dams, reservoirs and diversions canals. All developed countries and many developing countries regularly carry out such assessments and maintain databases. However, the level of detail and precision may vary. There are wide variations in water availability vs. use among the different regions in the world. Water scarcity problems arise when water availability of an area is lower than the water demand or use. Water available in a certain country may or may not be generated within its own borders. For instance, upstream countries like Bhutan, Nepal and China generate all their water within its geographical boundary, while a downstream country like Bangladesh receives over 90% of its water from across its geographical boundaries. Figure 3.2 shows a global map identifying areas of physical and economic water scarcity in varying degrees of severity. Water scarcity is often divided into physical and economic water scarcity (Molden et al. 2003) as in certain

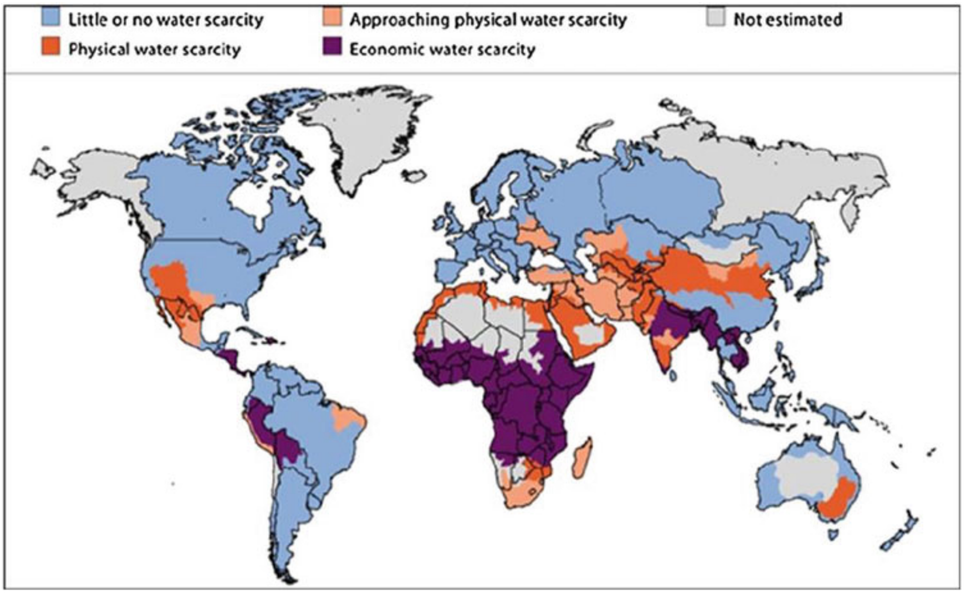


Fig. 3.2 Areas across the globe with physical and economic water scarcity in varying degrees of severity reproduced from Comprehensive Assessment of Water Management in Agriculture (2007)

places, such as in upland areas, water availability might be low although a large river is flowing a few hundred meters below in the valley. In such cases, if the upland areas have the economic means to access the river water through pumping, they do not have water scarcity issues. Similarly, groundwater or even shallow ground water might be available but due to lack of investment in infrastructure to pump ground water, many countries esp. in Africa and South Asia face economic water scarcity.

3.2.4.1 Water for Human Use and Consumption

Figure 3.3 shows the global water use differentiated as "blue water" and "green water". Blue water refers to naturally available freshwater found in rivers, lakes, reservoirs, and aquifers. Within the hydrological cycle the movement of 'blue water' is predominantly governed by gravitational forces (runoff, infiltration, seepage etc.). Due to this feature the management of 'blue water' can rely on hydraulic engineering techniques. Of the total renewable blue water resources available globally, 9% is used annually. Cities and industries extract 1200 km^3 of blue water per year but most of this water (90%) is returned to the sea (Comprehensive Assessment of Water Management in Agriculture 2007). Green water refers to soil moisture available to plants. 'Green water' is moved predominantly by molecular forces (capillary rise, evapotranspiration etc.). Consequently 'green water' management is overwhelmingly done by agricultural practices (selection of crops, change of soil structure etc.). Rainfed agriculture depends on green water, whereas irrigated agriculture depends on blue water, usually transferred from lakes and rivers. Of all the water uses, agriculture is the largest water user (See Fig. 3.3). Through the process of evapotranspiration, both green and blue water are consumed by the vegetation and not returned to the immediate water bodies as in the case of other use (Comprehensive Assessment of Water Management in Agriculture 2007).

3.2.4.2 Environmental Water Demands

Increasing demands for water to fulfill the diverse societal needs within the domestic, agricultural, industrial and commercial sectors is leading to plans to develop and exploit rivers and streams. The term "environmental flows" (EFs) is now commonly used to refer to a flow regime designed to maintain a river or stream in acceptable ecological conditions, balanced with water use for human needs. All components of the natural hydrological regime have ecological significance. In regulated basins, the magnitude, frequency and duration of some or all flow components is modified and the suite of acceptable flow limits for such modifications can ensure a flow regime capable of sustaining some target set of aquatic habitats and ecosystem processes (Poff et al. 1997). EFs can therefore be seen as a way to balance river basin development and maintenance of river ecology. According to the definition from the Brisbane Declaration (2007), environmental flows (EFs) describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. The Science of EF is a rapidly advancing field with new concepts, methods and tools being added to an ever-expanding knowledge base. Several reviews of the tools and concepts of EF are currently available (e.g. Tharme 2003; Acreman and Dunbar 2004; Poff and Zimmerman 2010; Pahl-Wostl et al. 2013; Acreman 2016).

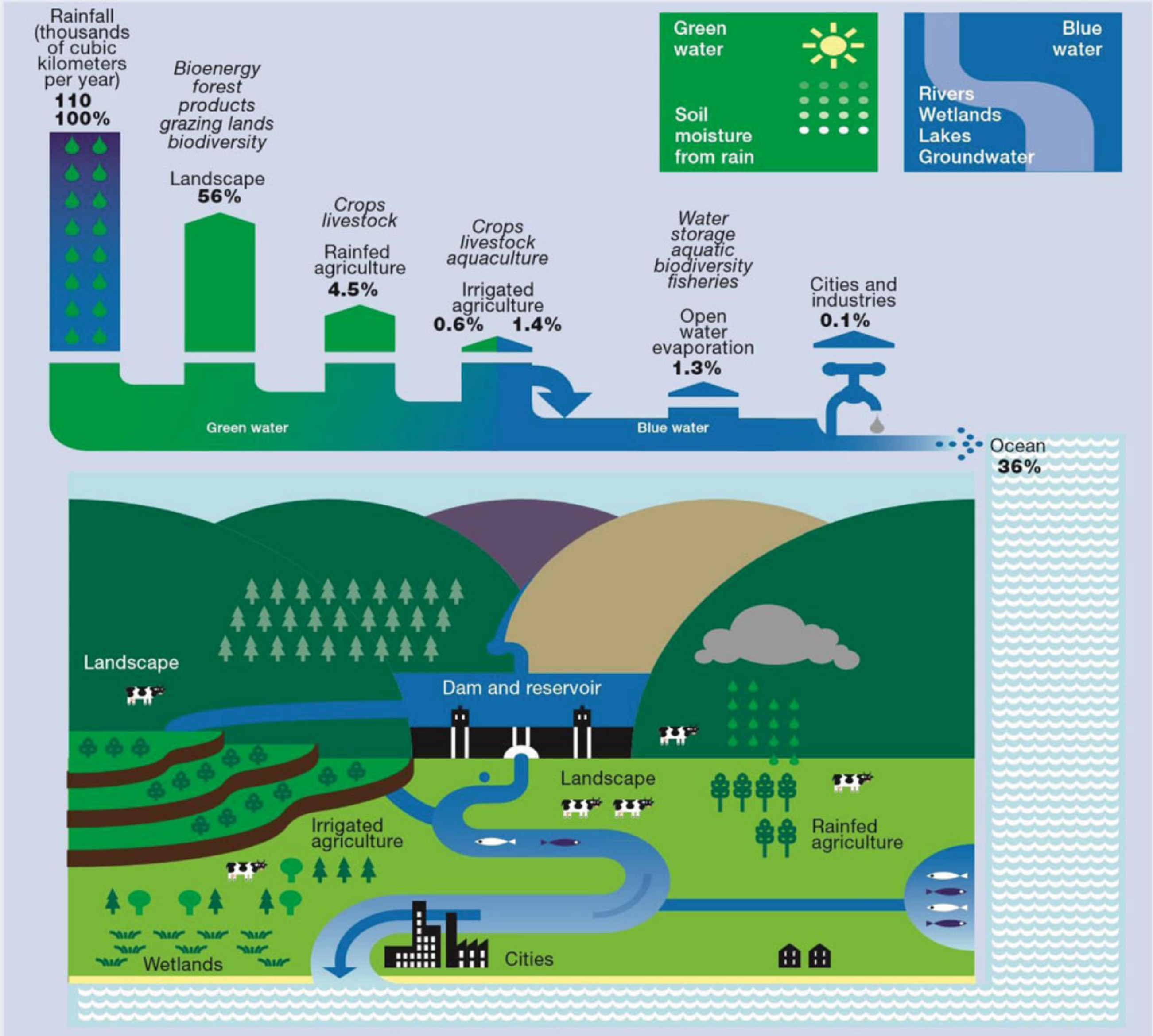


Fig. 3.3 Global water use reproduced from Comprehensive Assessment of Water Management in Agriculture (2007)

3.2.4.3 Water Accounting

Water balance calculations, usually focus on the physical processes in quantifying water fluxes and stores. Water accounting has therefore been in use to quantify/take stock of water use by natural and anthropogenic processes. The main objective is to understand weaknesses, strengths, and opportunities in existing water management practices. Water accounting therefore provides practical decision support tools that systematically links water balance, land use and water use, enabling users to understand implications of water and land management interventions. These methods categorize all water usage in the system as consumptive/non-consumptive, beneficial/non-beneficial, committed/non-committed or recoverable/non-recoverable, shifting the focus to the level of productivity in water management (Molden et al. 2003). To a certain extent, water accounting frameworks respond to the call for a globally consistent standardization of terminologies and methods in water management similar to that in finance (Karimi et al. 2013). These frameworks also promote that better management of existing water resources is key to address water scarcity in the twenty-first century (Fig. 3.4).

Different frameworks exist with varying levels of rigor in tracking the fate of every water drop in the system. AQUASTAT, developed by the FAO, represents one of the first attempts that compiled national data on water inflows and outflows. The United Nations' System of Environmental

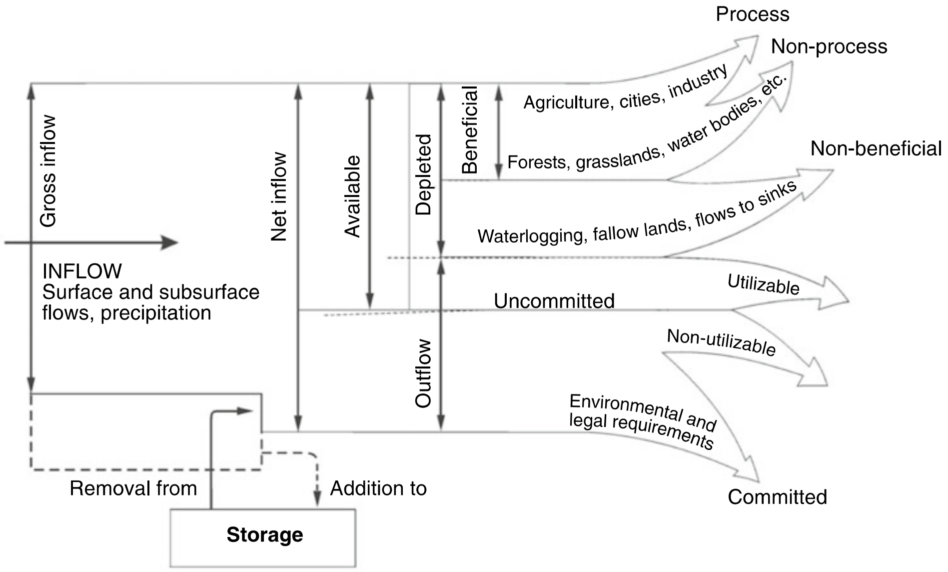


Fig. 3.4 Generalized diagram for water accounting. Reproduced from: (Molden et al. 2001)

Economic Accounting for Water (SEEA-Water) (United Nations et al. 2014) and the Australian general-purpose water accounting report (GPWAR) represent more comprehensive but data intensive efforts following financial accounting models (Burrell et al. 2018). Both SEEA-Water and GPWAR focus on accounting water flows and actual abstraction, leaving out evapotranspiration—one of the major processes leading to water loss in a river basin. Depletion based water accounting methods overcome this by considering processes that lead to depletion of water available in the system. Such methods are desirable when data on sector-wise withdrawal is not publicly available for most basins.

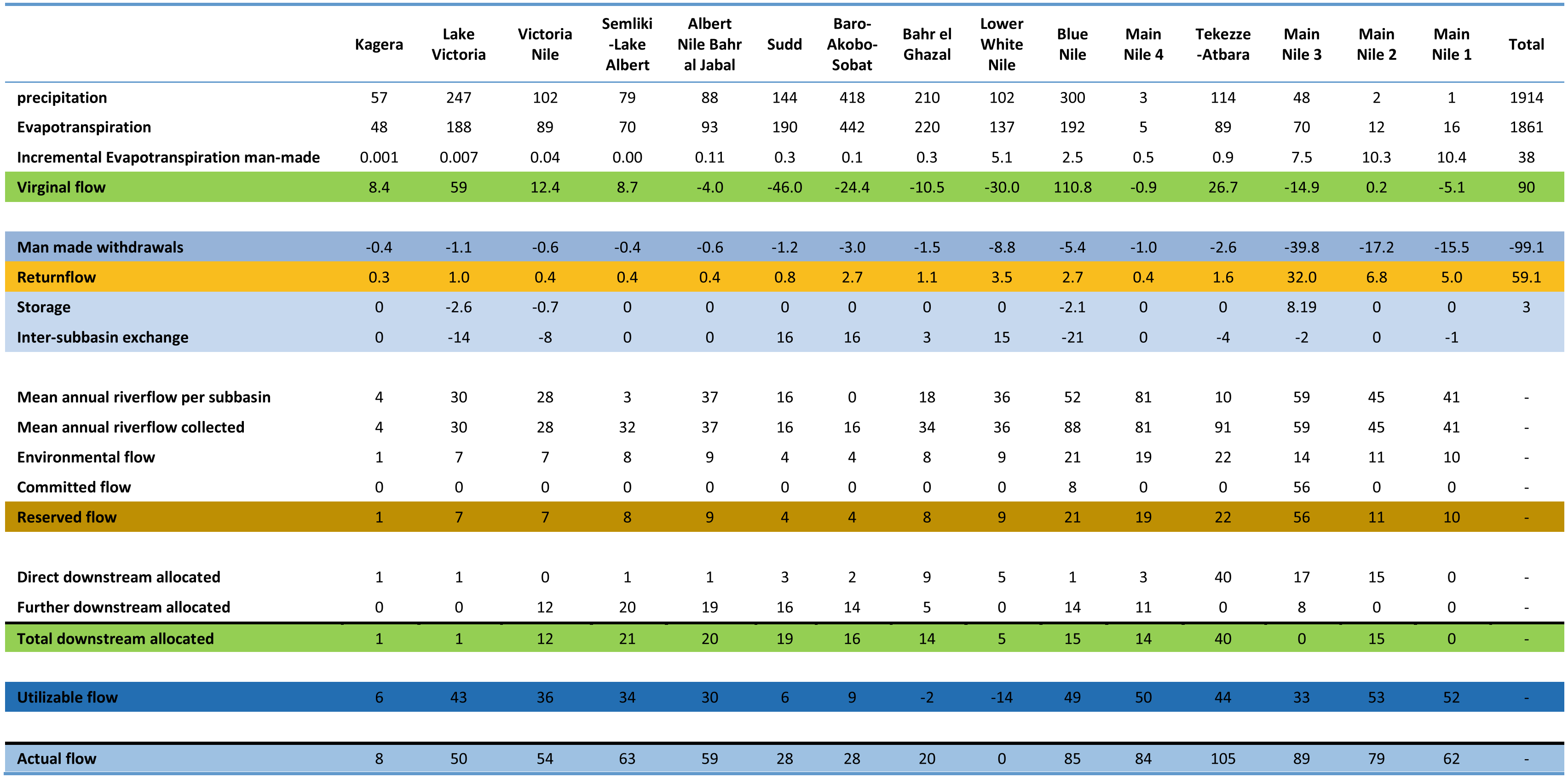
Water Accounting Plus (WA+) represents the state-of-the-art in depletion-based water accounting by utilizing freely available satellite based datasets for evapotranspiration to identify processes that lead to beneficial and non-beneficial water depletion in a basin (WA+ 2016). WA + uses gridded evapotranspiration datasets to quantify water depletion from natural processes, as well as anthropogenic processes based on the land use class in each grid. As such, the water balance used in WA+ directly links water depletion with land and water management practices (Karimi et al. 2013). Figure 3.5 presents a surface water balance for the Nile river basin conducted using WA+ (Karimi et al. 2012, 2013; WA+ 2016). WA+ is especially useful in a trans-boundary basin like Nile where field data collection and sharing is limited but satellite data is readily available.

