1 Water 101

Introduction

Before we can manage water sustainably to achieve water security – in the face of global challenges including rapid economic and population growth, rising demand for energy and food and climate change impacting the availability of water resources – we need to understand what is water and its natural variations in terms of quantity and quality. This chapter will first describe the physical properties of water, before discussing the Earth's hydrological cycle. The chapter will then discuss natural variations to water quantity and water quality before finally providing readers with an overview of the impacts of urbanisation on water resources.

1.1 What is water?

On Earth, 97.5 percent of all water is saltwater with only 2.5 percent in the form of freshwater. Of this 2.5 percent, 70 percent is locked up in ice or permanent snow cover in mountainous regions and the Antarctic and Arctic regions, while 29.7 percent is stored below the ground (groundwater). Surface water, including rivers and lakes, comprise the remaining 0.3 percent of freshwater resources available.[1]

A water molecule is made up of two hydrogen atoms bonded to a single oxygen atom. The connection between atoms is through covalent bonding: the sharing of an electron from each atom to give a stable pair. In the water molecule structure,

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the hydrogen atoms are not arranged around the oxygen atom in a straight line; instead there is an angle of approximately 105° between the hydrogen atoms.[2] The hydrogen atoms are positive and so do not attract one another, while the oxygen atom has two non-bonding electron pairs that repulse the two hydrogen atoms.

Water molecules are described as bipolar because there is a positive and negative side of the molecule. This enables water molecules to bond with one another; this is known as hydrogen bonding. In hydrogen bonding, the positive side of the water molecule (the hydrogen side) is attracted to the negative side (the oxygen side) of another water molecule, and a weak hydrogen bond is formed.[3] The hydrogen bonding of water molecules is responsible for a number of water's properties. For instance, based on water's molecular weight (MW = 20), water should evaporate and become a gas at room temperature, given that CO_2(MW = 44), O_2(MW = 32), CO(MW = 28), N_2(MW = 28), CH_4(MW = 18) and H_2(MW = 2) are all gases at room temperature. The reason why water does not evaporate at room temperature is due to water's high specific heat capacity (a temperature increase is effectively an increase in the motion of molecules and atoms comprising the substance). When water is heated, it causes a movement of water molecules – breaking of the hydrogen bonds. However, due to water's cohesiveness, water molecules have a high resistance to increasing their motion. Therefore, it requires a lot of energy to break the hydrogen bonds. As such, water does not evaporate easily. This high heat capacity means water is resistant to radical swings in temperature which is taken advantage of by organisms. Other properties of water include adhesiveness – water molecules are attracted to other substances such as chemicals, minerals and nutrients; solvency – water is a universal solvent as it can dissolve more substances than any other liquid on Earth and uniqueness – water is unique as its solid form (ice) is less dense than liquid water, and it can change from ice to water vapour without first becoming a liquid.[4]

1.2 Hydrological cycle

The hydrological cycle is the continuous movement of water in all its phases: liquid (precipitation), solid (ice) and gaseous (evaporation) forms. Because water is indestructible, the total quantity of water in the cycle does not diminish as water changes from vapour to liquid or solid and back again. In this cycle, evaporation from oceans (505 000 cubic kilometres) exceeds the 458 000 cubic kilometres of precipitation that falls on them. Meanwhile, 119 000 cubic kilometres of precipitation falls on land, which comprises one third of the Earth's surface, and 72 000 cubic kilometres returns through evaporation to the atmosphere. The difference (47 000 cubic kilometres) is either ground or surface water that eventually returns to the ocean.[5] The average amount of time a water molecule remains in a particular part of the hydrological cycle is known as its residence time. Streams and rivers usually have residence times of only days or months, while lakes and inland seas have residence times of years to decades. In comparison, oceans and groundwater systems have residence times of 3000–5000 years (Table 1.1).[6]

Table 1.1 Principal residence times of the global water stores

Compartment	Volume (1000 cubic kilometres)	Percent	Mean residence time (years)
Oceans	1 370 000	93.943	3000
Groundwater	60 000	4.114	5000
Actively exchanging groundwater	4 000	0.274	300
Glaciers and ice caps	24 000	1.646	8600
Lakes/inland seas	230	0.016	10
Soil water	82	0.006	1
Atmospheric vapour	14	0.001	0.027
Rivers	1.2	0.0001	0.032

CLOSS, G., DOWNES, B. J. & BOULTON, A. J. 2004. *Freshwater Ecology: A Scientific Introduction.* Malden, MA: Wiley-Blackwell

The hydrological cycle contains four key components: precipitation, runoff, evaporation and groundwater storage.

