Fresh clean water with low concentrations of contaminants is necessary to sustain life. Its importance in modern highly developed societies extends beyond the basic provision of drinking water to satisfying the much larger needs of industry and agriculture. Water is stored in the oceans, in ice, in surface water on land (lakes, swamps, and rivers), in the subsurface as groundwater, in the atmosphere, and in the biosphere. Most of the water in the atmosphere, hydrosphere and biosphere is contained within the oceans (~98%), but sea water is not suitable for most water uses because of its high salt content. Thus, water demand must be met from much smaller reservoirs such as surface water in rivers and lakes, and subsurface water stored in soil or rock. Ice is the second largest reservoir of water on the surface or in the near surface and schemes have been proposed to harvest large icebergs from the Antarctic ice sheet and tow them to dry regions suffering water shortages. Use of ice to provide freshwater is not presently economic largely because of the cost of towing icebergs from polar regions (there is also some cost impact from loss of ice volume by sublimation and melting during transport).

The distribution of rainfall and surface run-off are uneven across the US. Many of the western states, and in particular those in the south-west are impacted by a shortage of water. Rates of water use that exceed rates of natural replenishment are a major cause for concern. The amount of surface water available for extraction from rivers and lakes essentially depends on the amount of surface run-off. Run-off is precipitation (rain and snow fall) less evapotranspiration (losses to the atmosphere from evaporation and from transpiration during plant respiration) and infiltration (percolation of water in soil or sediment at the surface). [Some infiltration may later enter rivers and streams after travel through the subsurface as flowing groundwater]. Water is often made available in arid areas by impoundment of rivers behind dams, and then distribution via a network of pipes and aqueducts.

In industrialized societies such as the US, industry is the largest user of water, i.e., withdraws the largest volume of water each day. However, most of this water is returned soon after use to its point of origin. Power stations account for the largest proportion of industrial use, but 98% of the water they withdraw is returned to the point of origin and therefore not consumed. Agriculture is the second largest user of water. Much of the water used for agriculture is used for irrigation. Irrigation is the biggest consumer of water because well over half the water withdrawn for irrigation is not returned to its point of origin (it is taken up by plants, lost during distribution, or evaporates from the earth’s surface). Domestic use of water only accounts for about 10% of total use, and only about a quarter is consumed.

Water policy in the west for much of the past century has been driven by a desire to tame nature and to provide water via river diversion and dam construction to encourage and facilitate settlement and cultivation in sparsely populated arid regions. Current agricultural practice in these areas relies on irrigation, and irrigation demands a stable supply of water. A Federal agency, the Bureau of Reclamation was charged in 1902 with opening up the west to small farmers. In the decades that followed this the bureau pursued this objective aggressively by building countless dams including a number of very large ones (Hoover and Glen Canyon on the Colorado, and Grand Coulee on the Columbia). Water from these dam projects was made available to farmers and expanding cities by a network of aqueducts also constructed with federal funds by the Bureau of Reclamation. Another agency, the US Army Corps of Engineers, was also involved in water projects, although its assignment was to provide flood control in order to protect existing communities. Unfortunately much of the intent of those who established the Bureau of Reclamation has been unrealized. Large corporate owned farms have squeezed out small farmers, and large cities have grown in the desert, with an expansion of population that threatens to outstrip the supply of water. Provision of water for farming has proved to be expensive, and many farmers receive highly subsidized water to grow wet climate crops which farmers in the naturally wet south-eastern US are paid not to grow in order to prevent excessive supply and a consequent fall in prices.
Water supply issues will continue to be important in the western states in the next few decades. As population increases and water consumption rises, the states bordering the Colorado river will be dividing up a fixed volume of water between more people than ever before. Indeed it is likely that the amount of water available will be less than originally expected as the apportioning of Colorado river water between upper basin states (WY, CO, UT) and lower basin states (CA, AZ and NV) was set during a period of unusually wet years. Extensive irrigation and the growth of large metropolitan areas in the Great American desert may yet prove to be just a brief event in the long history of human presence in the North American continent.

Diversion of river water for human use requires good management, particularly if the end user is a consumer of water rather than a temporary user. Often there are competing claims for water from the many areas through which the river flows. Damming of rivers to provide a steady water supply can destroy habitats, historic sites, and wilderness areas of outstanding natural beauty. Water quality in areas downstream is adversely affected by river diversion and the use of river water for irrigation in naturally arid areas can lead to degradation of land because of the build up of salts in the soil as a result of evaporation. The reduction in water flows in the Colorado river is such that the river is reduced to a trickle by evaporation before it reaches the ocean in northern Mexico. The river water also becomes increasingly salty because of the addition of salt dissolved from rocks by water diverted for irrigation that finds its way back into the river along its course. Water released from dams is drawn from colder water than the natural river water because it comes from a deep still body of water rather than a turbulent moving body of water in close contact with warm air and rocks in canyon walls. The change in water temperature impacts downstream ecosystems. Damming a natural, wild river results in changes in water flow and sediment load. Construction of dams on the Colorado changed the river downstream of each dam from its original state - a warm sediment-laden river with large natural variations in discharge, to an artificial one - a highly controlled steady flow of cold clear water. Sediment which was originally carried by the river accumulates in reservoirs created behind the dams, ensuring that reservoirs have only a finite lifetime. However, dams have positive benefits as well as negative impacts. They provide a steady, largely dependable source of water, hydroelectric power, flood control and a recreational resource in the form of a large body of flatwater for boating.