3.2.5 Global Changes and Future Risks

3.2.5.1 Water Quality and Reuse

The problem of water quantity is most often also accompanied by the problem of water quality. Water quality is closely linked to human and environmental well-being. Contaminated waters are a threat to human health and to the sustenance of aquatic biodiversity. Many natural processes in the water cycle and symbiotic relationship between water bodies and their ecosystems provide water resources an inherent ability to self-regulate their quality, for example, removal of pollutants in runoff through soil infiltration, dilution of pollutants in large quantities of water. However, in many places dilution is not resolving pollution problems anymore as human activities have exhausted and saturated the natural capacity of surface water resources to maintain their quality. As freshwater resources become over-allocated and stressed by demands from multiple sectors, interventions to maintain water quality and subsequent reuse of water will be inevitable.

The quality of water is determined by its physical, chemical and biological composition commonly quantified in measures of turbidity, pH, temperature, dissolved oxygen, bacteria, ionic and organic content. Pure water, comprising strictly of hydrogen and oxygen seldom exists naturally. Surface water contains suspended solids, dissolved gases, minerals and organic and inorganic compounds accumulated



	Kagera	Lake Victoria	Victoria Nile	Semliki -Lake Albert	Albert Nile Bahr al Jabal	Sudd	Baro-Akobo-Sobat	Bahr el Ghazal	Lower White Nile	Blue Nile	Main Nile 4	Tekezze -Atbara	Main Nile 3	Main Nile 2	Main Nile 1	Total
precipitation	57	247	102	79	88	144	418	210	102	300	3	114	48	2	1	1914
Evapotranspiration	48	188	89	70	93	190	442	220	137	192	5	89	70	12	16	1861
Incremental Evapotranspiration man-made	0.001	0.007	0.04	0.00	0.11	0.3	0.1	0.3	5.1	2.5	0.5	0.9	7.5	10.3	10.4	38
Virginal flow	8.4	59	12.4	8.7	-4.0	-46.0	-24.4	-10.5	-30.0	110.8	-0.9	26.7	-14.9	0.2	-5.1	90
Man made withdrawals	-0.4	-1.1	-0.6	-0.4	-0.6	-1.2	-3.0	-1.5	-8.8	-5.4	-1.0	-2.6	-39.8	-17.2	-15.5	-99.1
Returnflow	0.3	1.0	0.4	0.4	0.4	0.8	2.7	1.1	3.5	2.7	0.4	1.6	32.0	6.8	5.0	59.1
Storage	0	-2.6	-0.7	0	0	0	0	0	0	-2.1	0	0	8.19	0	0	3
Inter-subbasin exchange	0	-14	-8	0	0	16	16	3	15	-21	0	-4	-2	0	-1	
Mean annual riverflow per subbasin	4	30	28	3	37	16	0	18	36	52	81	10	59	45	41	-
Mean annual riverflow collected	4	30	28	32	37	16	16	34	36	88	81	91	59	45	41	-
Environmental flow	1	7	7	8	9	4	4	8	9	21	19	22	14	11	10	-
Committed flow	0	0	0	0	0	0	0	0	0	8	0	0	56	0	0	-
Reserved flow	1	7	7	8	9	4	4	8	9	21	19	22	56	11	10	-
Direct downstream allocated	1	1	0	1	1	3	2	9	5	1	3	40	17	15	0	-
Further downstream allocated	0	0	12	20	19	16	14	5	0	14	11	0	8	0	0	-
Total downstream allocated	1	1	12	21	20	19	16	14	5	15	14	40	0	15	0	-
Utilizable flow	6	43	36	34	30	6	9	-2	-14	49	50	44	33	53	52	-
Actual flow	8	50	54	63	59	28	28	20	0	85	84	105	89	79	62	-

Fig. 3.5 Annual surface water inflow and outflow from different tributaries along the Nile River in km^3 using WA+ for 2010. Reproduced from (WA+ 2016) accessed on 25.09.2018

overtime as water moves through its surroundings. The composition of water can thus be considered an indicator of its origin and history of travel through the water cycle. Discharge of unwanted physical, chemical or biological contaminant and pollutants degrades the quality of water. These include for example: dissolved organic carbon, ammonia, phosphorous, pesticides, pathogens, organic micro pollutants, as well as heavy metals and unnatural trace elements. Such dissolved pollutants in water can be major health hazards while pathogens in water can cause water-borne diseases. Poor water quality can lower oxygen content in water or cause bloom of invasive aquatic species degrading the native aquatic biodiversity. Decline of ocean water corals is also attributed to pollutants in water.

Non-consumptive usage of water, where all or a fraction of the water is returned to the system, often alter its quality. For instance, excess water applied for irrigation that exits the farmland soaks away the surplus of fertilizers and pesticides used to enhance agricultural productivity. In various industries and in energy production, water may not be a direct ingredient but an aid for different processes, such as heating, cooling or transportation. Water discharged after such usage may contain dissolved organic or inorganic contaminants such as heavy metals, harmful gases and toxic substances. The returned water might also have substantially higher temperatures, posing an additional environmental hazard. Acid mine drainage, water used for hydraulic fracturing (fracking) and water for cooling of power plants are some controversial industries that discharge poor quality water. Babel and Wahid (2008) found that 70% (~300–500 million tons) of heavy metals, solvents, toxic sludge, and other wastes from industrial activities were discharged untreated alone into the Ganges–Brahmaputra-Meghna River Basin. Diffuse sources of pollution are considered a major threat to more than 40% of Europe's rivers (European Environment Agency 2016). Discharge of such pollutants to natural rivers, stream and lakes can result in rapid degradation of surface water quality. These diffuse and point sources of polluted water are caused by active anthropogenic usage of water.

Many other human activities generate liquid wastes that make their way into surface water resources. Sewage, municipal wastes and storm water containing unwanted sediments, debris, chemicals and disease causing pathogens can also end up in surface water bodies. In rural landscapes, open defecation and excretion are big threats to surface water quality. Direct dumping of solid and liquid wastes into flowing water is also a practice of serious concern plaguing waters in the global south. Karn and Harada (2001) found that municipal sewage contributed to nearly 85% of pollutants in river waters in Kathmandu (Nepal), Delhi (India), and Dhaka (Bangladesh) while infiltration of urban stormwater, leakage of wastewaters and septic reservoirs, and improper industrial activities were other sources of pollutants. Unmanaged solid waste and dirt from urban landscapes also make their way into rivers and the ocean as heavy rains wash them away and flood the sewers. In Kabul (Afghanistan) for example, over 70% of the city's solid waste is accumulated at the roadside, drains, and open places, ready for storm water to push them into open drainage pits and sewage channels (Scott et al. 2017).

Poor water and waste management at local scale ultimately affect our oceans as rivers transport polluted waters downstream. The great pacific garbage patch is a visible example of the intensity with which our surface waters are being infested (Eriksen et al. 2014; The Ocean Cleanup 2018; Lebreton et al. 2018). Scientists are studying this growing amalgamation of floating plastics and other wastes pushed from all over the world into the center of the Pacific Ocean by global ocean currents and wind patterns in hopes to reduce its impact on water quality. New water quality threats, such as microplastics and residues of medicines, have also emerged in recent decades as new industrial processes and new wastes are being developed.

The open and accessible nature of surface water resources makes them more vulnerable to water quality degradation through human interference than groundwater resources. Various sub-surface dynamics that provide natural filtering and purification of groundwater in underground aquifer are entirely missing for surface water. The constant flow of river waters through various terrains provides some grounds for filtration and oxidation of water to improve its physical and chemical composition. However, such natural carrying capacity is governed by the geomorphology of the river. Water quality control measures need to be put in place to control point and diffuse sources of pollution into water bodies. Impact of point sources can be reduced through complete or partial treatment of wastewater, sorting and selective removal of solid wastes prior to their release into natural water bodies. Control of diffuse pollutant sources such as agricultural leachates require interventions to reduce chemical applications in agricultural practices. Better solid waste management, including better designs of septic systems and landfill are also important for curbing water pollution. Policies and regulatory institutions need to be strengthened to support such measures for improving water quality.

While water quality degradation is an important issue on its own, its impacts will heighten under increasing water demand and water scarcity. Creative use of low or poor quality water for non-consumptive use is important to ensure water for various anthropogenic needs and equity in water allocation under socio-cultural hierarchies (Comprehensive Assessment of Water Management in Agriculture 2007). For example, in Hanoi (Vietnam), irrigation of 80% of vegetables are supplemented with wastewater, while and in Kumasi (Ghana), wastewater is potentially incorporated for irrigating a third of the country’s irrigated areas. Channeling of water through non-consumptive usage requiring varying quality of water can also help propagate circular economies by closing the loop of water demand across various sectors. Countries like Cyprus and Malta already reuse over 90% and 60% of their wastewater respectively, while the European Union (EU) is pushing to increase wastewater reuse potential (estimated as 6 km^3 annually) across all member states (European Commission 2018). Low quality water can be an important resource if it can be improved to acceptable standards for indirect usage in certain applications.

3.2.5.2 Impact of Climate Change

According to the World Economic Forum's Global Risks Report, Climate Change (CC) threats dominate the list for the third year in row (The World Economic Forum 2019). Climate change directly impacts the water cycle. The magnitude and seasonality of water availability in any surface water follows the changes in weather patterns, both local and global. While the hydrological cycle largely revolves around local patterns for temperature, precipitation and relative humidity, these local climate parameters are linked to global fluctuations in temperature and wind patterns. These linkages between global and local climate patterns are best demonstrated during the El Niño and La Niña or the El Niño-Southern Oscillation (ENSO) phenomenon, whereby warmer or colder than average surface temperatures in the Pacific ocean shifts the direction of atmospheric circulation inducing changes in weather patterns and consequently precipitation globally (NOAA 2016).

There is scientific consensus (IPCC 2013) that the planet is warming due to greenhouse gas emissions, which will impact the climate system. The fifth Intergovernmental Panel on Climate Change (IPCC) assessment reports projected change in global mean surface air temperature for the mid- and late twenty-first century relative to the reference period of 1986–2005 will likely be from 0.4 to 2.6 °C for 2046–2065 and 0.3 to 4. 8 °C for 2081–2100, under various levels of anthropogenic emission scenarios.

The IPCC warns that though projected changes in precipitation are not uniform globally, extreme precipitation events will become more intense and frequent in many regions. Figure 3.6 visualizes the potential shifts in probability distribution of climate variables under climate change (Stocker et al. 2013; IPCC 2014a, b).

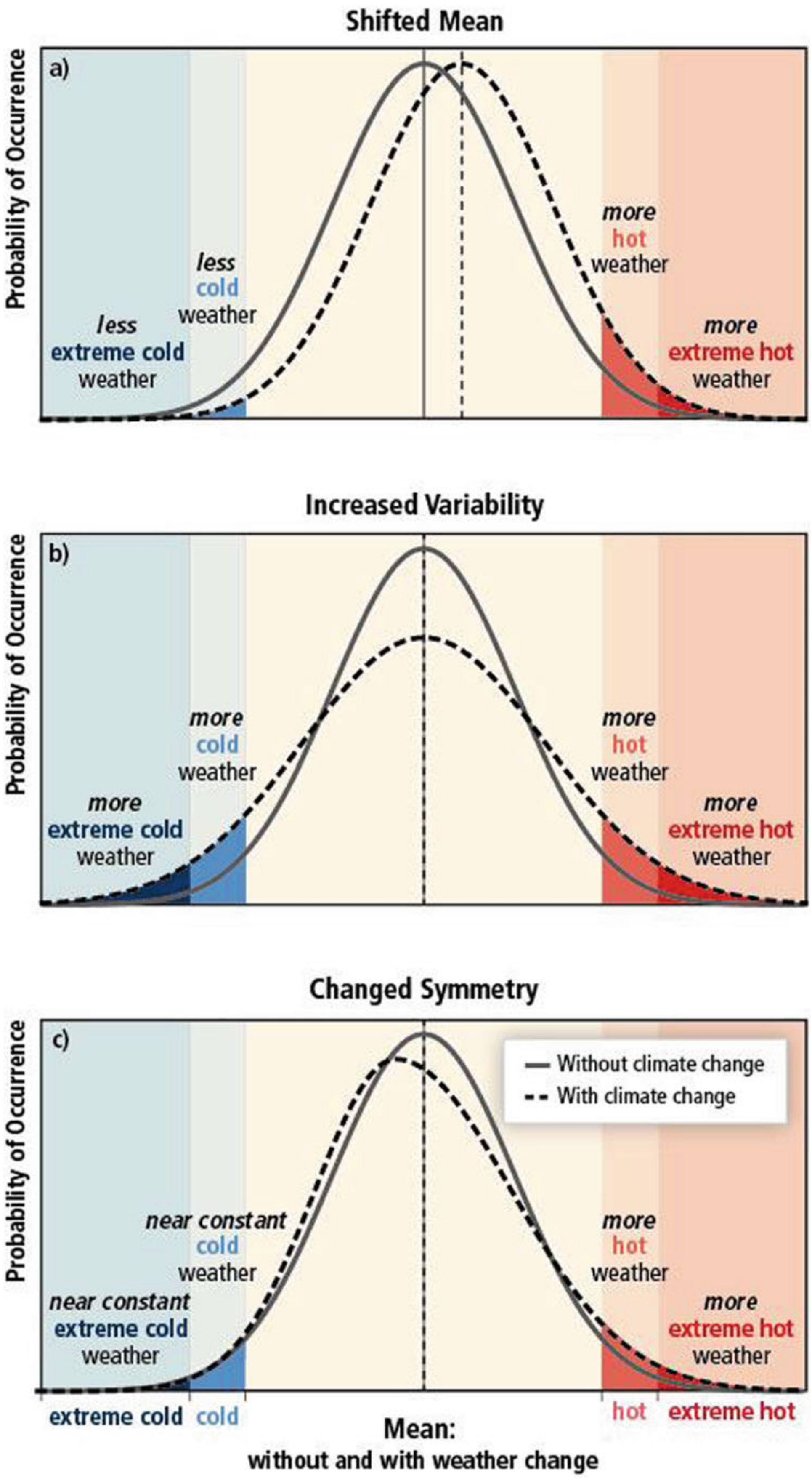
Such projections for global climate change are bound to alter the state of water resources in terms of both quality and quantity. A warming atmosphere holds more water vapor. Increasing temperatures will increase glacier and snow melt as well as evapotranspiration. Shift in precipitation will cause a shift in direct runoff contributions.

In the long run, temperature and precipitation changes will also induce changes in land cover as vegetation zones shift. Climate change induced desertification is gaining recognition as an important issue with its addition to the scope of sixth IPCC assessment (IPCC 2017). The threat of climate induced disasters such as hurricanes, floods, landslides and severe droughts are also imminent (IPCC 2014b). The impacts of climate change on water resources will be further multiplied by the domino effect on the various other sectors interlinked by the water-energy-food-environment-livelihood nexus. Climate inducted change in water availability will not only affect production of food, energy and nearly every other manufactured commodity, but it will affect human lives every day. Water infrastructure and management intervention decision makers should therefore be particularly wary of selecting designs and pathways that are climate-resilient. Coordination between management and governance systems is key challenge to ensure water resource management is done with the purview of balancing benefits across various stakeholders and future climate risks. The IPCC points out that future risks are higher for disadvantaged communities across the globe because of higher vulnerabilities (IPCC 2014b). According to IPCC vulnerabilities are not just a function of sensitivity and exposure to the bio-physical parameters but also very dependent on social and economic adaptive capacity, which includes structural inequities in the society related to gender, class, race, ethnicity etc. Many good adaptation strategies therefore might come from the non-water sector such crop insurance schemes or index based insurances, livelihood diversification, linkages to markets etc.

The future is also still uncertain. The multitude of regional and global circulation model (RCM and GCM) projections indicate change however; especially for precipitation there is sometimes no agreement on the magnitude and direction of this change (IPCC 2014a). Therefore, future water resources planning and adaptation strategies should not focus too much on future changes in averages and certain trends (increase and or decrease in precipitation) but plan for uncertainty and increases in variability of the system.

The example of the water shortage in Cape Town in 2018 aptly demonstrates that the projected dryer future might already be happening. Box 3.2 summarizes the dramatic situation in the first half of 2018.