1.2.1 Precipitation

Atmospheric vapour, which results in precipitation in both liquid (rainfall) and solid (snow) forms, accounts for less than 0.001 percent of the world's total water; however, due to its low residence times in the atmosphere, it is one of the main drivers of the hydrological cycle.[7]

Precipitation occurs when a body of moist air is cooled sufficiently for it to become saturated. Air can be cooled by a meeting of air masses of differing temperatures or by coming into contact with cold objects such as land surfaces. However, the most important cooling mechanism is the uplifting of air: as warm air rises, its pressure decreases while it expands and cools.[8] This cooling reduces the air's ability to hold water vapour and condensation forms. Condensation is composed of minute particles floating in the atmosphere, providing a surface for water vapour to condense into liquid water. Water or ice droplets formed around condensation particles are usually too small to fall directly to the ground as precipitation due to the upwards draught within the cloud being greater than the gravitational forces pulling the droplets down. In order to have a large enough mass to fall, raindrops grow through collision and coalescence. In this process, raindrops collide and join together (coalesce) to form larger droplets that collide with many other raindrops before falling towards the surface as precipitation. Whether precipitation is rain or snow depends on the warmth of the clouds. In warm clouds temperatures are above freezing point, and water droplets grow through collision (the coalescence process) to form rain. In cold clouds temperatures are below freezing point. These clouds contain ice crystals and supercooled water that is liquid water chilled below its freezing point without it becoming solid. In these clouds precipitation is in the form of snow.[9]

There are three types of precipitation: frontal and cyclonic, convectional and orographic precipitation. Frontal precipitation occurs in the narrow boundaries or fronts between air masses of large-scale weather systems. In this system, warm moist air is forced to rise up and over a wedge of colder, dense air. There are both warm and cold fronts each distinguished by the resulting precipitation: cold fronts have steep frontal surface slopes causing rapid lifting of warm air, resulting in heavy rain over a short duration, while warm frontal surfaces are much less steep, causing gradual lifting and cooling of air, leading to less intense rainfall but over a longer duration.[10] In cyclonic systems, there is a convergence and rotation of uplifting air. In the northern hemisphere, cyclonic systems rotate anticlockwise and in the southern hemisphere clockwise. Above and below the tropics in the northern and southern hemispheres, cyclonic systems usually have a weak vertical motion, resulting in moderate rain intensities for long durations, while in the tropics, because of greater heating of the air, there is more intense precipitation but of a shorter duration.[11] Convectional precipitation happens when the ground surface of a landmass causes warming of the air: as the warm air rises, it cools down and condenses, leading to localised, intense precipitation of a short duration. As this type of precipitation is dependent on the heat of the landmass, it is most common over warm continental interiors such as Australia and the United States. However, this type of precipitation does occur over tropical oceans with slow-moving convective systems producing significant amounts of rainfall. It is common for clusters of thunderstorm cells to be embedded inside convective systems, which commonly leads to flooding events.[12] Orographic precipitation is the result of moist air passing over land barriers such as mountain ranges or islands in the ocean. The South Island of New Zealand is an example of orographic precipitation: the warm moist air off the Tasman Sea reaches the West Coast of the South Island, and as it starts to lift over the Southern Alps, the warm moist air cools and condenses, producing significant rainfall on the West Coast, while on the leeward side the air descends and warms up resulting in low levels of cloud and rainfall.[13]

1.2.2 Runoff

Runoff, or streamflow, is the gravitational movement of water in channels. A channel can be of any size ranging from small channels in soils with widths in the millimetres to channels of rivers. The unit of measurement for runoff is the cumec, with one cumec being one cubic metre of water per second. Streamflows react to rainfall events immediately indicating that part of the rainfall takes a rapid route to the stream channel. This is known as quick flow, while base flow is the continuity of flow even during periods of dry weather.[14] Precipitation can arrive in stream channels through four ways: direct precipitation, overland flow, throughflow and groundwater flow. Direct precipitation comprises only a small amount of streamflow as channels usually occupy only a small percentage of the surrounding area; therefore, it is only during prolonged storms or precipitation events that direct precipitation contributes significantly to streamflow. Overland flow is water that instead of infiltrating soil flows over the ground surface into stream channels during periods of high-intensity rainfall. Overland flows usually occur on moderate to steep slopes in arid and semi-arid areas as these areas lack vegetation and so have dry, compact soil.[15] Throughflow is all the water that infiltrates the soil surface and moves laterally towards a stream channel. This type of flow occurs during periods of prolonged or heavy rainfall when water enters the upper part of the soil profile more rapidly than it can drain vertically. Finally, groundwater flow is water that has percolated through the soil layer to the underlying groundwater and from there into the stream channel.[16]

1.2.3 Evaporation

Evaporation is the transferral of liquid water into a gaseous state followed by its diffusion into the atmosphere. The presence or lack of water at the surface provides the distinctions in definitions for evaporation.[17] For instance, open water evaporation (E) occurs above a body of water such as a lake, stream or ocean. Potential evaporation (PE) is evaporation that would occur if the water supply was unrestricted, while actual evaporation (AE) is the quantity of water that is actually removed from a surface due to evaporation.