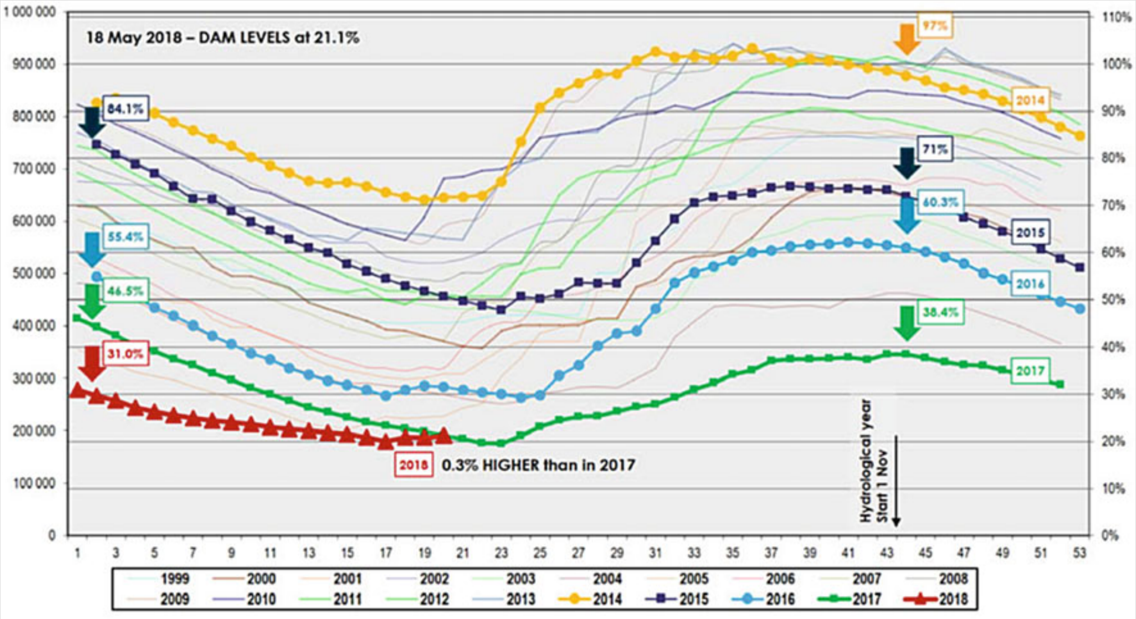
Fig. 3.6 Shift in climate patterns. Reproduced from: (IPCC 2014a)



Box 3.2 Day Zero in Cape Town, South Africa

Year 2018 saw the City of Cape Town (CCT) reduce municipal water allocation to as low as 50 liters per day per person (lpd). The CCT forecasted several dates for the approaching Day Zero, when the city's major dams would reach the critically low supply level of 13.5%, forcing the CCT to stop all municipal water supplies. Residents would then collect their allocation of 25 lpd per person from the 149 municipal water collection points. This water crisis is a harbinger of the severe water scarcity that can impact many other urban centers in the world. For the majority of cities, current water resources and management measures are not in line with expected increases in anthropogenic water demand due to consumerism, urbanization, industrialization, and population growth. Indeed, by 2025, over 3.5 billion people are projected to live in water-insecure regions worldwide.

Six major dams that harness streamflow dominate the CCT's water supply system. The total yield of the dams is 1500 million liters per day (MLD), augmented by over 200 MLD of groundwater. Very little treated wastewater is reused to supplement industrial demands, though there is potential to reuse over 200 MLD. An additional 350 MLD is required to make Cape Town sufficiently water secure. Diverse sources such as groundwater, desalination, and wastewater re-use are being explored by CCT. But augmentation projects have been slow under political and financial tensions. The climate-sensitive water supply system was thus hit hard by severe drought from 2015 to 2017. The drought is one of the worst the city has seen, a rare event occuring once in 300 years, resulting in some of the lowest water levels recorded for the city's dams.



Decline in dam water supply due to the 2015–2017 drought in the City of Cape Town compared to water levels over the decade. Reproduced from: City of Cape Town Water Outlook Report 2018.

Given the drought conditions, CCT launched aggressive demand management strategies to ensure the available water in the dams could be stretched until the end of the persisting drought. Water saving infrastructures were applied, pressures in the system reduced, detection and repair of leakages prioritized, and installation of water management devices was ramped up. Progressive tariffs were also applied to penalize water usage above 50 lpd per person February 2018 onwards. Communication campaigns warned citizens against the looming crisis and drive behavioral changes. An online dashboard enabled citizens to monitor dams and changes in sector-wise consumptions. Adherence to daily allocation was incentivized while those exceeding CCT's allocations were subject to public shaming. By May 2018, the CCT more than halved the unconstrained daily demand from 1346 MLD to 681 MLD. Such aggressive demand management, combined with heavier rains in May and June and donation of farmer's irrigation water to the city, allowed CCT to push back the imminent Day Zero to 2019. However, households in poorer neighborhoods, who cannot afford to have a private supply well bore the weight of the CCT's restrictions. Affluent households often exceeded their restricted allowances, as the higher tariffs were not a financial burden. For long-term reduction in domestic water demand, CCT needs to consider measures that impose restrictions that weigh evenly on all households.

Change in annual daily average water demand in the City of Cape Town (CCT) with restrictions placed on sector-wise water allocation by the city. Reproduced from: City of Cape Town Water Outlook Report 2018.

While Day Zero was narrowly avoided in 2018 in Cape Town, CCT continues to pursue measures to build water security. Many other cities in South Africa and beyond are functioning below the 50 lpd minimum allocation defined by the World Health Organization. Managing water, particularly in water-insecure areas, will require an integrated, targeted and aggressive approach. Day Zero is a much-needed reminder that addressing water insecurity needs to consider technical, institutional, economic, social and behavioral factors that affect water availability, water access and climate resiliency for all stakeholders.

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3.3 Groundwater: Dependence, Linkages and Challenges

3.3.1 Human Dependence on Groundwater

3.3.1.1 A Brief Historical Evolution

Since earliest times humankind has met much of its need for good quality water from subterranean sources. Springs, the surface manifestation of underground water, have played a key role in social development. The earliest waterwells were rarely more than 50 m deep, deployed manual or animal water-lifting and were sunk in Asia and the Middle East. But it was not until the nineteenth century that the foundations of modern hydrogeology were laid in Western Europe, by Henry Darcy and William Smith.

During the twentieth century, there was an enormous boom in waterwell construction for urban water-supply, agricultural irrigation and industrial processing. This was facilitated by major advances in waterwell drilling, pumping technology and hydrogeologic knowledge, which allowed deep boreholes to be drilled relatively quickly and extract large volumes. Groundwater became a key natural resource supporting human well-being and economic development—but one that continued to be widely misunderstood, undervalued, poorly managed and inadequately protected (Burke and Moench 2000).

Comprehensive statistics on groundwater pumping are not available, but global withdrawals are estimated to have reached 900 km^3/annum in 2010, providing some 36% of potable water-supply, 42% of water for irrigated agriculture and 24% of direct industrial water-supply (Dőll et al. 2012). The highest withdrawal intensity currently occurs over large areas of India, China, Pakistan, Bangladesh and Iran, and more patchily in North America, Southern Europe, North Africa and the Middle East. The social value of groundwater should not be gauged solely by volumetric withdrawals, since its use often brings major economic benefits per unit volume, because of local availability, scaling to demand, high drought reliability and generally good quality (requiring minimal treatment). The dependence of innumerable urban areas on groundwater is intensifying (for example, it provides the public water-supply for 310 and 105 million people respectively in the EU and US), and the contribution of groundwater to irrigated agriculture is high in terms of crop yield and economic productivity (Llamas and Martinez-Santos 2005).

3.3.1.2 Importance of Hydrogeological Understanding

Groundwater systems constitute the predominant reservoir and strategic reserve of freshwater on our planet, but calculating their huge volume is not straightforward. Indeed, the precision of any calculation will inevitably be open to question, since major assumptions about the effective depth and porosity of the freshwater zone will be involved. If only relatively shallow groundwater in 'active circulation' is considered (some 5–8 million km^3) then groundwater would amount to 95–97% of total freshwater stocks (UNEP 1996), with only 2–3% being held in lakes, reservoirs, rivers and swamps, and with soil-moisture storage representing about another 1%.

Groundwater normally moves very slowly through the myriad of pores and/or fractures in aquifer systems, from areas of recharge to areas of discharge (determined by the geologic structure). If not intercepted by waterwell pumping, tens, hundreds or thousands of years can elapse until eventual discharge to a spring, river, wetland or the coast (Fig. 3.7). Understanding groundwater also requires knowledge of the near-surface (unsaturated) 'soil-moisture regime', which plays an important role in the hydrologic cycle.

The characterization of groundwater systems requires an interdisciplinary approach, and must integrate geology, hydrology, physics, chemistry and biology. Being the study

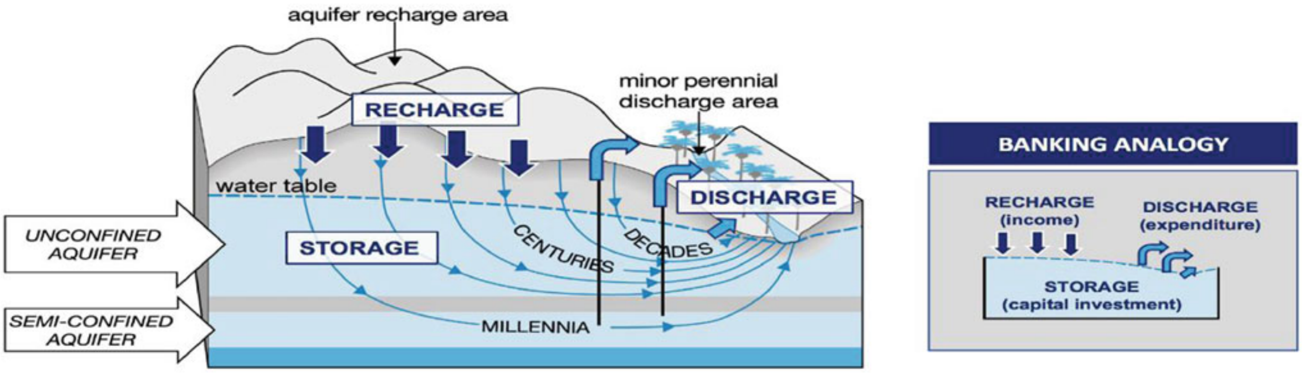


Fig. 3.7 Typical groundwater flow regime with the 'banking analogy' for aquifer storage

of geological environments that control groundwater occurrence, the physical laws that describe groundwater flow and the (bio)chemical processes occurring during this flow determine groundwater quality. It is also essential to assess the influence of mankind on the natural groundwater regime and the influence of the natural groundwater regime on mankind. Groundwater science therefore has to incorporate consideration of the socioeconomic dimensions and embrace facets of engineering and ecology.

3.3.2 Groundwater Systems: Some Essential Concepts

3.3.2.1 Nature of Groundwater Storage and Flow

All aquifers have two fundamental characteristics: a capacity for 'groundwater storage' and a capacity for 'groundwater flow'—but different formations vary considerably in their properties, for example:

- unconsolidated deposits—such as sand and gravel, with porosities storing water in as much as 30–35% of their total volume and permitting significant groundwater flow
- consolidated rocks—such as some limestones storing water only in micro-fractures rarely occupying more than 1% of rock volume, but limestones can enlarge markedly by dissolution forming so-called 'karst systems' which transmit groundwater very rapidly.

The vast storage of many groundwater systems is their most distinctive characteristic, but can result in the false impression that 'groundwater resources are inexhaustible' (Foster et al. 2013). Whilst this storage provides an effective 'natural buffer' against climatic variability, contemporary recharge is finite and controls the long-term physical sustainability of groundwater resources (Fig. 3.7).

Groundwater bodies are naturally recharged by rainwater and snow-melt where they infiltrate through the soil zone and drain by gravity to the water-table. It usually takes various years for infiltrating water to reach the water-table. Assessing the relationship of surface water to underlying aquifers is important, and it is essential to distinguish between:

- streams and lakes on which an aquifer is dependent for significant recharge
- rivers that in turn depend significantly on aquifer discharge to sustain their dry-weather flow.

Slow flow rates and long residence times, consequent upon large aquifer storage, are another distinctive feature of groundwater systems, and they naturally transform highly variable recharge regimes into more stable discharge regimes. Groundwater flow regimes are shaped by geologic structure—with some formations of low permeability ('aquicludes') virtually blocking all groundwater flow and others ('aquitards') only allowing limited movement.

3.3.2.2 Evaluation of Groundwater Recharge and Balance

The evaluation of contemporary recharge rates to aquifers is of fundamental significance when considering the sustainability of groundwater resources. With increasing aridity, direct rainfall recharge generally becomes progressively less significant than indirect recharge from surface runoff and incidental artificial recharge from human activity. However, there is often substantial scientific uncertainty in quantifying individual recharge components due to the inherent geo-complexity of natural systems, and the wide spatial and temporal variability of rainfall and runoff events (Scanlon et al. 2002). Figure 2.9 in Sect. 2.2.3 shows the long term average groundwater recharge worldwide.

Understanding the intimate linkage between land-use and aquifer recharge is an essential basis for integrated water resources management (Foster and Cherlet 2014). The common paradigm of 'constant average groundwater recharge rates' is false and leads to serious 'double resource accounting', especially in more arid regions. Recharge rates vary considerably with:

- changes in land use and vegetation cover—notably the introduction of irrigated agriculture, but also vegetation clearance and soil compaction
- urbanisation processes—in particular the level of water-mains leakage, proportion of unsewered sanitation and degree of land-surface impermeabilisation
- widespread water-table lowering by groundwater abstraction and/or land drainage—leading to increased areas and/or rates of infiltration in some aquifer systems
- changes in surface water regime—especially diversion or canalization of river flow.

All waterwell pumping results in a decline in water-table over a certain area. Some decline may be desirable, since it improves land drainage and maximizes groundwater recharge by providing additional storage space for excess wet-season rainfall. But all groundwater flow is discharging somewhere, and extraction from waterwells reduces these discharges. Any attempt at defining some form of 'acceptable aquifer yield' must thus make value judgements about the importance of maintaining (at least a proportion of) 'natural beneficial discharges' from the aquifer system, and also clearly distinguish consumptive use and catchment export of extracted groundwater from non-consumptive uses which generate return water.

Past episodes of natural climate-change have transformed some large land areas (which formerly had much wetter climates) into deserts, and virtually eliminated all contemporary groundwater recharge, although some discharge to oases is often still occurring. Groundwater reserves which are not being actively recharged are known as 'fossil groundwater'. These reserves can be, and are being, tapped by waterwells but once pumped out may never be replenished—they are thus termed 'non-renewable groundwater resources' and as such merit special governance provisions (Foster and Loucks 2006). The large non-renewable groundwater resources of some major aquifers can provide very reliable sources of water-supply, which are completely resilient to current climate variability. However, in the end their use will be time-dependent and as such deserves careful consideration in terms of efficient utilization, ecological impacts and inter-generational equity. It should always be considered a strategic development subject to special investigation, monitoring and management.

3.3.2.3 Consequences of Excessive Aquifer Exploitation

Prior to large-scale anthropogenic activity (mainly pre-1950 but in some places 1920) human capability to abstract groundwater was tiny in comparison to available resources, and most groundwater bodies (outside hyper-arid regions) were in physical equilibrium. In subsequent years rapid (and often uncontrolled) expansion in groundwater exploitation generated major socioeconomic benefits, but encountered some significant problems. In many locations, abstraction rates are now not physically sustainable in the long-term (Foster et al. 2013).

While it is accepted that over-drafting aquifer storage can be a legitimate strategy during social transformation to a less water-dependent economy, large overdrafts can have various consequences whose implications must be weighed against the socio-economic benefits of resource development. These include waterwell yield reductions and/or increased pumping costs; degradation of groundwater-dependent ecosystems; saline water intrusion or up-coning; and in certain settings land subsidence causing extensive and expensive damage to urban infrastructure and increased flood risk.

There are numerous examples of major aquifer depletion from groundwater use for agricultural irrigation with water-table lowering over extensive areas. Cumulative resource depletion from 1900 to 2008 (but mainly since 1950) has been estimated to be at least 4,500 km3 (mainly in India, USA, Saudi Arabia and China) (Konikow 2011), although estimates are subject to uncertainty over the average specific yield of strata dewatered. More localised depletion occurs around some major urban conurbations, especially where the main aquifer is semi-confined. Aquifer depletion contributes indirectly to sea-level rise by creating a water transfer from long-term terrestrial storage to active surface circulation with net water transfer to the oceans. A volume-based assessment for depletion during 2000–08 gave a minimum estimate of 106 km^3/a, equivalent to 0.3 mm/a (or 18% of current sea-level rise).

3.3.2.4 Processes of Groundwater Quality Degradation

Groundwater, for the most part, is naturally of excellent microbiological and chemical quality. The underlying reasons for this are:

- capacity of subsoil profiles to filter-out faecal micro-organisms pathogens, and all suspended solids and organic matter, from percolating recharge
- long sub-surface residence time (decades to millennia) compared to the environmental survival of pathogens (usually <50 days and rarely >300 days)
- relatively low solubility and non-toxic nature of the matrix of most aquifers.

There are, however, some important exceptions to this since some aquifers exhibit both natural groundwater contamination with trace elements that create a health hazard (arsenic and fluoride) or nuisance (dissolved iron and/or manganese) and elevated vulnerability to pollution from the land surface due to their thin vadose zone and/or the presence of highly-preferential pathways to the water-table. Moreover, all aquifers are vulnerable to pollutants that are resistant to subsurface adsorption and/or biodegradation such as nitrate, salinity and numerous man-made organic chemicals. Sustainable development is thus not only constrained by resource availability, but also by quality deterioration.

Globally, significant non-coastal areas are suffering serious groundwater salinization (Foster et al. 2013, 2018) as a result of various processes (Fig. 3.8) including principally:

- fractionation of salinity into irrigation water returns to groundwater—especially in situations where groundwater is main source of irrigation-water
- natural salinity being mobilized from the landscape—consequent upon natural vegetation clearing for farming development with increased rates of groundwater recharge
- excess infiltration causing rising groundwater tables—usually associated with inefficient irrigation using imported surface water in areas of inadequate natural drainage

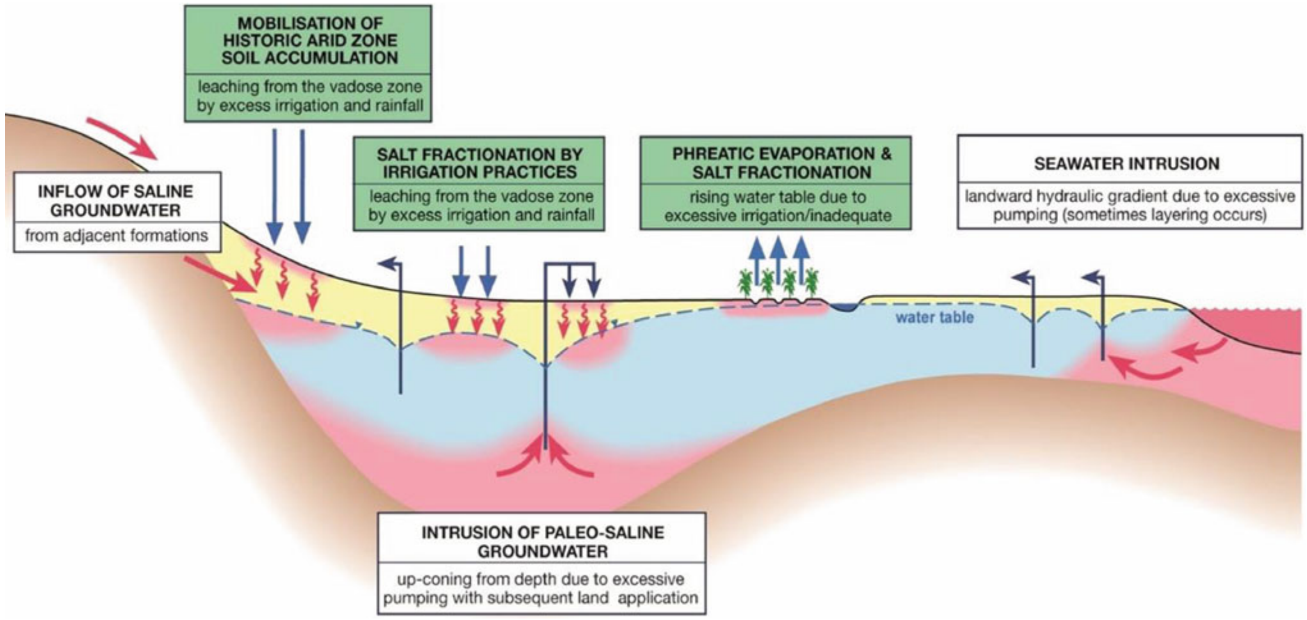


Fig. 3.8 Schematic representation of salinization of groundwater recharge by irrigated agriculture and other mechanisms (modified after Foster et al. 2018)

- excessive disturbance of natural groundwater salinity stratification—through uncontrolled waterwell construction and pumping.

The above mechanisms are in addition the intrusion of saline water in coastal aquifers due to excessive groundwater abstraction. Groundwater salinization is very costly to remediate and often quasi-irreversible, since the saline water which invades macropores and fissures diffuses rapidly into the matrix of porous aquifers, and then can take decades to be flushed out even after flow of freshwater has been re-established.

An important characteristic of porous media is their natural potential for contaminant attenuation. Since not all subsurface profiles are equally effective in this regard, the (albeit simplified) concept of aquifer pollution vulnerability is useful (Foster et al. 2006)—with vulnerability being expressed as a function of the intrinsic properties of the unsaturated (vadose) zone (or confining beds) separating the aquifer from the land surface. An important factor, especially in consolidated strata, is the possibility of downward contaminant transport via preferential pathways, which will greatly increase aquifer vulnerability to pollutants that would otherwise be retarded by adsorption and/or eliminated by biodegradation.

The location and evaluation of pollution incidents, and pollution prevention, monitoring and remediation, are all much more challenging for groundwater than for surface water. Pollution from human activity, especially agriculture at the land surface has been increasingly reported since the 1970s in industrialized countries, and from somewhat more recently in industrializing and developing nations, due to absence of proactive aquifer protection policies. Many more pollution incidents are likely to be occurring unreported (because of inadequate groundwater monitoring) and incidents that occurred decades ago may still be threatening groundwater quality, with the legacy being detectable around industrially-contaminated land.

Spectacular groundwater pollution incidents with large plumes can be associated with industrial point sources from major spillage or casual discharge in vulnerable areas, but much more insidious and widespread problems arise:

- if urban sanitation is achieved by on-site arrangements—leading to major increases in recharge rates but deterioration of recharge quality (nitrate, organic carbon and possibly of toxic synthetic compounds)
- where mains sewerage delivers minimally-treated wastewater used for flood irrigation of agricultural crops—incidentally resulting in the augmentation and contamination of local groundwater
- if small-scale industries (notably textile manufacture, leather processing, garment cleaning and vehicle maintenance) dispose of liquid effluents (including spent oils and solvents) to the ground
- from intensification of irrigated and rainfed agricultural cultivation sustained by ever-increasing quantities of inorganic fertilizers and a wide spectrum of synthetic

pesticides—with close correlation of high nitrate in shallow groundwater being widely reported, together with soluble and mobile pesticides whose degradability decreases markedly once leached below the soil zone.

Whilst groundwater is much less vulnerable to anthropogenic pollution than surface water, once polluted aquifers are very difficult to clean-up given their inaccessibility, the large volume of groundwater usually involved and the very slow rates of diffusion of contaminants out of the finest pores and fractures.

3.3.2.5 Approaches to Groundwater Pollution Protection

Groundwater pollution is usually insidious and invariably expensive. Insidious because it often takes many years to become fully apparent in waterwell abstraction, by which time it will normally be too late to have prevented serious contamination. Expensive because of the high cost of providing an alternative water-supply and of remediating polluted aquifers. Indeed, restoration to drinking-water quality standards is often impractical.

The 'polluter-pays-principle' should thus be interpreted to require all potential point-source polluters to pay for adequate groundwater protection, and the 'precautionary principle' applied to pollution control. In the case of groundwater this approach is essential because determining who is to blame for actual pollution is made difficult by both the hydraulic complexity and the large time-lag in pollutant transport (even in some cases just to reach the water-table).

Since groundwater is a very important source of water-supply for public use, sensitive industrial production, terrestrial ecosystems and river baseflow, it is essential that its quality be protected for present and future use. This requires mapping of high pollution vulnerability and drinking-water source protection zones, with application of appropriate controls on hazardous activities corresponding to each zone so as to reduce the risk of major groundwater pollution (Foster et al. 2006). More targeted groundwater monitoring is required in most countries to establish quality status reliably, and identify trends in any quality degradation, as an iterative feedback to proactive aquifer protection.

3.3.3 Linkages to Social and Environmental Sustainability

3.3.3.1 Food Security and Groundwater

Groundwater proved to be a critical input for enabling food production to increase by 250% during the 'Asian green revolution' (1970–2000). This witnessed a remarkable investment in private waterwell construction for agricultural irrigation, because groundwater is more reliable than surface water, and guarantees higher crop yields and economic returns to farmers. Current withdrawal rates for irrigated agriculture in more arid areas, however, are not physically sustainable, and are resulting in long-term depletion of aquifer reserves. Elsewhere, widespread waterlogging and salinization of shallow groundwater is an insidious menace resulting from inadequate surface-water irrigation management. The implication of both of these threats is that at least 15% (and perhaps more) of current global food production may not be sustainable (IAH 2015a).

Agricultural land-use practices also exert a major influence on aquifer recharge rates and quality, although the impact varies with hydrogeological setting (especially water-table depth) and whether groundwater or surface water is the irrigation water-supply. Changing from flood irrigation to precision drip or sprinkler technology can reduce the volume of water applied to a specific crop and thus energy use for pumping—but this (so-called) 'efficient irrigation' is not usually a significant 'water-resource saving measure', and its introduction often has negative consequences for groundwater (Foster and Perry 2010). Intensification of agricultural cropping also widely leads to groundwater resource depletion and diffuse pollution of groundwater by plant nutrients, salinity and some pesticides—and improved land management measures need to be promoted so as to provide farmers with incentives to enhance groundwater recharge and reduce agrochemical leaching (Foster and Custodio 2019).

3.3.3.2 Urbanization and Groundwater

Groundwater is a major source of urban supply worldwide, and aquifer storage represents a key resource for water-supply security under extended drought and climate change scenarios. To achieve this, groundwater must be managed more effectively through promoting as 'best engineering practice' (IAH 2015b):

- establishment of more water-utility wellfields outside cities, with their 'capture areas' as drinking-water protection zones
- more widespread use of groundwater and surface-water resources conjunctively
- adoption of 'adaptive management strategies' recognising that aquifers are in continuous evolution, with some uncertainty over their precise behaviour.

Private waterwell construction for in-situ self-supply has 'mushroomed' in many developing cities as a 'coping strategy' during periods of inadequate utility water-service, and continues for years after as a 'cost-reduction strategy'. These unregulated private wells often draw water from shallow aquifers which have already been polluted by local urban or industrial waste disposal. Broad groundwater quantity, quality and economic assessments of current and likely private waterwell use need to be undertaken to allow the public administration to formulate balanced urban water policy (Foster and Hirata 2011).

In-situ sanitation practices and wastewater handling/re-use from mains sewerage provide a component of urban groundwater recharge but simultaneously pose a serious threat of shallow groundwater pollution (including pathogenic micro-organisms, ammonium or nitrates, toxic community chemicals and pharmaceutical residues) (Fig. 3.9). The pollution risk varies widely with the local hydrogeological setting, density of population served, design of in-situ sanitation units or the level of wastewater treatment, and location/mode of wastewater reuse. Thus it is critical that groundwater vulnerability and dependence are taken into consideration in the planning and implementation of sanitation investments however—the governance and operational arrangements for this to occur are still widely lacking.

3.3.3.3 Human Health and Groundwater

The naturally excellent quality of most groundwater bodies has long been a vital factor for human health. A prerequisite for preserving this quality is that potable groundwater sources must be carefully sealed to prevent direct entry of pollutants, such as pathogenic organisms and hydrocarbon fuels or lubricants, from the land surface. All waterwells and springs used as drinking-water sources require quality surveillance in relation to perceived pollution risks—and if used untreated those at serious risk (or already impacted) should be clearly marked as suitable only for non-potable uses. Aquifers exploited for drinking-water supplies should be subject to systematic assessment of both actual polluting processes and potential pollution vulnerability from pathogenic microorganisms (which present an acute health risk) or chemical pollutants (which constitute a chronic health risk) (IAH 2016c). These risks can then be managed by designating land protection zones of appropriate dimensions to the local hydrogeological conditions in which potentially-polluting activities can carefully vigilated and controlled.

The most widely-distributed threat to potable groundwater quality comes from land-cultivation for intensive agriculture, which employs heavy applications of nutrients and pesticides that can be leached from soils to the underlying aquifers. Some synthetic organic chemicals of widespread industrial and community use (including the so-called 'emerging contaminants' with endocrine-disrupting or carcinogenic implications) are resistant to degradation in the subsurface and constitute a long-term health hazard. However, currently the most serious groundwater contamination hazard and health threat at a global scale comes from excessive arsenic and fluoride concentrations, which arise naturally through sediment or rock dissolution under certain hydrochemical conditions (IAH 2016c).

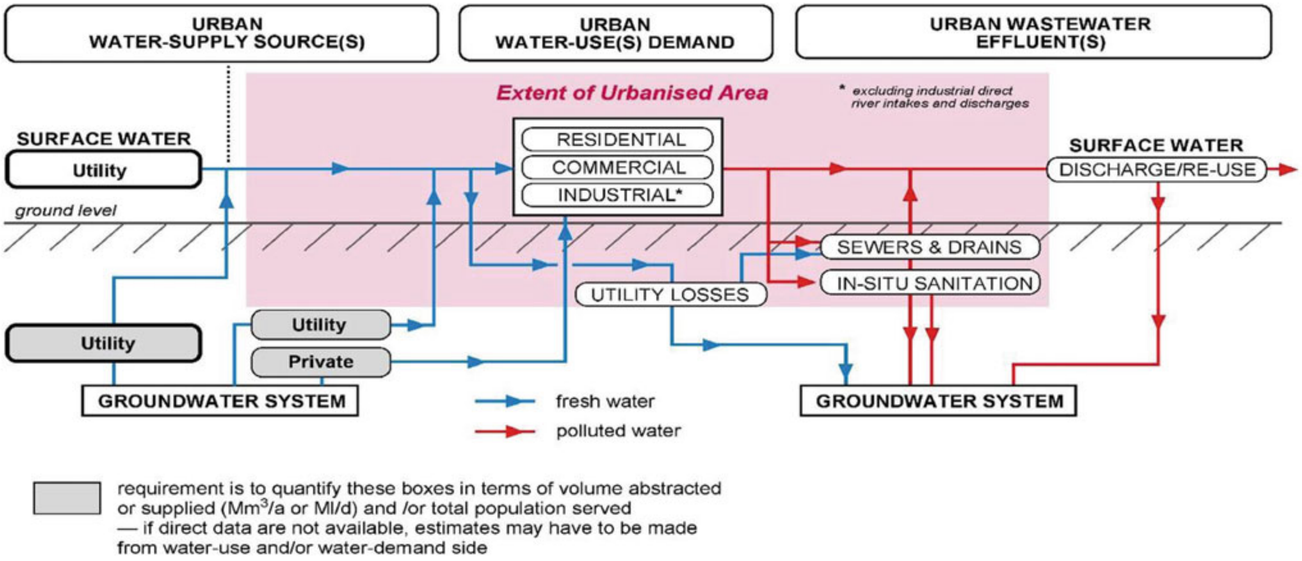


Fig. 3.9 Schematic representation of urban groundwater processes in cities underlain by unconfined aquifers (modified after Foster and Hirata 2011)

3.3.3.4 Ecosystem Conservation and Groundwater

Groundwater-dependent ecosystems (GDEs) comprise a complex subset of ecosystems of major significance in the conservation of biodiversity (Fig. 3.10), including many vital sites covered by the RAMSAR Convention (IAH 2016b). Such ecosystems are usually characterized by phreatophytic plants which derive most of their water needs from saturated soils, and long-term groundwater depletion will eliminate these species and their ecosystem function. GDEs also have direct value for the human population from fish and plant production, water storage and purification, and indirect value in terms of landscape and habitat. There is a pressing need to identify GDEs according to type (aquatic, terrestrial or subterranean) and improve understanding of their relationship with underlying groundwater.

Degradation of GDEs can occur because of anthropogenic modifications to aquifer flow regimes and salinization or pollution of their groundwater. Potentially negative ecological impacts, with the extermination of key species, can arise from uncontrolled groundwater withdrawals for irrigated agriculture or urban water-supply and/or modest increases in groundwater salinity and/or pollution (with nutrients and pesticides). Social awareness of the importance of groundwater for sustaining viable ecosystems must be promoted to mobilize appropriate stakeholders for GDEs such as conservation NGOs and local land authorities. GDEs can be conserved by integrating their protection into basin and aquifer scale water-resource planning and management, or at least acting selectively to incorporate GDE protection zones into overall groundwater resource use and land-use control policy (IAH 2016b).

3.3.3.5 Extractive Industries and Groundwater

On-shore hydrocarbon exploitation requires full hydrogeological risk assessment, appropriate environmental regulation, diligent operational control and secure management of subsurface waste injection. In non-renewable hydrocarbon development the principal concern is to prevent shallow aquifer pollution with formation brines, hydrocarbon compounds, fracking fluids and ‘stray gas’, and much improved hydrogeological monitoring of such activities is needed (IAH 2015c). Applied hydrogeological science is also required for:

- development of hydrogeothermal energy (particularly of ‘very low enthalpy’ for space cooling or heating), with long-term monitoring and modelling of groundwater system response being required to assess sustainability and improve design
- the nuclear power sub-sector in power station siting and radioactive waste disposal, so as to build political and public confidence in selection of safe geological repositories for radioactive waste.