Evaporation over a land surface occurs two ways, either as actual evaporation from the soil or transpiration from plants. Transpiration occurs as part of photosynthesis and respiration and is controlled by the plant leaf's stomata opening and closing.[18] The main source of energy for evaporation is the sun. The term used to describe the amount of energy received from the sun at the surface is net radiation (Q^*), and its calculation is

$$Q^* = \mathrm{QS} \pm \mathrm{QL} \pm \mathrm{QG}$$

where QS is sensible heat, the heat we feel as warmth; QL is latent heat and is the heat absorbed or released during water's phase change from ice to liquid water or liquid water to water vapour (there is a negative flux (when energy is absorbed) when water moves from liquid to gas and a positive flux when gas is converted to liquid) and QG is solid heat flux and is the heat released from the soil that has previously been stored within the soil.[19]

1.2.4 Groundwater

Below the Earth's surface, water can be divided into two zones – unsaturated and saturated. In the unsaturated zone, water is referred to as soil water and occurs above the water table, while the saturated zone is referred to as groundwater and occurs beneath the water table. In the unsaturated zone, the majority of water is held in soil that is composed of solid particles (minerals and organic matter) and air. The infiltration rate is used to determine how much water enters the soil over a specific period of time. The rate is dependent on the current water content of the soil and the soil's ability to transmit water. For instance, soil that has high moisture content will have a low infiltration rate because water has already filled voids between the soil's solid particles.[20]

Once water has infiltrated the unsaturated zone, it percolates down through the water table to become groundwater. Groundwater can be found at depths of 750 metres below the surface. It is estimated that the volume stored as groundwater is equivalent to a layer of water approximately 55 metres deep spread over the entire Earth's landmass.[21] Most groundwater is in motion; however, unlike stream and river flows, groundwater moves extremely slow at rates of centimetres per day or metres per year with the actual rate dependent on the nature of the rock and sediment it passes through. Porosity is the percentage of the total volume of a body of rock that contains open spaces (pores). Therefore, porosity determines the amount of water rocks can contain, while porosity in sediments is dependent on the size and shape of the rock particles it contains and the compactness of their arrangement.[22] Meanwhile, permeability is the measure of how easily a solid allows fluid to pass through. Rocks with a very low porosity are likely to have low permeability; however, rocks with high porosity does not mean they have high permeability. Instead, it is the size of the pores, how well they are connected and how straight the path is for water to flow through the porous material that determines the permeability of a rock or sediment.[23]

An aquifer is a body of highly permeable rock, typically gravel and sand, that can store water and yield sufficient quantities to supply wells, while an aquitard is a geological formation that transmits water at a much slower rate (aquitards are usually defined as a formation that confines the flow over an aquifer, while the term aquifuge is sometimes used to define a completely impermeable rock formation).[24] There are two types of aquifers: confined and unconfined. A confined aquifer has a boundary (aquitard) above and below it that constricts the water into a confined area. Geological formations are usually the most common form of confined aquifers because they often occur as layers, and so the flow of water is restricted vertically but not horizontally.[25] Water in confined aquifers is normally under pressure: when it is intersected by a borehole, it will rise up higher than the restrictive boundary. If the water rises to the surface, then it is known as an artesian well. Unconfined aquifers have no boundaries above, and so the water table is free to rise and fall depending on the amount of water in the aquifer.

The movement of groundwater can be described by Darcy's law: Henry Darcy was a nineteenth-century French engineer who conducted observations on the characteristics of water flowing through sand. Darcy observed that the rate of flow through a porous medium was proportional to the hydraulic gradient. The most common formula for Darcy's law is

$$Q = -k_{\text{sat}} \times A \times \frac{dh}{dx}$$

The discharge (Q) from an aquifer equals the saturated hydraulic conductivity (k_{sat}) multiplied by the cross-sectional area (A) multiplied by the hydraulic gradient

(dh/dx). The negative sign is based on the fact that a fall in gradient is negative.[26] The h term in the hydraulic gradient includes both the elevation and pressure head.

1.2.5 How old is water?

Determining the age of water is important for managing water resources as the age provides an indication of how quickly contaminated water can move towards an extraction zone and how long ago the contamination occurred. Because Darcy's law cannot be used to determine the time it takes for water to reach a certain position, scientists instead conduct chemical analyses of dissolved substances in water to estimate its age. Carbon dating is common for testing the age of groundwater; however, it is problematic for young groundwater because it is only accurate if the sample is more than thousand years old.[27] When testing old groundwater, carbon dating involves the analysis of the rate of decay of ^{14}C in dissolved organic carbon. For younger groundwater, chemical dating of water involves determining the concentrations of material that humans have polluted the atmosphere with as these substances are dissolved in precipitation. The concentrations of these substances provide an estimate on the average age of the groundwater tested. Tritium is a radioactive isotope of hydrogen and was added to the atmosphere in large quantities as a result of hydrogen bomb tests in the 1960s and 1970s. Tritium concentrations in the atmosphere peaked in 1963 and have since declined to background levels.[28] This particular radioactive isotope has a half-life of 12.3 years. Chlorofluorocarbon (CFC) compounds were commonly used in aerosols and refrigeration from the 1940s until they were banned in the 1990s. There are two CFC compounds: CFC-11 which has slowly declined since 1993 and CFC-12 which is still increasing but at a slower rate than before 1990. Sulphur hexafluoride is used for cooling and insulation mainly in electronics.

Another method for dating groundwater is analysing the ratio of the two isotopes of oxygen and/or the two isotopes of hydrogen found in water molecules. When water in the atmosphere condenses to form rain, there is a preferential concentration of heavy isotopes of hydrogen and oxygen in the water molecules.[29] The heavy isotope of hydrogen is known as deuterium, and the heavy isotope of oxygen is ^{18}O, and the colder the temperature at the time of condensation, the more enriched in deuterium and ^{18}O the water sample is. Therefore, in climates with distinct seasons, the amount of deuterium and ^{18}O will vary with each season, and so if the groundwater shows variations in deuterium and/or ^{18}O, then it comprises relatively new rainfall. If there is little variation in deuterium and/or ^{18}O, it indicates that there has been mixing of rainfall from both past summers and winters and therefore it is older.[30]

1.3 Natural variations to water quantity

There are two types of natural variations to water quantity: floods and droughts.

1.3.1 Floods

Floods occur when precipitation and runoff exceed the capacity of the river channel to carry the increased discharge. Flood frequencies are used when planning land use and infrastructure design and are calculated based on the history of a river, that is, how often it has flooded in the past and what the historical extremes of high precipitation are. Flood frequencies are expressed as a recurrence interval – the probability a particular flood will occur in a given year, for example, a hundred-year flood means there is a one in a hundred chance of it occurring in that particular year.[31] Recurrence intervals are calculated using models that incorporate probable maximum precipitation (PMP) and probable maximum flood (PMF) calculations. The PMP is the finite limit for precipitation from a single storm event – the maximum depth (amount) of precipitation that is reasonably possible during a single storm event. Flood events have maximum extremes, and the PMF is the maximum surface water flow in a drainage area that could be expected from a PMP event.[32] Floods can cause significant damage to buildings and properties with water washing away soils and crops, depositing sediments on land and property and be potentially fatal to humans and animals. Services are usually designed to resist floods or be serviceable against the following probabilities: important roads are designed to withstand a hundred-year floods, that is, a 1 percent chance of being overtopped in any given year; general roads and buildings are designed to withstand 50-year floods and less important roads, 20-year floods and storm water drains and pipes can be designed to withstand anything from a 2- to 20-year recurrence interval depending on the consequences over overtopping.[33]

1.3.2 Droughts

A drought is a period of unusually dry weather that persists over a long enough period of time to cause crop damage and/or water supply shortages. There are four different ways a drought can be defined. Meteorological droughts are a measured departure of precipitation from normal levels. Agricultural droughts refer to situations in which the amount of moisture in the soil no longer meets the needs of a particular crop. Hydrological droughts occur when surface and groundwater supplies are below normal levels. Socioeconomic droughts occur when physical water shortages begin to affect people.[34,35] Droughts have varying levels of severity and return periods ranging from minor droughts that have a return period of 3–4 years, with slowing of growth in crops and pastures, to exceptional droughts with a return period of over 50 years with widespread crop and pasture loss and shortages of water in reservoirs (Table 1.2).

Both the onset and end of droughts can be predicted by meteorologists observing precipitation patterns, soil moisture and streamflow data. To do this, meteorologists use a variety of indices that show deficits in precipitation over a period of time. One common tool is the Standardised Precipitation Index (SPI), which is a drought index based on the probability of an observed precipitation deficit occurring over a period of time ranging from 1 to 36 months. This variable timescale allows the index to describe drought conditions important for a range of

Table 1.2 Drought severity classification

Drought severity	Return period (years)	Description of possible impacts
Minor	3–4	Going into drought: short-term dryness slowing growth of crops or pastures Coming out of drought: some lingering water deficits, pastures and crops not fully recovered
Moderate	5–9	Some damage to crops or pastures, streams, reservoirs or wells low, some water shortages, developing or imminent voluntary water restrictions requested
Severe	10–17	Crop or pasture losses likely, water shortages common, water restrictions imposed
Extreme	18–43	Major crop and pasture losses, widespread water shortages or restrictions
Exceptional	44+	Exceptional and widespread crop and pasture losses, shortages of water in reservoirs, streams and wells, creating water emergencies

SMITH, K. 2013. *Environmental Hazards: Assessing Risk and Reducing Disaster*. Hoboken, NJ: Taylor & Francis

Table 1.3 Palmer Drought Severity Index

Index	Description
4.0 or more	Extremely wet
3.0 to 3.99	Very wet
2.0 to 2.99	Moderately wet
1.0 to 1.99	Slightly wet
0.5 to 0.99	Incipient wet spell
0.49 to −0.49	Near normal
−0.5 to −0.99	Incipient dry spell
−1.0 to −1.99	Mild drought
−2.0 to −2.99	Moderate drought
−3.0 to −3.99	Severe drought
−4.0 or less	Extreme drought

CENTER, N. D. M. 2011. *Comparison of major drought indices: Palmer Drought Severity Index* [Online]. Available: http://www.drought.unl.edu/Planning/Monitoring/ComparisonofIndicesIntro/PDSI.aspx (accessed 10 May 2016)

meteorological, agricultural and hydrological applications. For example, soil moisture responds to a precipitation deficit immediately, while groundwater recharge and reservoir levels respond to precipitation deficits over many months. When describing the severity of droughts, the common index used is the Palmer Drought Severity Index. This index is a soil moisture algorithm that includes water storage and evapotranspiration levels with a scale ranging from ≥ 4.0 (extremely wet) to ≤ -4.0 (extreme drought) (Table 1.3).