Mining enterprises also present a significant risk of perturbing groundwater flow and polluting groundwater quality (IAH 2018), and in particular:

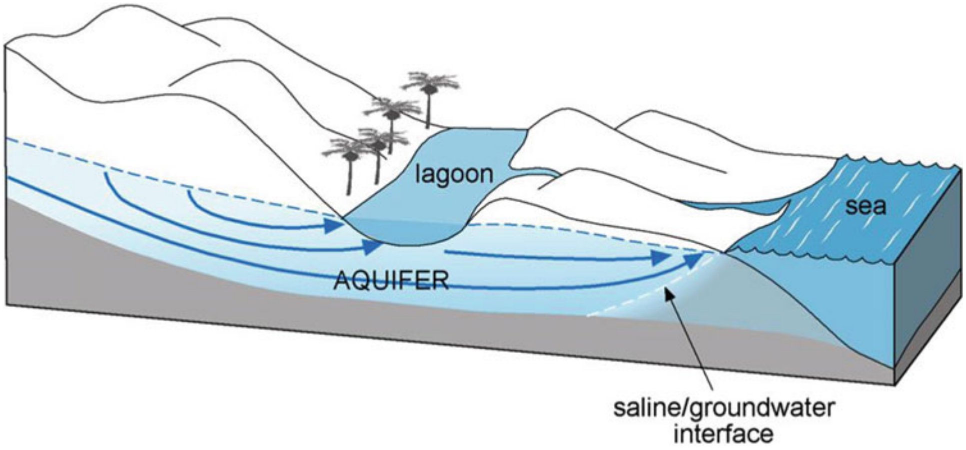


Fig. 3.10 Coastal freshwater lagoons—an example of a widespread groundwater-dependent ecosystem

- open-cast extraction of sand-and-gravel or coal/lignite usually produces a significant disturbance of the local groundwater regime and can be a groundwater quality hazard
- deeper mining activities (for coal, metals, salt/potash, precious minerals, etc.) often involve pumping large groundwater volumes for drainage, modifying the flow and quality regime, and on abandonment with water-table rebound can lead to the discharge of highly-acidic and polluted groundwater.

Cross-sector regulation planning of such activities is required to facilitate harmonization, with long-term provision for environmental management throughout the entire mining 'life-cycle' (for the mining and water nexus, see Chap. 21).

3.3.3.6 Geotechnical Hazards and Groundwater

Groundwater plays an important role in various geotechnical processes—constituting a serious geotechnical hazard whose presence reduces the engineering strength and slope stability of many soils. Of particular concern here are the potential impacts of either falling or rising water-table as a result of changes in groundwater resource extraction (or other processes).

- falling water-table—which can lead to significant land subsidence (consequent upon dewatering and settlement of aquitards) and result in serious damage to urban infrastructure (such as building foundations, sewer lines, tunnels, etc.) with increased flood risk
- rising water-table (or water-table rebound)—which can lead to inundation of subsurface structures (such as basements, car parks and subways) and structural damage of 'watertight subsurface structures' due to uplift.

Some construction activities can also perturb groundwater systems and create a potential groundwater quality hazard including the emplacement of buried fuel tanks and pipelines, underground railways and roads, car parks and deep basements.

3.3.4 Global Change and Groundwater

3.3.4.1 The Need for Adaptive Management

Groundwater management to confront situations of excessive and unstable resource exploitation will require demand-side management interventions (such as restricting waterwell use at certain times, reducing consumptive use by irrigation or industry) and in-situ supply-side engineering measures (such as rainwater harvesting, management or aquifer recharge enhancement). It is important to stress that constraining demand for groundwater abstraction will normally be essential to achieve groundwater balance, irrespective of what local supply augmentation measures can be economically undertaken.

The large natural storage of aquifer systems means that they play a vital environmental role in 'buffering' rainfall variability—receiving recharge seasonally (or only in years of exceptional rainfall in arid terrains) but generating a more uniform water discharge back into the surface environment and thus, even during drought, maintaining the baseflow of lowland streams and sustaining many aquatic ecosystems. In low-flow periods the groundwater contribution to river flow widely rises to 90% or more. The natural resilience of groundwater systems to drought is also of major significance (IAH 2016a) for securing drought-reliable low-cost water-supplies for the human population generally and providing a reliable water source for agricultural irrigation during periods of more extended drought (particularly valuable in assuring yields of high-value crops). These functions will be critical in adapting to climate change.

In view of the uncertainties associated with both climate change and groundwater system behavior, adaptive management is needed. It will be necessary to maintain a reasonable balance between the costs and benefits of interventions, and thus take account of the susceptibility of the system in question to degradation and the legitimate interests of water users. And where groundwater quality is concerned, preventive management approaches will be far more cost-effective than purely reactive ones.

3.3.4.2 Impact of Global Warming

Climate change (with increasing ambient temperature, variation of rainfall rate and intensity, modifying the vegetation cover and its evapotranspiration) will eventually impact groundwater resources (Taylor et al. 2012). Graphic evidence of this exists in the paleo-hydrological record of aquifers containing groundwater at depth which is up to 20,000 years old, and which originated as recharge in past wetter and colder millennia. However, given the large volume of many aquifer systems, only marked climatic change will have measurable influence on groundwater resources overall. Global warming is likely at many latitudes associated with an increasing incidence of high-intensity rainfall episodes, it is also likely to result in increased preferential flow through the vadose zone and thus increased leaching of agrochemicals. It may also result in peak water-table levels higher than previous maxima and cause 'groundwater flooding'.

3.3.4.3 Impact of Land-Use Change

In contrast, major land-use change is capable of exerting a marked impact on both the amount of recharge and quality of groundwater within decades. Most groundwater originates as excess rainfall infiltrating the land surface. Thus land-use has a major influence on both groundwater quality and recharge. Every land-use practice has a 'water resource footprint', and may result in diffuse groundwater pollution. Similarly, land-use practices will influence groundwater recharge rates considerably, especially under more arid conditions.

Some of the more significant changes for underlying groundwater include clearing natural vegetation, converting pasture to arable land, extending irrigated agriculture, intensifying dryland and irrigated agriculture, introducing biofuel cropping, and reforestation and afforestation with commercial woodland (Foster and Cherlet 2014), but extending irrigated agriculture using surface-water has the greatest impact—significantly increasing groundwater recharge but degrading its quality.

Globally there is a need to increase production of staple grains (such as maize, rice, and wheat), whose yields are generally only 30–50% of those in 'more advanced' agriculture, but concerns are growing about its impact on groundwater recharge due to increasing consumptive water-use, and excessive nutrient and/or pesticide leaching. For the intensification of vegetable and fruit cultivation, farmers tend to use 'precision irrigation' (such as pressurised drip and micro-sprinkler systems), which markedly decreases recharge rates. In some senses the large-scale introduction of solar panels is a welcome development, since it reduces land-use pressure on groundwater, but the energy generated is required to be incorporated into the 'national or local grid' and not used directly for powering waterwell pumps.

3.4 The Main Challenges of Water Resources Management in the 21st Century

3.4.1 Drivers and Constraints

There are good reasons to debate what are the major, globally relevant issues which bear upon how the water resources of the world should be used and safeguarded. With this utilitarian concept, but also through the necessary stewardship, water has been put in a direct human- resource context. This context is shaped by drivers. Drivers can be interpreted as events, development processes or the likes emanating predominantly from within societal realms. They are taking place irrespective of the human-resource context and its potential limitations. Drivers can also be associated with aspirations of society. Availability and quality of the resource constrain the feasible decision space for solutions accommodating the respective achievement levels of the drivers. No doubt that once certain levels are reached, drivers may directly redefine constraints. Achievement on one account can limit the feasible space for other drivers.

Drivers thus may exert pressures on resources. As long as the respective service provision expected to be provided by a certain resource can continue virtually indefinitely, pressures may not impair the resource base. However, extreme pressure levels, or the combination of various pressures may accumulate and can become stressors. Stressed water resources systems may gradually, or even precipitously lose their sustainable service function. (For more detail see Sect. 11.2).

Drivers and constraints are thus directly associated with human demands and aspirations, but can also be the consequence of malfunctions of society. These may be explicitly formulated by societal actors, or emerge indirectly and sometimes unnoticed as the consequence of societal activities, human behavior and their change and interactions with other natural or/and socioeconomic processes.

3.4.1.1 The "Immediate" Drivers: Population Dynamics, Poverty and Pollution

The most direct drivers and constraints in the context of human society and water resources are associated with the three "P"s: Population dynamics, Poverty and Pollution.

Population dynamics encompasses more than population growth. While the rapid increase of population, especially in water scarce regions represents by far the biggest challenge to cope with (see Sect. 2.2.4), the decrease of population can also imply water management problems, for example in form of underutilized (and underfunded) water infrastructure in economically shrinking areas.

Population dynamics includes also vertical (upward) mobility, the increase of the standard of living with its consequences manifested in increasing demands, consumption and resource use. However, vertical mobility can also refer to downward movement of impoverishment and other forms of decline.

Finally, population dynamics accounts also for "horizontal mobility", displacement (forced or voluntary), including the exodus from rural livelihoods towards urbanized areas and different forms of temporary or permanent (including trans-border) migration.

The most momentous manifestation of population dynamics is the ongoing rural migration towards urbanized settlements. Already more than half of humanity lives in urban areas and this percentage is expected to grow rapidly. By 2050 the world population is projected to reach about ten billion people with nearly seventy per cent of the population living in cities (UN DESA 2017 and 2018 resp.). Most of these people will be born in developing countries where drinking water and adequate sanitation are still to be provided. Burgeoning cities also present challenges because of their demand for water and pollution of rivers, lakes and aquifers. Losses from municipal water supply systems and seepage from sewers can reach alarming proportions as maintenance is often neglected (Sewilam and Rudolph 2011). The rapid, and to a large extent disorganized, influx of rural population creates an enormous stress on water in the recipient urban spaces. The existing urban water infrastructures are usually insufficient to provide adequate service for the newly arrived people and rehabilitation and/or extension may not be able to keep the pace with the population increase.

The more and more concentrated demand centers and consequently pollution sources are challenges, but also an opportunity to tackle the problems "at the source" with appropriate and efficient technological and "soft" solutions. In spite of these challenges, cities provide also opportunities for improvements in water supply and sanitation because concentrations of people and wealth in cities can enable the deployment of efficient technical solutions that are unaffordable or/and infeasible in rural areas. The other side of the coin is the relative depopulation of rural areas. Labor shortage could precipitate in declining maintenance of rural water infrastructure (wells, irrigation and drainage canals etc.). However, like urban challenges, the rural ones could also be regarded as opportunities for ecologically sound rehabilitation and redefinition of water resources management in rural contexts.

The threefold increase of the global population during the twentieth century has coincided with a six-fold increase in water use (FAO 2009). Widespread water pollution has made good-quality freshwater scarce. Human health and biodiversity are among the first affected (Vörösmarty et al. 2010). The magnitudes of environmental transformations, including climate change, are signs of unsustainable socioeconomic activities at global scale. Number and intensity of these transformations raise the question, well beyond the strict realm of water management alone, how the planet will be able to accommodate the achievement of the (sometimes contradicting) goals summarized in the Sustainable Development Goals (SDGs) (United Nations 2015). As the consequence of the population dynamics, by 2050 an additional two to three billion people will increase the number of inhabitants of the world to around ten billion (UN DESA 2017). All SDGs, irrespective of their time horizon till 2030, should consider the additional needs and impacts of the burdening population.

Water resources management of areas with large human population concentration is a special challenge. Many urban agglomerations, even megacities are located in explicitly water scarce areas. Providing water services to these urban centers implies water transfers from remote, and frequently multiple sources. Coastal settlements, mainly in developing countries are among the fastest growing urban spaces.

Population dynamics ultimately also includes large scale (international) migration. Permanent, but even temporary displacement of people creates new demand (and pollution) centers in virtually unexpected places. Migration can also be triggered by water-related disasters and consequences of both land degradation and climate change.

Poverty is frequently the underlying driver of many manifestations of population dynamics (different migratory responses). But poverty can also be defined as an unwanted consequence of population dynamics. However, it is also a fairly static state, frequently called the "poverty trap". Poverty hampers pro-active participation in efficient use of water resources, but also in resource protection.

Even without poverty-triggered displacement extreme economic stratification within societies poses a major hindrance to meet water related humanitarian and political objectives, like the Millennium Development Goal 7 Target 7c, or the Sustainable Development Goal No. 6 targets 6.1 and 6.2.

Sustainable water provision and resource management cannot take place without overcoming poverty and many facets of poverty cannot be eliminated without sustainable provision of safe water supply and sanitation services. Additionally, fighting other attributes of poverty like hunger, malnutrition, lack of energy access and decent housing all have implications for water demand and water pollution. Breaking through this vicious cycle is the paramount pre-requisite of sustainable water resources management.

Pollution is a widespread phenomenon as far as water is concerned. Increasing resource use, lack of resource protection and meager investment in waste water collection and treatment technologies are the sad consequences of unregulated population dynamics, but also that of political short-sightedness and carelessness. In this respect providing water supply without simultaneous solutions for wastewater disposal and treatment is unfortunately an often repeated bad example. As the consequence roughly twice as many people have no access to adequate sanitation than to safe water supply. This uneven situation threatens to undermine the sustainability of achievements in the field of improved and safe water supply. As of 2017 an estimated 80% of all wastewater of the world is discharged without treatment into recipient water bodies. The municipal wastewater problems are becoming increasingly vicious. Population growth and mushrooming urban agglomerations, especially the so called informal settlements, are causes for fundamental concerns. They are exacerbated even by otherwise positive trends like improving health care provision and higher standard of living for an increasing number of people. These lead to increasing wastewater volume, but also to substances in it (pharmaceutical and cosmetic residues, nanoscale pollutants etc.) which may not be removed by traditional state-of-the-art wastewater treatment technologies. Increasing number of people and consumer behavior drives industrial production (and automatically pollution) as well as more food production with corresponding pesticide and fertilizer use (and respective residues in receiving water bodies). Increasing water use may indicate the achievement of societal aspirations for better service provisions and increased human well-being~~.~~ However, these developments will not prove being sustainable if the resource pollution will not be controlled swiftly and effectively, preferably at the source of pollution.

Due to humanitarian but also socioeconomic imperatives associated with the main driver, the increasing world population both agricultural and industrial activities are expected to increase (Vörösmarty et al. 2000). Economic development—without adequate water treatment or/and recycling—inevitably perpetuating pollution that endangers ecosystem and human health (Vörösmarty et al. 2010). Residues of hundreds of pharmaceutical and cosmetic products enter fresh water bodies through municipal sewage. Even if treated, these substances are slipping through state-of-the-art biotechnological treatment plants unabated. Their long-term environmental consequences are still not understood well (Howard et al. 2006; Frimmel and Müller 2006).

Population dynamics, poverty alleviation and pollution elimination and control are powerful drivers. However, without addressing them head on, they can turn into imminent stressors of the socioecological systems in our planet, of which water is a crucial component. No doubt that these drivers affect much more aspects and human resource contexts than water alone. However, their manifold effects can propagate through different socioecological pathways and causing additional~~,~~ indirect impacts on water.

3.4.1.2 "Slow" Drivers: Climate Change and Land Use/Land Cover Change

Successes in addressing the immediate ("P") drivers, but also tragedies and exigencies related to these unfold literally "on line". The three "P" drivers are potent stressors affecting water resources in many parts of the world and ultimately can impact the complex global socioecological system. Irrespective of this perspective, climate change is certainly more present both in the political and in the natural science dominated discourses than any of the above outlined challenges. Climate change can already be seen as a stressor of its own. However, its potential implications as far as the hydrological cycle is concerned are well pronounced even if uncertain in their magnitude and occurrence. Shifting hydrological regime (more and stronger floods and droughts, see Sect. 3.2.5) is considered indicating a more unstable world in the future. Global warming may imperil agricultural production levels, thus the need for more water storage and irrigation-supported agriculture can be expected. Climate change can trigger further migratory waves. Thus taking into account of the climate change related consequences is wise. It follows the precautionary principle.

However, at least at present, climate change is rather an "add on" amplifier factor for the challenges contemporary water resources management is facing. Climate change, but also the less discussed land use/land cover change are eminently associated with population dynamics and inherent pursuance of societal aspirations "at the lowest price", thus without using environmental friendly technologies, remedial actions as piece and parcel of comprehensive and sustainable development. Exploitation of environmental resources and disregard of the consequences, should they remain unaddressed, would further aggravate the seriousness of the very pressing, immediate triple "P" challenges.

These are not only very much contemporary challenges, but also latent problems inherited from the twentieth century. They are manifestations of the 'business as usual' attitude. Even in the most developed countries where environmental rehabilitation started a few decades ago the old "impair first and then repair" mentality as the resource development paradigm can still be traced (Vörösmarty et al. 2010).

This concern is more than justified as far as SDG 6, the dedicated water goal and its targets, the products of intergovernmental agreement (see Box 3.5), are concerned. Water is irreplaceable and non-substitutable. Where and when it is in short supply (droughts) or in excess (floods), it is a major source of risk, strife and insecurity. Even where water is in abundant supply, its quality may compromise its use by humans and its ability to sustain aquatic biodiversity. Water is a universal solvent and, hence, is a vector of compounds and transport medium, a climate regulator, a carrier of energy, and cooling and heating agent.