1.4 Natural variations to water quality

Natural processes, including temperature, dissolved oxygen, pH, dissolved and suspended solids, turbidity, minerals, salinity, inorganic and organic chemicals and nutrients, affect the quality of water resources, specifically those discussed in the following text.

1.4.1 Temperature

Numerous physical, biological and chemical characteristics of water bodies are dependent on temperature. For instance, temperature is an important signal for spawning and migration. Sudden changes in temperature can be deadly for many species, and this usually occurs when deep, cold reservoir water is released into warm waterways.[36,37] Temperature and dissolved oxygen are interdependent with warmer water holding less dissolved oxygen than colder water.

1.4.2 Dissolved oxygen

The presence or absence of dissolved oxygen in an aquatic ecosystem is one of the main determinants of whether organisms can live in that environment or not. Habitats that have a presence of oxygen are aerobic, while environments lacking dissolved oxygen are anaerobic.[38] Dissolved oxygen levels are an indicator of water quality, with high concentration levels indicating high water quality. Oxygen however is only slightly soluble in water, and so there is high competition among aquatic organisms including bacteria for it. Dissolved oxygen is important for aquatic plants and animals as it allows species to breathe.[39] When dissolved oxygen levels decrease below 5 milligram per litre, most sensitive organisms such as fish become stressed. If dissolved oxygen levels reach 1 milligram per litre, most species will not survive for more than a few hours.[40]

1.4.3 pH

The pH (p, power; H, hydrogen) level of a solution indicates its basicity or acidity, and it is defined as the negative logarithm of the hydrogen proton. Solutions with a pH less than 7 are said to be acidic, and those with a pH greater than 7 are basic or alkaline. Because the scale used to measure pH is logarithmic, each number represents a 10-fold change in the proton activity in a solution. Therefore, water with a pH of 4 is 10 times more acidic than that with a pH of 5.[41] Different water bodies have differing pH levels, for instance, bogs and wetlands have acidic conditions with pH levels between 4 and 7, while water in rivers and lakes usually have pH levels between 4 and 9. Fish in water bodies usually have a narrow range of pH preference which varies greatly with specie. If the pH level of a water body changes to a level outside a fish's preferred level, it can cause physical damage to skin, gills and eyes and eventually be fatal.[42]

1.4.4 Dissolved and suspended solids

As water passes through the soil column or over a surface, it dissolves substances attached to the soil particles. Water also dissolves particles in the air as it passes through the atmosphere in the form of rain. The amount of dissolved substances in a water sample is known as the total dissolved solids (TDS), and the higher the TDS, the more contaminated the water body is.[43] TDS can also be used to estimate the conductivity of water. Conductivity is the amount of electricity that can be conducted by water, and the more the ions present, the higher the conductivity. Conductivity is correlated roughly to productivity because high-nutrient water has high conductivity.[44]

The measuring of total suspended solids (TSS) is another key measure of water quality. Rivers and streams carry suspended sediment as part of the natural erosion and sediment transport process in which sediment is deposited/picked up whenever river velocity decreases/increases. Soil particles are usually naturally carried as suspended load in water bodies. However, events such as landslides remove natural vegetation exposing bare soils. This can lead to excessive suspended loads in water bodies, increasing turbidity and decreasing water clarity.[45] When sediment enters waterways and becomes suspended in the water body, it can severely damage the wildlife inhabiting the waterway. For instance, suspended sediment abrades and damages fish gills, increasing the risk of infection, disease and death. This leads to the loss of sediment-sensitive fish species. Suspended sediment also reduces sight distance for fish, reducing feeding efficiency. It also blocks light from entering the water, reducing photosynthesis in plants, leading to a reduction in aquatic food for many species. Deposited sediments also affect aquatic wildlife in waterways. For instance, it physically smothers benthic aquatic insect communities, which in turn reduces the amount of food available for species higher up the food chain. Deposited sediments also cover and destroy spawning grounds reducing fish populations. It also smothers fish eggs reducing their survival rates.[46]

1.4.5 Turbidity

Turbidity is the measure of clarity in water and is dependent on the amount of suspended matter in the water that reduces transmission of light. It is caused by suspended matter, including clay, silt and organic material, in the water creating cloudiness. High turbidity levels indicate that there are problems in the water body as turbidity blocks out sunlight needed for aquatic vegetation, impacting on the health of the aquatic ecosystem. Turbidity can also create water quality problems with toxic chemicals attaching themselves to suspended particles in water bodies.[47] Because turbidity is a measure of the cloudiness of water, TSS and turbidity are directly related.[48]

1.4.6 Minerals

As water moves through the terrestrial system, materials containing minerals are dissolved or weathered from the land. Chemical weathering involves the dissolving of materials, while mechanical weathering reduces particles of matter to sizes that may be dissolved at a later stage. The total concentration of dissolved solids carrying minerals is inversely dependent on the amount of runoff – the greater the runoff, the less the time taken for water to dissolve the ions.[49] The minerals that enter water bodies through chemical and mechanical weathering are important for plant and animal life as minerals are needed to control chemical reactions. The main minerals required in human diets include calcium, magnesium, phosphorus and potassium.