By token of its occurrence phase in the terrestrial compartment of water cycle as a fluid, and hence gravity driven downwards flowing resource, water bodies, including groundwater aquifers usually occupy the lowest parts of a landscape. Therefore, they accumulate naturally all substances being released from whatever socioeconomic activities or/and natural processes take place in the respective landscape and carried by free flowing streams or by seepage towards these recipient sinks. This is evident from the presence of high concentration of nutrients, agrichemicals, industrial wastes and persistent organic pollutants in many water bodies, high nitrate levels in subsurface waters, heavy metals in river and lake sediments, and algal blooms and depleted oxygen that lead to fish death.

Along this voyage from source to sink river deltas are of particular importance. They are the transitional zones between the freshwater and saline water (marine) compartments of the water cycle. As such they are both coveted economic spaces and valuable ecosystems. They are being threatened by human activities, especially by storage facilities and increasing withdrawals. In addition, to climate-change induced sea-level rise, many river deltas are subsiding due to upstream dams and reservoirs trapping sediments. Missing this recurring sediment deposits deltas further subside and could become increasingly vulnerable for coastal erosion. Overexploitation of coastal aquifers are a further reason of subsidence (Syvitski et al. 2009). Abstracting water from fossil groundwater bodies further aggravate sea level rise (see Sect. 3.3.2). Upstream modifications of river flows and dam construction obstruct migratory routes for fish and limit the transfer of nutrients that would enhance agricultural productivity in flood plains and in deltas. Environmental flow allocations can be planned to protect ecosystems including sensitive deltas, but implementation remains a concern (Poff et al. 2010).

Water is a renewable and revolving resource. This renewal cycle is visualized by the water cycle (see Figs. 2.1, 2.4, 2.5 and 3.1). The expected effects of climate change (more liquid than solid precipitation, faster melting glaciers and snow, more intensive rains and longer lasting dry spells and droughts) imply the loss of natural storage capacities and more variable sequences of water availability and shortage. This could lead to a vicious cycle, whereby in some areas new dams may be needed to replace the lost and increase the water storage capacity to alleviate droughts, and control floods. The construction of new dams and their operation to meet societal demands could cause further deterioration of aquatic ecosystems and disturb the delicate sediment balance along the watercourses.

Through the unique hydrological cycle water is globally interconnected. Irrespective of the less than global scale of water resources management in the practice (basin or aquifer, or national, regional, municipal scales) its consequences propagate much beyond the given geographical demarcation. Water flows across jurisdictions and management spaces. Terrestrial water evaporates and transpires into a common atmosphere. There it may be carried as vapor across oceans and continents before precipitating again (see Fig. 2.17 in Sect. 2.2.4). Finally, it may even be traded as the "virtual water content" of exported agricultural or industrial products. Water thus connects several, interlinked, geophysical, socio-ecological and economic systems and, in this sense, constitutes a "global water system" (Global Water System Project, GWSP 2005). Since the industrial revolution humans have been changing the global water system in globally significant ways without adequate knowledge of the system and its response to change (Alcamo et al. 2008). There are also important uncertainties over the state of global water resources as well as the dynamics and interconnections of water, nutrient and material cycles.

Land use and land cover are subject to both rapid and relatively slow changes. Rapid changes are associated with the main (immediate) drivers, while natural vegetation succession and climate change are associated with the slower pace changes. Achieving legitimate goals (among them the key SDGs) will unavoidably accelerate land use/land cover changes. Increasing, partially unexpected stresses may occur.

This is problematic due to two reasons. Land tenure and ownership of water follow different governance systems. Furthermore, the state of the world's fresh waters (both "blue" and "green" water fluxes but also its stocks, see Sect. 2.2) are not adequately monitored, creating significant obstacles to management and mitigation or prevention of water scarcity and water quality degradation. Impacts of changes on biodiversity and ecosystems will also be hard to predict, given that, for example inventories for freshwater fauna are very incomplete globally, particularly in the tropics (Balian et al. 2008).

3.4.2 The Water Discourse: An Overview and Trends

'Water discourse' can be defined as the ongoing, multifaceted, recurring discussion and search attempting the identification of the most urgent problems and the formulation of (preferably) consensus concepts, methodological approaches and ultimately solutions. It reflects the problem perception(s) of the participating actors. While in Sect. 3.4.1 the three "P"s, climate change and land cover change have been identified as the key drivers (and inherent potential stressors), this conviction and narrative might not be shared by all participants (and moderators) of international water debates. Water discourse is heavily influenced by beliefs and ethical imperatives and the respective knowledge base of the participants (for more detail, see Chap. 5). Water discourse (s) are increasingly influenced by representatives of the civil society, but also some governments are active in the water discourse, either in the political arena or in the NGO-IGO-national governments discourse. Ironically, and regrettably some, mainly disciplinary, professional and scientific associations are almost entirely absent especially from the public and transdisciplinary debates. While stakeholder involvement is, in what used to be an exclusively professional domain, a difficult exercise, there is no other option than involving all interest groups in the search for sustainable, negotiated solutions.

The advent of the water discourse can be seen as coinciding with the wake of environmental awareness. This is frequently pegged to the UN Conference on the Human Environment, held in Stockholm in 1972. As far as the contemporary water discourse is concerned it is worth to review the evolution and key milestones starting from the United Nations Conference on Water held in 1977 in Mar del Plata, a mere five-year long time lag after the Stockholm conference. The International Drinking Water Decade 1981–1990 (United Nations 1980) was initiated at the Mar del Plata conference. As part of an international awareness raising drive 22 March was declared as World Water Day and it is observed worldwide since 1993 (United Nations 1992).

The International Conference on Water and the Environment, held in Dublin in January 1992 was not only an important preparatory meeting of the UN Conference of Environment and Development (Rio 1992) but with its "The Dublin Statement on Water and Sustainable Development" shaped for decades the water discourse. This conference and the "Dublin Principles" are also discussed in Sect. 8.1.2. The four principles formulated in Dublin (see Box 3.3) triggered much debate, especially over Principle 4, defining water as an economic good.

Many organized international meetings and conferences with explicit water focus emerged in the 1990s. First and foremost, the annual Stockholm water events (at present called Stockholm World Water Weeks) since 1991 and the triannual World Water Fora since 1997. These events are frequently copied mainly with a more explicit regional or national foci. A number of recurring water weeks and other platforms proliferate and serve as regular opportunities to pursue the water discourse like the Singapore or Amsterdam water weeks. Besides frequent, but standalone water events, the international water decades or recently launched water conference series (like the triannual Budapest Water Summits since 2013) two other mechanisms can be mentioned.

At a larger decennial scale, environment, development and sustainability oriented intergovernmental events like the United Nations Conference on Environment and Development in 1992 in Rio de Janeiro, the World Summit on Sustainable Development in Johannesburg in 2002 and the United Nations Conference on Sustainable Development (Rio +20) in 2012 which was held again in Rio de Janeiro took place. Water played an ever increasing role in these high level events. A further sign of the increasing political prominence of water is reflected in the proliferation of high level panels and working groups initiated by politicians or by the UN Secretary General. Several examples can be mentioned. The UN Secretary General's Advisory Board on Water and Sanitation (UNSGAB 2004–2015) had a prominent membership. Activities of UNSGAB are summarized in its final report UNSGAB 2015).

Box 3.3 The "Dublin Principles" Guiding Principles

Concerted action is needed to reverse the present trends of overconsumption, pollution, and rising threats from drought and floods. The Conference Report sets out recommendations for action at local, national and international levels, based on four guiding principles.

Principle No. 1:

Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment. Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or ground water aquifer.

Principle No. 2:

Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels. The participatory approach involves raising awareness of the importance of water among policy-makers and the general public. It means that decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in the planning and implementation of water projects.

Principle No. 3:

Women play a central part in the provision, management and safeguarding of water. This pivotal role of women as providers and users of water and guardians of the living environment has seldom been reflected in institutional arrangements for the development and management of water resources. Acceptance and implementation of this principle requires positive policies to address women's specific needs and to equip and empower women to participate at all levels in water resources programmes, including decision-making and implementation, in ways defined by them.

Principle No. 4:

Water has an economic value in all its competing uses and should be recognized as an economic good. Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources.

UNSGAB and the UN-led International Strategy for Disaster Reduction (ISDR) addressed the ever increasing loss issue of water related disasters (UNSGAB and ISDR 2009). Further, the High Level Expert Panel on Water and Disaster, a multi-agency initiative produced the report Water and Disasters (Delli Priscoli and Hiroki 2019) which put additional emphasis on a specific, transdisciplinary concern area. The Global High Level Panel on Water and Peace, an initiative of 15 nations (2015–2017) with its final report "A Matter of Survival" (Global High-Level Panel on Water and Peace 2017) and the High Level Panel on Water, established by the UN Secretary General and the President of the World Bank in January 2016 with its outcome document "Making Every Drop Count" (High Level Panel on Water 2018) are further examples of the efforts bringing water issues into the political conscience of the world.

Besides these political and public awareness raising efforts other intergovernmental initiatives focused on formalizing the global governance of water with special concern on its international dimension. Significant, legally relevant achievements of this, several decade long process and engagement are the Convention on the Protection and Use of Transboundary Watercourses and international Lakes of UN Economic Commission for Europe (UN ECE 2004). It was in force for regional parties since 1996 and became global in its scope in 2013. It can be acceded by member states outside of Europe since 2016. The global UN Convention on the law of non-navigational use of international watercourses from 1997 entered into force only in 2014 (United Nations 2014) after its ratification by the 35th party of the convention, though its principles guided the transboundary water discourse since its inception.

Two other institutionalized initiatives deserve to be mentioned for their role in contributing to and moderating the international water discourse. Both the World Water Council (legally an association according to French law) and the Global Water Partnership (operating in an intergovernmental setup) were initiated in 1996. Their respective key contributions like the triannual World Water Fora and guides, toolboxes, promotion of integrated water resources management (IWRM) are discussed in the respective chapters, in particular in Chaps. 7 and 12.

Water featured relatively modestly in the Millennium Development Goals (MDGs) as the water related targets 7c in MDG Goal 7 Ensure Environmental Sustainability (United Nations 2000), see Box 3.4.

However, this impressive list of actions and successes should not strengthen the temptation of complacency. Water problems are neither solved universally nor sustainably and there is ample reason to believe that the tasks ahead are increasingly difficult. As Box 3.4 reveals the water supply target is formulated as "safe" drinking water, while the reporting refers to "improved" sources of water, thus leaving certain concern unanswered, whether the water supply target has indeed been reached, or not. Therefore, the ongoing and future water discourse has the essential task to moderate the process and helping the emergence of consensus concepts and unbiased reporting to tackle the un(re)solved and emerging water problems.

Box 3.4. The Water Related MDG Targets and their Achievement Goal 7: Ensure environmental sustainability

Target 7.C: Halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation

The world has met the target of halving the proportion of people without access to improved sources of water, five years ahead of schedule.

Between 1990 and 2015, 2.6 billion people gained access to improved drinking water sources.

Worldwide 2.1 billion people have gained access to improved sanitation, Despite progress, 2.4 billion are still using unimproved sanitation facilities, including 946 million people who are still practicing open defecation.

Source: http://www.jn.org/millenriumRoal5/ enviror.shtm.

As far as water was concerned the explicit targets in MDG 7 specified to halve the number of people without access to safe drinking water and adequate sanitation. These targets were to be achieved by 2015. There is still fierce debate whether these targets were met. By changing the term "safe" to "improved" as 2015 approached there were justifiable comments claiming that not even the drinking water target was achieved. It was unanimously acknowledged that the sanitation target was clearly missed. Even if, by 2015, all water-related MDG targets would have been achieved, major water challenges would have remained:

How could access levels be made sustainable?
How could water services be provided for an ever-growing human population?
How could be ensured that provision of drinking water and sanitation did not endanger freshwater biodiversity and

threaten the ecosystem goods and services that underpin human livelihoods?

Needless to say that these challenges still exist and the same questions can be asked as far as the present water related targets of SDG 6 are concerned.

One of the most important (and somehow underestimated) milestone of "putting water on the international agenda" was The Ministerial Declaration of the 2nd World Water Forum in 2000 (World Water Council 2000a; b) which called for water security by:

> …ensuring that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy and productive life and that the vulnerable are protected from the risks of water-related hazards.

To achieve these goals, seven challenges were formulated (World Water Council 2000a; b):

- Meeting basic (human) needs;
- Securing the food supply;
- Protecting ecosystems;
- Sharing water resources;
- Managing risks;
- Valuing water; and
- Governing water wisely.

These seven challenges put three water demand categories in a clear hierarchy to satisfy as paramount aspect of water security. The water use category, direct human needs, was clearly given the highest priority. Further the role of water in food security was emphasized. In this list ecosystem needs were mentioned at the third place. Interestingly neither industrial nor energy related water needs were mentioned explicitly. Relatively strong emphasis was put on the remaining four challenges which described the recommended "how" to achieve water security. It distinguishes between governance and management, though does not mention explicitly integrated water resources management. It underlines water as a shared resource and valuing water implies, though implicitly, that water services come at a price. Valuing, however, is not meant as endorsement of an exclusive monetarization of value judgement. While pioneering on its own right, this list does not identify water as the key factor binding nature and society. The Ministerial Declaration, while product of high level negotiation of governmental actors was not a formal intergovernmental process. Ever since the 2nd WWF in The Hague, subsequent World Water Fora are gradually becoming broad multiple stakeholder events. While the size of World Water Fora (in terms of participant numbers) increases unabated, due to the multitude of various water events, high level committee reports, conference declarations, UN resolutions and conventions their impact on the water discourse remains rather disproportionate.

The momentum which prevailed in the early years of the present millennium is well characterized by the declaration of 2003 as the International Year of Freshwater (United Nations 2000) and the International Decade for Action "Water for Life" 2005–2015 (United Nations 2003).

Human water security, irrespective of the controversies associated with this terminology (Bogardi et al. 2016) is a major political issue. Chapter 8 presents an in-depth analyses of the water security discourse and its main actors.

Broadening water security in the water, energy and food security (WEF security nexus) context came by not earlier than 2011 (Bonn Conference on WEF) (Hoff 2011). Deliberations of the World Economic Forum, held prior and after the Bonn Conference on WEF were instrumental to trigger very broad and still intensive WEF discourse. Chapter 17 presents the WEF nexus in context of the Gulf region.

The UN resolution 64/292 declaring water and sanitation as human right (2010) and the appointment of a Special rapporteur for the Human Right to Water and Sanitation elevated the water issue into a new ethical level, irrespective of the fact that these human rights are legally not enforceable. Chapters 5 and 6 address these issues in more detail.

The latest, most comprehensive and intergovernmental binding agreement the Sustainable Development Goals (SDGs) (United Nations 2015) call for eliminating completely by 2030 the proportion of people without sustainable access to safe drinking water, and have been extended by adding the same requirement for sanitation. UN resolution 70/1 on the Sustainable Development Goals (SDGs) includes with SDG 6, the dedicated water goal (United Nations 2015). The SDGs (see the list of associated 8 targets of SDG 6 in Box 3.5) made the historical step by going beyond the hitherto exclusive intergovernmental praxis addressing only "WASH" (water supply, sanitation and hygiene) objectives and targets. SDG 6 is addressing water quality, freshwater ecosystem related targets and specifying the application of integrated water resources management (IWRM) and other implementation means and targets. In addition to the dedicated water goal SDG 6, freshwater issues are embedded, at least implicitly, in nearly all other SDGs. Hence the critical role of good water stewardship is essential not only for the achievement of the water goal but for the entire SDG architecture.

Of particular concern is the likelihood that the water-related Sustainable Development Goals (SDGs) targets may not be achievable not only due to lack of good governance, professional capacities and funding commitments, or a failure of delivery mechanisms but also due to some inherent conflicts between the achievements of competing targets. Eliminating hunger can hardly be achieved without additional water and fertilizer use. Improved health services likely to imply more pharmaceutical residues in receiving water bodies. Constraints on water availability and reductions in water quality jeopardize secure access to this resource for all legitimate stakeholders, including aquatic and terrestrial ecosystems. Thus the implementation of the SDGs, next to a sustained political will, needs to rely on adaptive approaches and consideration of interdependencies and tradeoffs between goals and their respective targets. The SDGs from the water perspective are highlighted in Bhaduri et al. (2016).

Water problems in the public perception and discourse are first and foremost related to direct human needs and use. Despite this decades long focus, approximately one billion people still lack access to safe drinking water and about two billion people live without basic sanitation (Water Supply and Sanitation Collaborative Council 2011). Depending on the consideration of the ever increasing human population, especially in water sector and least developed countries, as well as more rigorous estimations (High Level Panel on Water 2018) refer to rather 2 billion people without access to safe drinking water and 4 billion people (more than 50% of humanity) without adequate sanitation.

Box 3.5 The dedicated water goal no. 6 of the Sustainable Development Goals and its targets (Source: United Nations 2015) Goal 6. Ensure availability and sustainable management of water and sanitation for all

6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all.

6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.

6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.

6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.

6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.

6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.

6.a By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.

6.b Support and strengthen the participation of local communities in improving water and sanitation management.