1.4.7 Salinity

Surface water runoff and groundwater percolation from precipitation and irrigation can cause salts to leach, that is, dissolve from the soil and contaminate surface and groundwater supplies. The term salinity is used to describe the presence of excess salts in water and is harmful to certain plants, aquatic species and humans. In humans, high salt levels in water can lead to increased blood pressure, while in plants saline soils harm plants by pulling moisture out of the root system reducing the uptake of water and fertiliser.[50]

1.4.8 Inorganic and organic chemicals

Inorganic chemicals are any chemicals that do not contain carbon. In low quantities, metals such as calcium, zinc and iron are healthy for the human body, while copper, lead, mercury and arsenic can be toxic or poisonous. Organic chemicals contain carbon and hydrogen and can be classified as natural or synthetic with natural organic chemicals extracted from sugars, carbohydrates, amino acids and proteins. Synthetic chemicals are mass-produced and persist in the environment for long durations. This is because natural enzymes are unable to break down their complex compounds. In addition, many synthetic chemicals are carcinogens and can be divided into two categories: volatile organic chemicals that are lightweight and dispersed through the air and non-volatile chemicals that are heavy and settle at the bottom of rivers and lakes into sediments.[51] Pesticides are synthetic organic chemicals and include insecticides for killing insects and herbicides for killing plants and weeds. They are designed to be applied to a target area to control a specific pest and then degrade; however, pesticides frequently contaminate ground and surface water supplies.

1.4.9 Nutrients: Nitrogen and phosphorus

The most common form of nitrogen in the biosphere is nitrogen gas, which comprises 78 percent of the atmosphere. In water, nitrogen is dissolved as a gas and is less soluble than oxygen in water; however, despite being less soluble than oxygen, its higher atmospheric concentration means its dissolved concentration is similar to oxygen.[52] Nitrogen is an important nutrient in water quality and exists as five main types: proteins, amino acids and urea, nitrite, nitrate and ammonia. However, when excessive nitrogen enters a water body, an oxidation process called nitrification occurs. There are two associated problems with nitrification occurring in natural water bodies: first, oxygen demand increases, and second, nitrification is highly toxic resulting in fish populations dying or migrating.[53]

Phosphorus is required in large amounts by plants and is one of the most important nutrients for plant growth in aquatic ecosystems. The main sources of phosphorus are phosphorus-bearing minerals such as iron, aluminium and calcium phosphates that occur in low concentrations in soils.[54] Therefore, in natural unpolluted waterways the primary source of phosphorus is watershed soils and bottom sediment. Rock phosphate is mined and processed to form a highly soluble calcium phosphate compound for use as agricultural, domestic and industrial phosphates. The main concern of excessive nitrogen and phosphorus in water bodies is eutrophication. Nitrogen enhances the growth of not only agricultural plants but also aquatic plants including algae, leading to the overproduction of plant matter in lakes, rivers and streams.[55] The negative impact of excessive aquatic plant and algae growth in water bodies is the depletion of dissolved oxygen caused by the decomposition of dead vegetative matter, resulting in the subsequent decline in aquatic species numbers and water body health.[56]

1.5 Impacts of urbanisation on water resources

Urbanisation into river basins can lead to pollution of rivers, lakes and wetlands from point and non-point source pollution. In addition, urbanisation impacts aquatic ecosystems, while impervious surfaces lower water quality and groundwater levels.

1.5.1 Point source pollution

Point source pollution is the contamination of a water body through a pipe or other clearly identified location. This type of pollution is easily measured and impacts assessed. The most common sources of point source pollutants are factories, wastewater treatment plants, landfills and underground and aboveground storage tanks holding fuel, solvents and other industrial liquids.[57] Industrial-related wastewater can contain a number of pollutants including microbiological contaminants, chemicals from industrial activities including solvents, organic and inorganic chemicals and heavy metals. In addition, point source pollution can include suspended matter and the discharge of warm water into cooler waterways.[58]

1.5.2 Non-point source pollution

Non-point source pollution is generated from numerous sources, and therefore its origin is difficult to identify. Fertiliser runoff from gardens and agricultural activities is a common source of non-point source pollution. Nitrate is commonly used as a fertiliser because it is highly soluble and therefore easily taken up by plant's root systems. However, because it is highly soluble, it is easily flushed through the soil into rivers and streams resulting in eutrophication of waterways.[59] In urban areas precipitation events flush large amounts of pollutants including heavy metals and oils into water bodies.[60] Groundwater is a significant source of drinking water; however it is one of the most neglected sources of water due to its low visibility. Pollution of groundwater is a serious issue, even if the source of the pollution is removed, due to groundwater's high residency times – groundwater can remain contaminated for hundreds of years. There are many sources of groundwater contamination that includes industrial wastes, septic tanks, landfills, agriculture, municipal landfills, mining and petroleum products and saltwater intrusion.[61]