Irrespective of this state of “unfinished business”, improvement of access to water and sanitation is one of the successful examples of global water governance. Significant progress has been made during the last decades. However, the proclamation of access to water and sanitation as a human right by the UN General Assembly Resolution in 2010 underscores the point that the then valid MDG targets such as stipulated in MDG 7, that is to halve by 2015 the number of people without access to safe drinking water and sanitation, which left many people without water services and adequate sanitation were ethically not justifiable, even if they represented commendable development milestones. Similar success of water governance cannot be reported for another global water target, the institutionalization of integrated water resource management (IWRM), irrespective that the Plan of Implementation of the Johannesburg Summit in 2002 called for IWRM and water efficiency plans by 2005 in all countries (Johannesburg Plan of Implementation of the World Summit on Sustainable Development 2002). Sectoral fragmentation and institutional inertia still impedes effective implementation of integrated water governance and sustainable management practices at global, regional and national levels. Chapter 12 addresses IWRM in more detail examples.

Given its global scope and interconnectedness water must be a priority on all political agendas. In spite of the importance of water to climate change, it has been largely ignored in the climate debate. Water tends to be considered as one of the “sectoral adaptations” which overlooks its central role in the interlinked socio-ecological system, and the ethical imperative espoused also by the UN General Assembly’s resolution RES/64/292 (United Nations 2010) which declared access to water and sanitation a human right.

Although accurate forecasts are elusive, trends that will carry into the future are clear: human populations and the demand for water are increasing, and this is occurring also in the context of anthropogenic climate change (Gedney et al. 2006). Climate change should be seen as a catalyzer for long-overdue water governance reforms, and improved integration in water resources management. First steps in this context should be "no-regret" measures, so that uncertainties in climate-change projections cannot be used as excuses for postponing action.

Aspirations for "water security" involve protecting and living with the water cycle. It includes safeguarding the service function and relying on engineered storage facilities and protection infrastructure, developing risk awareness and preparedness, in combination with a coordinated legal framework, implementing policies and better operational water management directed by effective governance. An additional challenge is that provision of water and its management and governance must be applied in conjunction with other processes shaping societies, economies and the environment (World Economic Forum 2011). This implies the societal endorsement of new water use concepts, valuation, and readiness to change and to share.

Political stability, economic equity and social solidarity are much easier to maintain if supported by good water management and governance. The future should therefore be viewed through a "water" lens and implications of the complexities, role and intricate feedbacks of the global water system fully considered at all levels of the interlinked socio-ecological system. Oversimplification may yield one-sided, unsustainable solutions; overcomplicating could lead to inaction (Bogardi et al. 2012).

The connections between nature and engineered water infrastructure, the high rates of freshwater biodiversity loss, and the linkages between water and land use must all be addressed in the quest for sustainability (Alcamo et al. 2008).

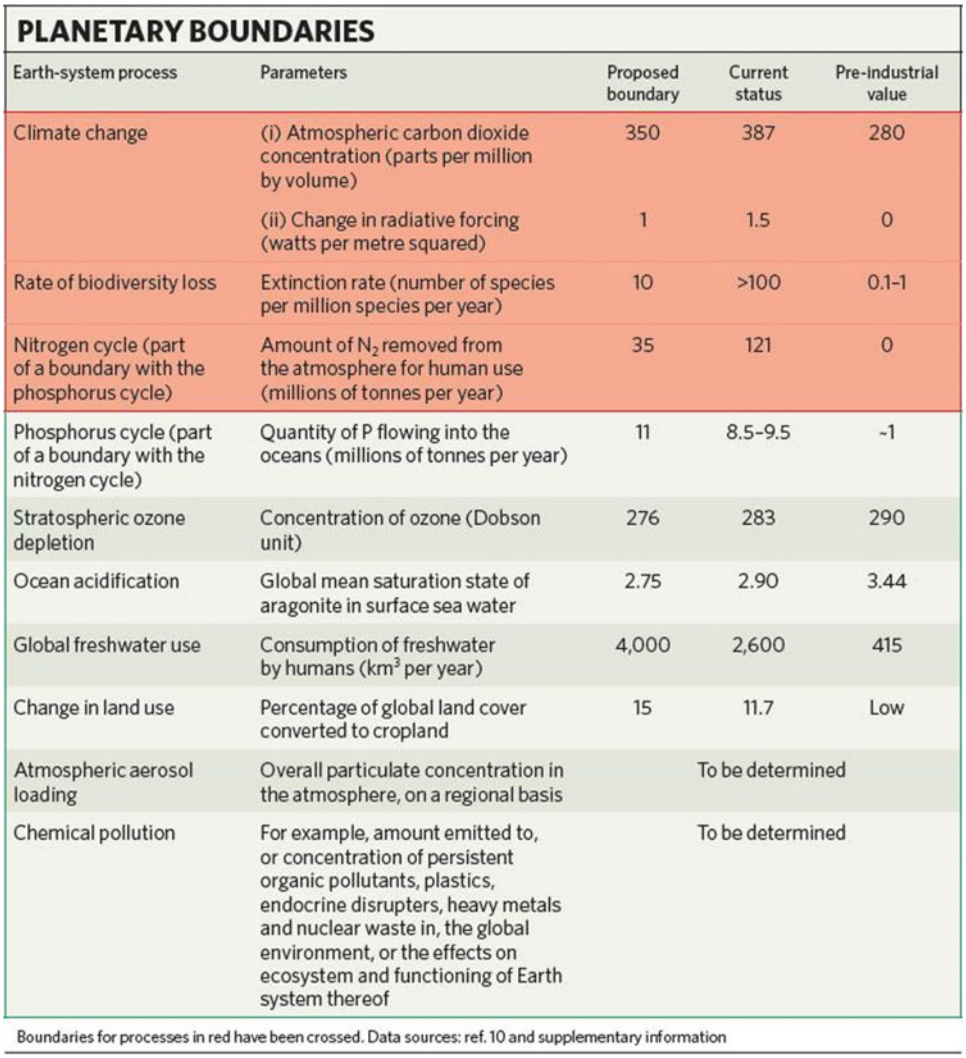
A sustainable "water world" must reflect social and political dynamics, aspirations, beliefs, values and their impact on human behavior, along with physical, chemical and biological components of the global water system at different spatial and temporal scales. One thing is certain: development of a sustainable "water world" requires innovative, interdisciplinary science and will need the engagement of all stakeholders. The development and presentation of what may be called the common knowledge base of the participants of the water discourse is the aim of the present handbook.

The water discourse can hardly be separated from the broader, presumably all-encompassing sustainability discourse. While the concept of planetary boundaries is not without controversies and scientific debates (Blomquist et al. 2012) it contributes undeniably to the visualization of the prevailing problems and hence to awareness raising. The assessment of whether the planet is on a sustainable trajectory has indicated that three consensus-based "planetary boundaries" (see Table 3.1) have already been significantly transgressed (Rockström et al. 2009a; b). There is the need to improve the scientific knowledge on the interdependency of planetary boundaries, including the understanding of how many and which planetary boundaries can be transgressed and how long, before system collapse would occur.

There is clear evidence that human activities at present are on an unsustainable trajectory. Freshwater use, at least at global scale, is not yet among the most critical threats for global sustainability. The proposed planetary boundary for global water consumption by humans and for human use was estimated as 4000 km^3 annually (or about 10% of the annual freshwater flows to the oceans; see Fig. 2.4). As of 2009 an estimated 2600 km^3 was "consumed" before returning as waste water or via evapotranspiration to the hydrological cycle (Rockström et al. 2009a). Given the expected increase of population and better nutrition as stipulated by the SDGs the need to improve water use efficiency is evident. While present water consumption is below the critical threshold proposed in Table 3.1, this does not imply that withdrawals could increase indefinitely. Furthermore, global values do not account for local conditions. Many watersheds and aquifers are significantly overstressed with water withdrawal for agricultural use alone close to or exceeding locally available renewable water resources (UNESCO 2006). The respective scientific community drafted a road map to refine planetary boundaries for freshwater use, accounting for different scales (Gleeson et al. 2020; Zipper et al. 2020).

Through its interconnecting functions, water has a role to play in many planetary boundaries. For instance, the unsustainable loss of global biodiversity in Table 3.1 appears to be far higher from freshwater ecosystems than from the marine or terrestrial realms (Strayer and Dudgeon 2010). Furthermore, changes in land use and water availability are intricately intertwined. Water vapor plays a crucial role in all atmospheric processes and is a potent greenhouse gas affecting climate change. Should "business as usual" continue then transgression of the planetary boundary for water can be anticipated within this century as human population growth continues.

Table 3.1 Planetary boundaries proposed by Rockström et al. (2009a, b)



PLANETARY BOUNDARIES

Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1-1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis		To be determined	
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof		To be determined	

Boundaries for processes in red have been crossed. Data sources: ref. 10 and supplementary information

3.4.3 Concepts and Issues in Water Governance and Management

3.4.3.1 Ecology Centered Versus Utilitarian Considerations

Human water security implies the provision of quality drinking and domestic water, water for energy generation, industry, and transport, maintenance of ecosystems and biodiversity and water for food security. Tradeoffs and potential for considerable conflict exist. Over 70% of “blue” water withdrawal is used for food production (Cosgrove and Rijsberman 2000), and the links between water security and food security will become increasingly evident as the demand for food grows in parallel with increased water requirements for industry and energy generation (Hoff 2011) In addition, biodiversity in freshwater and terrestrial ecosystems also depend upon provision of adequate quantities and quality of water. Meeting the future needs of growing human populations will have major implications for maintaining adequate quantity of water for ecosystems. In a global analysis addressing 23 threat factors or stressors for human water security and freshwater biodiversity (Vörösmarty et al. 2010) shows that, threat to human water security and biodiversity frequently coincide (red shaded areas in Fig. 3.11) but, in many places—especially in the developed world—human water security is achieved at the expense of freshwater biodiversity (yellow shaded areas). There are virtually no places where a high degree of water security for humans has been achieved without considerably impacting biodiversity. This result reflects the “traditional” management mentality “impair, then repair”. Tolerating

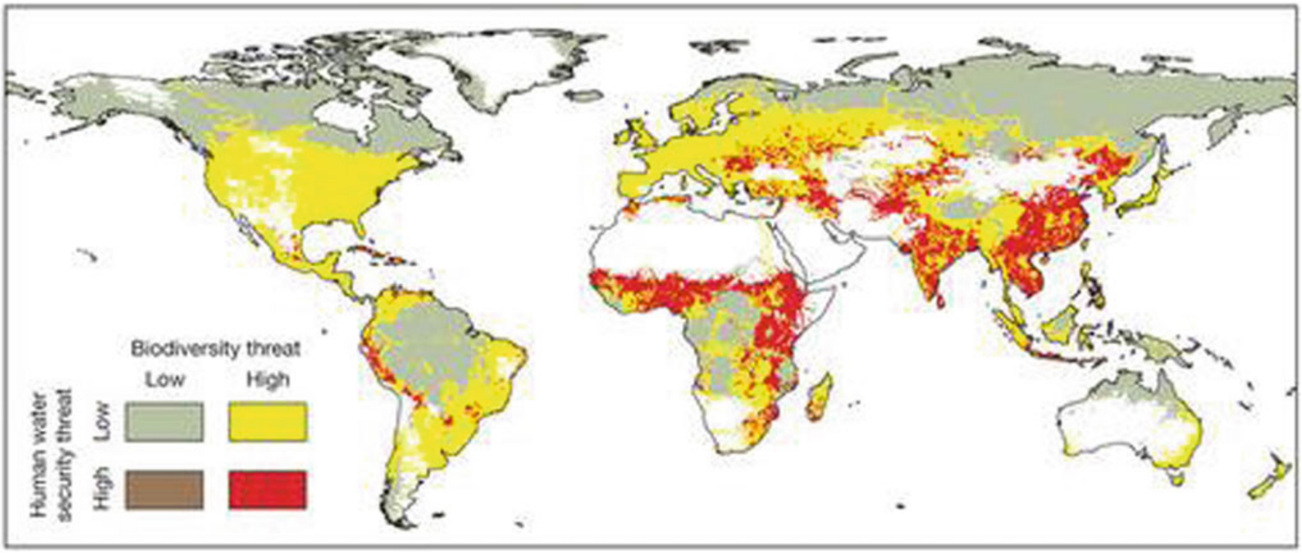


Fig. 3.11 Prevailing patterns of threat to human water security and biodiversity from Vörösmarty et al. (2010)

degradation of ecosystems and then applying expensive remediation strategies (if at all) after the damage has been done is not only costly but likely to be infeasible as well. The more so, as the robustness and resistance of the impacted socioecological systems cannot be easily assessed whether and how long they would endure increasing deteriorations without local, regional or even larger scale collapse. Competition for water between humans and nature will intensify in the future. New approaches, aiming to satisfy human demands while, at the same time, securing biodiversity and ecosystem services are urgently needed. It is perceived that compromises would be unavoidable. Yet, we still have knowledge deficits to propose sustainable tradeoffs at various scales and in different contexts. Chapter 16 discusses in more detail the global distribution of water as resource and biotope, as well as the status of freshwater biodiversity, ecosystem services and the impacts through human induced pressures and stresses.

3.4.3.2 Socioecological Interconnections: Virtual and Physical Water Transfer

Economy and trade create spatial interconnectivities for water. Water circulates in the global economic system as an embedded ingredient. It is the so called “virtual water”, incorporated in or/and used to grow food and manufacture other internationally-traded products (Oki and Kanae 2004). Arid countries may compensate for national water scarcity by importing water-intensive commodities. These water fluxes, which are entirely mediated by societal needs expose important international or inter-regional water dependencies that should be considered in governance discussions (Oki and Kanae 2004) but also in the general water discourse.

The physical transfer of water between basins is a direct interconnectivity that sometimes triggers conflicts due to its high economic and ecological costs, and competition among potential users (UNESCO IHP 1999). Despite these controversies, large-scale transfers are ongoing or planned (Shumilova 2018). Moreover, as climate zones may start to shift, interbasin water transfers might have to be considered in the future as adaptive measures.

Changes in land cover and use have a major influence on water movement and consumption, and through changing land–atmosphere feedbacks, affect precipitation patterns. Deforestation of the tropical rain forest, and the expansion of commercial and energy crops, depletes terrestrial biodiversity, and the resulting monocultures are more vulnerable to pests and climate vagaries than the natural vegetation (Marengo 2010). As noted earlier, the unique role of water as connecting medium among ecological and social systems mandates that water must be managed in a multisector environment. Conversely no socioecological system can be sustainably managed without adequate consideration given to water. Joint development strategies, especially for land and water management are needed. It can be concluded that in light of these strong interconnection, further development of integrated water resources management (IWRM) towards a truly integrated land and water resources management paradigm seems to be an important and urgent scientific/professional development issue. IWRM is addressed in several of the following chapters, especially in Chaps. 9 and 12.

3.4.3.3 Water Governance, Security and Conflicts

Sustainable and, equitable allocation and protection of water resources must occur within the framework of integrated management and embedded in a conducive water governance framework. While these principles are likely to be widely endorsed implementation remains problematic. Ongoing global climate change, increasing population, urbanization, and aspirations for better living standards present a challenge which cannot be ignored. While water use at global scale currently seems to be within its proposed planetary boundary, shortages already prevail in several water-scarce and overpopulated regions (see Sect. 2.2.4). All signs and trends seem to project shortages to increase (see Chap. 16). Furthermore, the ongoing large scale impoverishment of aquatic biodiversity, ecosystem degradation and reductions in water quality are unaddressed "side effects" even in areas where water can be secured for municipal and economic uses.

Water connects several socio-ecological, economic and geophysical systems at multiple scales and hence constitutes a "global water system". This must be considered both in technical interventions and governance frameworks. How to govern the water system with hierarchically structured, yet interdependent scales is still more a research question than implemented praxis. Chapter 9 provides an overview about water governance issues and recommended solutions.

Water security in the twenty-first century will require direct linkage of science and policy, as well as innovative and cross-sectorial initiatives, adaptive management and polycentric governance models that involve all stakeholders. Consensus solutions will need to be achieved by evidence-based mediation within multiple stakeholder processes. Chapter 9 highlights the inherent key governance and management issues in more detail.

Ensuring that no one remains without access to adequate water and sanitation should be a core aim of global water governance. Securing water for other vital human needs such as food and energy production, as well as safeguarding the quality and quantity of water for nature should not be neglected in pursuance of the undoubtedly primary water supply and sanitation goals. If existing governance structures are not adequate to address water problems in an integrated way what kind of new institutions are required? Will greater efficiency arise from a worldwide, uniform approach to water governance, or from a diversity of regional and local approaches? How far could polycentric governance models be successfully adopted? In short, the global "water crisis" is ultimately a "governance crisis" extending from the local to the planetary scale (Bucknall et al. 2006).