Runoff from roads and highways contain numerous types of contaminants. Sediments in runoff from roads are usually due to the clearing of land near roads for construction. When sedimentation enters nearby waterways, it reduces the amount of light that can penetrate the water, affecting photosynthesis rates of aquatic plants. It can also damage fish gills causing disease and death. When sediments settle on the beds of waterways, it smothers spawning grounds further reducing fish populations. Fertilisers are commonly applied near roads for plant vegetation. Runoff containing fertiliser can lead to excessive algal growth in waterways nearby; eventually decreasing the water's dissolved oxygen content and killing aquatic life. Heavy metals are commonly found in waterways near transport routes. Heavy metals often adhere to sediment, degrading water quality and harming aquatic wildlife by interfering with the processes of photosynthesis, respiration, growth and reproduction.[62]

1.5.3 Damage to aquatic ecosystems

The impacts of urbanisation on aquatic ecosystems include loss of wetland and riparian buffers. Stream ecosystems are dependent on extensive freshwater wetlands, floodplains, riparian buffers, springs and flood channels – all of which are lost during urbanisation. Hard (impervious) surfaces and accompanying storm water systems can cause lower base flows in streams and faster runoff during storms. Water running off impervious surfaces often has a higher temperature than naturally flowing water due to its higher residence time on hard surfaces. Meanwhile intensive urbanisation can raise stream water temperatures by 5–10 degrees Celsius due to the loss of shading from riparian vegetation and lower water levels. Urbanisation usually leads to a shift in energy sources. In natural streams the aquatic ecosystem is driven by an energy source comprising decomposing vegetation, woody debris and falling insects, all of which is lost through urbanisation. In urban waterways, reduced tree canopies in addition to nutrient accumulation results in an increase in aquatic plants and algae, significantly lowering the health of the overall aquatic ecosystem. There is also a reduction in biological diversity with urban waterways only supporting a fraction of the fish and aquatic invertebrates that would exist in an undeveloped waterway.[63]

1.5.4 *Impervious surfaces modifying hydrological cycles*

The hydrological cycle is the continuous movement of water between land, water bodies and atmosphere. When precipitation reaches the surface, some evaporates, some percolates through the soil becoming groundwater and the remainder becomes surface water. Impervious cover (hard surfaces that do not allow water to penetrate the soil, for example, streets, driveways and rooftops), however, alters the natural amount of water that takes each path of the hydrological cycle. In urban areas, impervious cover and urban drainage systems increase the volume and velocity of surface runoff into waterways. It has been estimated that in areas of natural groundcover, a quarter of rainfall infiltrates the soil and becomes groundwater while only 10 percent ends up as surface runoff. As impervious cover increases with urbanisation, 20 percent of rainfall becomes surface water, while in highly urbanised areas, 55 percent of rainfall becomes surface water.[64] This increased surface water causes severe erosion of stream and riverbanks and transportation of sediment, clogging stream channels and damaging natural habitats. In addition, there is a larger volume and faster discharge of surface water during storm events compared to natural lands, resulting in more flooding and habitat damage. Because of the increased surface runoff in urbanised areas, there is greater risk of flooding, and so many waterways become drainage channels that are frequently lined with rocks and concrete. The result of this is loss of riparian vegetation and habitats for aquatic wildlife.

1.5.5 *Impervious surfaces lowering water quality*

Increased impervious cover also results in lower water quality in waterways because pollutants, collected on impervious surfaces, are frequently washed into streams, rivers and lakes. In catchments with less than 10 percent impervious cover, waterways remain healthy; however, above 10 percent stream degradation is frequent and includes excessive stream erosion, reduced groundwater recharge, increased size and frequency of floods, loss of riparian vegetation, increased contaminants in water and decrease in stream biodiversity. In addition, contaminated surface water containing pollutants including nitrogen compounds, dissolved organic carbon, synthetic organic compounds and petroleum products can infiltrate the surface, severely degrading groundwater quality.[65]

1.5.6 *Impervious surfaces affecting groundwater recharge*

Many urban areas are dependent on groundwater supplies for reticulated public water supplies and domestic and industrial use. Urbanisation can affect the groundwater system by changing the patterns and rates of aquifer recharge.

In urban areas where abstraction of groundwater is heavy and exceeds the rate of local recharge, aquifer levels may continue to decline over decades resulting in deepening of wells and declining water table levels. This can lead to the intrusion of saline water and ground subsidence, resulting in physical damage to buildings and underground engineering structures and services such as tunnels and sewers.[66]

While impervious surfaces can reduce normal soil infiltration of water paths, car parks and other low-permeability surfaces unconnected to storm water drains can recharge urban groundwater. In addition, water mains can leak around 20–25 percent of water carried and lead to further recharge of groundwater as can excess irrigation of gardens and parks.[67] Increased groundwater recharge can cause hydrostatic uplifting of the surface resulting in damage to infrastructure. It can also lead to rising water tables inundating subsurface infrastructures such as building foundations and basements.[68]