Constraints slowing the achievement of water security can arise from a lack of local knowledge, and institutional, professional and vocational capacities, shortage of funding and delivery capacity, including a lack of legislation or limited implementation of rules and regulations at all levels (UN-Water Decade Programme on Capacity Development 2011). During periods of water scarcity, these constraints can accentuate the conflict potential among water users at local, basin and international scales. Thus far, however, sharing water of transboundary rivers and lakes has been relatively successful (Wolf 2010). Although wars triggered by water conflicts between sovereign states are unlikely to occur, the potential for violence in water disputes at lower than the sovereignty level increases with the extent of dependence of livelihoods on water (Wolf 2010) and the increasing human demand for a finite resource. Emerging tensions in shared river basins could be reduced or deferred by use of more water efficient irrigation techniques, alternative land management, and new water use and purification technologies. Adopting common governance principles and sharing benefits derived from water at all levels and implementing efficient water management practices will help facilitating cooperation on water issues. Chapters 7, 8 and 11 addresses several aspects of this discourse.

Research on water governance is a relatively new interdisciplinary field. Comparative analyses of water governance systems around the globe reveal that their performance is context sensitive but not context specific. Good water governance is achievable in most countries although financial resources help. Funding is a necessary but by no means sufficient condition for efficient and effective improvement. Improved water governance can be realized through polycentric governance, effective legal frameworks, reduced inequalities, open access to information, and meaningful stakeholder participation (D'Haeyer et al. 2011). The water sector needs institutional reforms towards effective and adaptive governance and management systems. This will require multi stakeholder debates at national and international levels placing water at the center of social and economic development including energy, food, climate change and biodiversity issues. Neither markets, nor governments nor civil-society movements can provide water security alone, on their own (Pahl-Wostl 2009).

3.4.3.4 Integrated, Adaptive and Nexus Management of Water Resources

Integrated water resources management (IWRM) is an internationally accepted framework (Global Water Partnership 2011; Ibisch et al. 2016). However, IWRM is far from being a simple and universal panacea. Its practices must be adapted to changing conditions with testing and long-term monitoring of their performance (Pahl-Wostl et al. 2013). IWRM cannot deliver the promised results unless it is embedded in an adequate governance framework and guided by political will (Ibisch et al. 2016). Chapter 12 provides additional in-depth analysis of IWRM along with examples.

The management of water cuts across multiple sectors such as agriculture, industry, sanitation, health, energy, etc. and several concern areas such as governance, equity, well-being and economic development. Thus water resources management activities that are too narrowly defined to suit one use of water inadvertently affect water availability for other usages. The boundaries or river basins can also cut across administrative and country boundaries thus providing the potential for conflict between the riparian countries or other jurisdictionary entities. The connectivity of surface and groundwater resources across the basin adds further complexity. River basin boundaries are more visible, while transboundary aquifers have still not yet been extensively mapped in many parts of the world irrespective of their importance and inherent conflict potential. Hence calls for a 'unified', 'comprehensive' or 'holistic' approach integrating multiple water sources and usage, in a framework where river basin is considered the spatial unit of analysis has been made repeatedly (Molle 2006).

Global discussions to formalize an integrated approach to water resources management initiated at the first global water conference in Mar del Plata in 1977, followed by the Agenda 21 and the World Summit on Sustainable Development in 1992 in Rio de Janeiro. The Global Water Partnership (GWP) popularized the concept of Integrated Water Resources Management (IWRM) with the formal definition—"a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership 2011). The IWRM aimed to bridge fragmented sectorial approaches to water management by bringing all stakeholders to the discussion table to set policies that balance and coordinate between various water users, including the ecosystem.

Alongside, the integrated river basin management (IRBM) gathered momentum in the twentieth century as large-scale water infrastructure development, such as dams and water diversion projects, highlighted the need for considering upstream and downstream linkages in a river basin (Molle 2006; Benson et al. 2015). The "ecosystem approach" introduced by the Secretariat of the Convention on Biological Diversity (2004) as "a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way" is similar to IWRM in its end goals but further highlights the interdependencies between biodiversity and natural resources, including water.

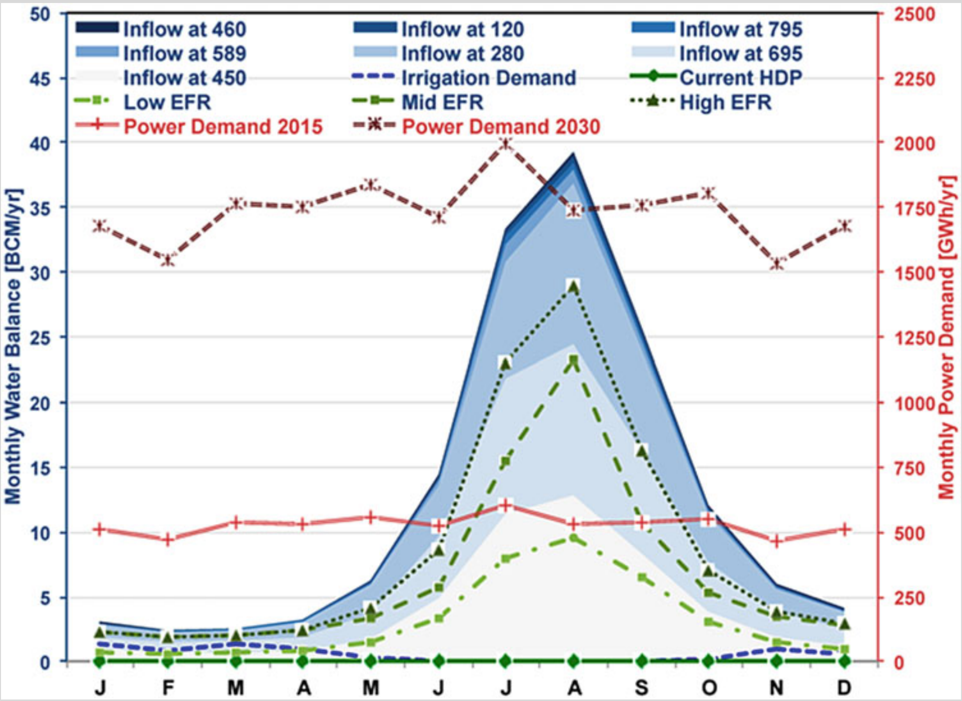
Nevertheless, the concept of IWRM needs be extended towards a broader integrated and context-specific resource management accounting framework for a wide range of ecosystem services, which can differ widely within and between countries (Vlek et al. 2017). Research results (Vörösmarty et al. 2010) imply that integrated land and water management are crucial to achieve human water security while preserving ecosystems (See Sect. 3.4.3.1 and Fig. 3.11).

While many tools and guidance for implementation of IWRM have emerged over time (NeWater Project 2006, 2009), the discourse on implementation of various approaches is still evolving. In essence, all approaches are univocal that sustainable growth across the globe is only possible through integration of policy and practices governing resource allocation between water, energy, food, environment and other related sectors. Many institutions and practitioners have developed their own qualitative frameworks based on problems at hand. System analysis based tools such as optimization and simulation models, hydroeconomics etc., can provide quantitative basis for integration of water management policies and practices (Bazilian et al. 2011; Brown et al. 2015). Representing complex interconnected systems within a framework that is easy to adopt and scalable across spatial scales and management context is a formidable challenge (Bazilian et al. 2011), Opinions are divided on best practices and best decision-making platforms for operationalizing the various integration approaches. Demarcating "boundaries" for integrated systems assessments can also be problematic as cross-cutting areas such as health or gender should also be incorporated.

Furthermore, despite the abundance of integrated water management frameworks and assessment tools, few examples of their application are found in the real world. The actual management of water, especially in developing countries is still very fragmented and sectorial, leading to tension and conflict between various sectors and countries rather than synergies and collaboration (Hellegers et al. 2008; Biswas 2008; Suhardiman et al. 2015). Some of the main barriers for implementing integrated water management approaches include neglect of existing political structure and processes within and beyond the water sector (Allan 2003), inadequate inclusion of tradeoff assessments between the various objectives (Molle 2006) and a lack of data and information necessary for planning. The ministries and implementing agencies under them often compete for resources so there is lack of incentives to cooperate. These criticisms recommend an explicit recognition that decisions related to water resource management are political choices (Wester et al. 2003). It is imperative to shift from unrealistic blueprint institutional arrangements to adaptive, flexible and inclusive approaches such as polycentricity (Blomquist and Schlager 2005; Suhardiman et al. 2015).

More recently, the increasing human demand for water, energy and food under the pressures of globalization, urbanization, adoption of resource intensive lifestyles has stressed the need to build resilient societies that are water, food and energy secure even in the face of societal and environmental crises (Hoff 2011). The World Economic Forum Annual Meeting in 2008 introduced the Water-Energy-Food-Climate Nexus from the perspective for water security. The Bonn 2011 Nexus conference formalized the Water-Energy-Food (WEF) security nexus as an approach to "enhance water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors" (Hoff 2011). The nexus approach fosters sustainable economies built by maximizing efficiency in resource use and productivity across all sectors by closing resource flow loops and capitalizing on existing synergies. The concept has also been expanded to include environment and livelihood in the nexus framework recognizing that "security" depends not only on resource availability but also on access of individuals to resources and their ability to utilize these under the dynamics of existing social power relations and institutions (Biggs et al. 2015). The nexus approach, based on analyzing trade-offs and synergies across sectors in an integrated framework, has also proven useful for streamlining sustainable development goals, often operating in sectorial silos, to fulfill multiple objectives concurrently (Weitz et al. 2014). Chapter 17 provides further insights into the implementation of the nexus concept. Box 3.6 presents an application of multi-objective optimization to operationalize the WEF nexus.

Box 3.6 Multi-Objective Optimization for Quantitative Analysis of the Nepalese Nexus To unleash the estimated hydropower potential of over 43,000 MW, the Nepalese government plans to increase hydropower capacity from current levels (~790 MW) to 37,628 MW by 2030. Achieving this will require altering natural flows through construction of many dams, with implications for water availability for irrigation, fisheries and environmental services as well as water-induced disaster management. Multi-objective optimization can provide a systematic basis for assessing tradeoffs across the various water-energy-food-environment nexus linkages under hydropower infrastructure development. Monthly average water and power demand in Nepal as well as water availability across the major basins are shown in the following figure. While water is clearly abundant, nearly 80% of river flows arrive between June-September. Irrigation water demand is high in the dry period when rain-fed agriculture is not possible. The power demand doesn't vary significantly within the year, but low water levels in the dry period result in frequent power outages. Trade off exists not only in when and how the available water is allocated but also where the benefits are reaped.

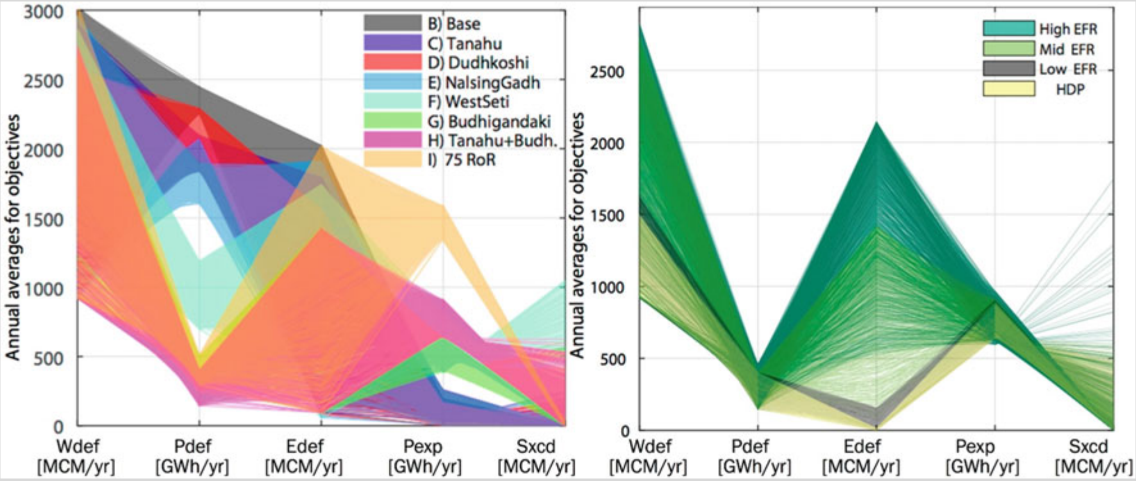


Average monthly water demands, power demand and inflows across seven major basins of Nepal. Reproduced from Dhaubanjar et al. (2017).

Dhaubanjar et al. (2017) used multi-objective optimization to couple two water and power system models in a single objective function to represent the linkages in the water-energy-food-environment nexus. The national scale optimization model compared how eight Nepalese power development scenarios affect five management objectives: minimization of power deficit, maintenance of water availability for irrigation to support food self-sufficiency, reduction in flood risk, maintenance of environmental flows, and maximization of power export. It is important to consider these objectives jointly, because prioritizing some may undermine others. For instance, storage reservoirs provide an opportunity to stock up excess wet period flows to minimize deficits in power and irrigation water demand in downstream basins during dry periods; however, this decreases year round environment flows and reservoir flood storage capacity. For each hydropower development scenarios, 1500 different weighted combinations of the five objectives were run. Such variable weighting allows for simulation of real life scenarios where stakeholders would prioritize the objectives differently.

The figure below shows the range of possible annual tradeoffs under each scenario with medium environmental flow requirements (EFR) and for scenario H) under varying levels of EFR. It is clear that prioritization of different management objectives can impact the level of fulfillment of other objectives. Some pathways offer a better balance between the objectives. Generally, environmental deficit, power deficit, and power export are in relative harmony, as all require higher reservoir releases. The trade off in annual power and water deficit indicates that seasonality and the spatial distribution of power and water demand should be further analyzed. Prioritization of power production can have large impacts on the water objectives. Higher EFRs can support more power exports but may increase flood risks as wet period reservoir storage may be increased to ensure dry period EFR. Multi-objective optimization provides a quantitative basis to understand the trade-offs and synergies across different objectives.

Source Dhaubanjar S, Davidsen C, Bauer-Gottwein P (2017) Multi-Objective Optimization for Analysis of Changing Trade-Offs in the Nepalese Water–Energy–Food Nexus with Hydropower Development. Water 9:162. doi: https://doi.org/10.3390/w903016.



Range of possible annual average tradeoffs across five management objectives in the Nepalese nexus: minimization of irrigation water deficit (Wdef), environmental deficit (Edef), power deficit (Pdef) and flood storage exceedance (Sexcd) and maximization of power export (Pexp). Each line indicates combinations for one model run. Subfigure a) shows tradeoffs across 8 hydropower development scenarios under mid EFR and power demand for 2015. Subfigure b) shows tradeoffs for scenario H) under varying levels of EFRs. Reproduced from Dhaubanjar et al. (2017).

Nexus planning does not always lead to win–win situations. Tradeoffs also need to be calculated and assessed in designing nexus solutions. It is known that taking a systems view increases efficiencies and optimizes the production value. On the other hand, it is often not possible to optimize all components in the system equally, because there are synergies as well as tradeoffs. Discussions between Nepal and India on the development of large dams in the upper Ganges basin have also been ending in a deadlock because India wants larger dams for energy as well to store water for downstream irrigation requirements. However, Nepal is not in favor of large dams as large reservoirs consume prime agricultural land and have long-term ecological impacts (Bharati et al. 2016). Gaining efficiency in one sector could also lead to waste or inequity in another; e.g., when electricity becomes cheaper it is typically used more, which may have unintended consequences such as unsustainable extraction of groundwater for irrigation. Therefore, understanding the connections among the water, energy, food and land nexus within a broader context perspective can help promote efficiency, manage trade-offs and could lead to sustainability, greater equity in their distribution and greater food, water and energy security (Vlek et al. 2017).

Chapters 9 and 12 go in more detail as far as IWRM is concerned, whereas Chap. 17 provides a detailed regional example of the application of the nexus concept.

One billion people suffer hunger; two billion people exist on inadequate diets and approximately one billion people do not have access to adequate energy resources while the global population is still rapidly increasing. To meet the nutritional needs of all food production will have to double in the next 25 years (Kendall and Pimentel 1994). Consequently, agricultural water use will increase, unless potentially offset by improvements in water and land use efficiency. Chapter 19 provides several examples of interconnected land and water management.

There is much scope for such improvement: globally, at least half of the water withdrawn for irrigation does not reach the crops for which it is intended (Food and Agriculture Organization of the United Nations 2016). The recent increase in growing energy crops may supplement rural incomes, but it creates competition for water and land with food crops, and thus between food and energy security.

Hydropower is an important source of energy globally, and its share of the energy sector will increase at the expense of fossil fuels. The benefits accruing need to be compared with the loss of biodiversity and vital ecosystem functions that accompany dam construction and modification of flow regimes to generate electricity (World Commission on Dams 2000). Hydropower is certain to remain part of the global energy mix, the more so as substantial dam constructions are undertaken to increase hydropower generation worldwide (Zarfl et al. 2015). Thus policies and practices need to be put in place to mitigate impacts on freshwater ecosystems. Science-based compromises will have to be found and hydropower generation managed adaptively to account for environmental flow requirements (Pahl-Wostl et al. 2013).

Even water resources management itself consumes energy. Water purification and desalination are very energy intensive, and energy is needed to pump and distribute water from rivers and aquifers. Saline groundwater or seawater has to be desalinized to meet water demands in arid areas, and this consumes substantial energy. Microfiltration and membrane technologies used in sewage treatment also have high energy consumption (Frimmel and Niessner 2010).

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