1.6 Water and wastewater treatment processes

When it comes to consumption of drinking water, there are two types of drinking water standards: primary and secondary. Primary standards are designed to protect public health by establishing maximum permissible levels of potentially harmful substances in water. Secondary standards apply to aesthetic aspects of drinking water that do not pose a risk to health (such as colour and odour).[69] Water utilities use both natural and chemical processes to ensure drinking water is free of contamination to meet primary standards. Drinking water purification comprises four stages: sedimentation, coagulation and flocculation, filtration and disinfection. Impurities in drinking water are either dissolved or suspended solids. Under the process of sedimentation, water under quiescent conditions has minimal flow velocities and turbulence, and so particles denser than water can settle out at the bottom of a tank in the form of sludge.[70] Not all suspended particles are removed during the process of sedimentation with very small turbidity-causing particles called colloids remaining. In the coagulation stage, chemicals called coagulants are mixed into the water causing particles in the water to stick together and form larger and heavier particles called flocs. After the chemicals are added, the water is slowly stirred – a process called flocculation – and this increases the sticking of particles to one another. The combined process of applying chemicals and then stirring of the water is known as coagulation.[71] After coagulation around 5 percent of suspended soils can remain as non-settling floc particles. Filtration involves the removal of suspended particles from water by passing it through filter beds of porous granular material such as sand. As water passes through the filter bed, the suspended particles become trapped within the pore spaces. Because pores eventually become blocked, backwashing occurs at times – a process involving clean filtered water being forced back up through the filter carrying away the accumulated particles. Coagulation, sedimentation and filtration remove nearly all microorganisms and suspended sediments from the water. However, it is usually not enough to remove completely all pathogen bacteria and viruses present in the water. To achieve this, the final treatment of water is disinfection involving most commonly chlorination but also ozone and ultraviolet radiation treatment.[72]

To reduce the potential for waterborne disease and damage to ecosystem health, wastewater is treated before it is returned to the natural environment. Wastewater treatment comprises three stages: primary, secondary and tertiary. Primary treatment involves the removal of suspended solid material from wastewater. Floating material such as wood, paper and oil are removed first; otherwise it will block the filters and pipes. Wastewater is then pushed into a grit chamber where sand and small stones settle to the bottom of the chamber. This process is common in areas with combined storm water drainage and sewer systems because in these systems sand and gravel often wash into sewers after storm events. Following this, wastewater proceeds into primary settling tanks where suspended solids settle as sludge for removal.[73] The secondary treatment process involves the removal of oxygen-demanding organic matter. This involves two types of processes; trickling filters and activated sludge systems. Wastewater is passed through trickling filters which are beds filled with coarse material comprising rocks and gravel. As the wastewater passes through the beds, a microbial filter develops on the surface of the rocks and gravel trapping oxygen-demanding organic matter as the wastewater passes through. In the activated sludge system stage, the effluent is constantly agitated and aerated so that sludge forms. This sludge contains aerobic organisms that digest any remaining organic material. By now the wastewater contains only between 5 and 20 percent of its original organic matter and can be safely discharged into waterways. However, nitrates and phosphates still remain and require tertiary treatment. Nitrogen is removed through the biological oxidation of nitrogen from ammonia to nitrate (nitrification) followed by denitrification, which is the reduction of nitrate to nitrogen gas. From which, nitrogen gas is released to the atmosphere (removed from the water). Meanwhile, phosphorus can be removed biologically using a process called enhanced biological phosphorus removal that involves special bacteria called polyphosphate-accumulating organisms that accumulate large quantities of phosphorus within their cells. These organisms can then be separated from the treated water to form a bio-solid that can be used as a fertiliser.[74]

1.6.1 Ensuring drinking water safety

The World Health Organization's (WHO) *Guidelines for Drinking-water Quality* provides a guidance on how to develop and implement risk management strategies to ensure safety of drinking water supplies. The guidelines outline a preventative management framework for safe drinking water that comprises five key components:

1. *Establish health-based targets*: Health-based targets should be established by a high-level authority responsible for health in consultation with water suppliers, affected communities, etc. The targets should take into account the overall public

health situation and contribution of drinking water quality to disease from waterborne microbes and chemicals as part of an overall water and health policy.

2 *Conduct system assessments*: System assessments determine whether the drinking water supply can deliver water that meets health-based targets: assessment of the drinking water supply system is applicable for large utilities, small community supplies and individual domestic supplies. Assessments can be of existing infrastructure, plans for new supplies or upgrades of existing supplies. As drinking water quality varies throughout the system, assessments should aim to determine if the final quality of water delivered to consumers routinely meets established health-based targets.

3 *Conduct operational monitoring*: Operational monitoring is the conducting of planned observations or measurements to assess whether control measures that ensure drinking water quality are operating properly. Usually, operational monitoring involves simple and rapid tests, for example, turbidity rather than complex microbial or chemical tests, which are generally conducted as part of the validation and verification activities.

4 *Implement management plans*: Management plans document system assessment and operational monitoring and verification plans describe actions in both normal operation and during incidents where loss of control of the system may occur. The management plan should also outline procedures and programmes required to ensure optimal operation of the drinking water system.

5 *Conduct independent surveillance*: The surveillance agency is responsible for independent and periodic review of all aspects of safety, while the water supplier is responsible for regular quality control, operational monitoring and ensuring good operating practices. Surveillance contributes to the protection of public health by promoting the improvement of quality, quantity, accessibility, coverage, affordability and continuity of drinking water supplies. Surveillance requires a systematic programme of surveys that cover the whole drinking water system, including sources, activities in catchments, transmission infrastructure, treatment plants, storage reservoirs and distribution systems.[75]

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