In areas where consumption of surface water supplies are at a maximum level consistent with sustainable use, additional supplies may require tapping groundwater. Groundwater is water stored in the subsurface in porous rocks (and sediments and soils) in the saturated zone below the water table. In the saturated zone all pore space is filled with water. The water table separates the saturated zone from the unsaturated zone, where pore space is only partially filled with water (the rest is air). The water table will migrate in response to changes in the amount of water in the groundwater system. If addition of water (termed recharge) exceeds withdrawal then the water table will rise. If recharge is less than withdrawal then the water table will fall. Natural changes in rates of recharge and withdrawal occurring as a result of seasonal changes in precipitation and evaporation cause water level to rise and fall with the seasons. The water table may be located in soil layers close to the surface or in bedrock at deeper levels. Water residing in unsaturated soils is termed soil moisture. Some of this water will slowly percolate downwards to recharge groundwater supplies below. Where the water table level lies above the ground surface, we see the development of lakes if there is a suitable local depression. Where the water table intersects a sloping land surface, we will see a flowing spring. Streams with beds that lie below the local level of the water table will be influent streams, as seepage of groundwater will occur into the stream through the sediments of the stream bed. Streams with beds lying above the local water table will be effluent streams and water seepage will be in the opposite direction, i.e., from the stream to the subsurface.

In the same way that water in streams on the surface flows downhill under the influence of gravity, groundwater will flow downhill within the rock or sediment layers in which it resides.
Rates of groundwater flow (~10 - 100 meters/year) are much slower than rates of surface flow because the water must make its way through a tortuous pathway of interconnected pore space. The ease with which water can travel through a material is the permeability of the material. Groundwater flows under the influence of gravity from areas where the water table is at a high elevation to areas where the water table is at a lower elevation. If the height of the water table can be determined by the level of water in a number of wells drilled into the ground then the water table heights can be contoured. The contours are lines connecting points of equal water table elevation. Groundwater flows downhill at right angles to the contour lines (i.e., down the steepest gradients in the water table). The speed of groundwater flow is determined both by the slope of the water table (the hydraulic gradient) and the permeability of the rocks. Water moves fastest in highly permeable rocks where there is a steep hydraulic gradient.

The actual amount of water that can be stored within a rock layer is determined by the porosity of the material. Rock or sediment layers that have high porosity and high permeability are effective sources of groundwater and are termed aquifers. High permeability is desirable because it means that water extracted locally by pumping can potentially be replaced fairly rapidly by flow from upstream parts of the aquifer. High porosity is also desirable as this has a direct impact on the size of the water resource. Coarse grained sandstones with well rounded grains without cementing mineral growth between grains have high porosities; cemented sandstones, fine grained sandstones and sandstones with angular grains all have lower porosities. Rocks with low permeabilities are termed aquitards (groundwater flow is retarded), while rocks with very low permeabilities are termed aquicludes.

Groundwater does not only flow out of an aquifer as a result of pumping. The eventual fate of groundwater is to be transferred to other parts of the hydrologic cycle, either via springs back into surface run-off and evaporation or into the oceans via aquifers that reach the coast. An aquifer in steady state will contain about the same volume of water from one year to the next, aside from natural fluctuations due to seasonal changes or climatic events such as prolonged droughts. In order for this to be the case there must be recharge (or replacement) of water lost from the aquifer. Recharge involves capture of some surface run-off by infiltration. Recharge can occur over a broad area, but mountainous regions are often important recharge areas because of the heavy rainfall and high elevation that results in a large pressure driving water flow in an aquifer. Wetlands are also important recharge areas.

Aquifers may be confined or unconfined. In an unconfined aquifer the water level lies at the water table and infiltration of water from the surface can recharge the aquifer directly across the whole area of the aquifer because there is no impermeable barrier above the aquifer. In a confined aquifer the water level will follow the upper boundary of the aquifer if the water table lies above the aquifer boundary. The top and bottom of the aquifer are bounded by impermeable layers which prevent flow of water through them. Recharge of a confined aquifer is only possible where the aquifer intersects the land surface directly. Recharge by infiltration in other areas is prevented because of the impermeable barrier along the top of the aquifer surface. A confined aquifer may support an artesian well if the well head lies below the height of the potentiometric surface at the place where the well is drilled. The potentiometric surface is simply the height water would rise to if able to move freely upwards, without confinement due to the presence of a confining aquiclude. An unconfined aquifer will not support an artesian well as either the water table will lie below the water surface at the well site and drilling a well will result in water only reaching up to the water table level, or if the water table lies above the land surface, surface water will be present, eliminating the need for a well in the first place.

Areas in which a small pocket of permeable and porous rock lies above an aquiclude can result in the formation of a perched water table. A perched water table results when infiltration into a small aquifer results in formation of a saturated zone above the regional water table as a result of limited transport out of the base of the small perched aquifer because of the aquiclude beneath. Although drilling would intersect water fairly close to surface, the presence of water could mislead the well-driller into thinking that the regional aquifer had been found. Pumping
from the small aquifer rock would soon result in exhaustion of the small amount of water stored there and the well would be dry. Beneath the aquiclude may be a large confined aquifer representing a much larger reservoir of water recharged in areas of higher elevation. This would be a better long term groundwater source.

Excessive groundwater withdrawal leads to the development of a cone of depression around a well, or in the case of many wells, overlapping cones of depression and a regional lowering of the water table. Subsidence, fracturing and the formation of fissures can occur as compaction of aquifers proceeds following removal of water in pore spaces. The water quality of the remaining groundwater declines, as the amount of dissolved material (TDS - total dissolved solids) increases. Human consumption requires TDS values to be less than 500 - 1000 ppm, whereas water for livestock can contain up to 2000 ppm TDS. Intrusion of dense salt water into the base of aquifers previously containing fresh water can also result from excessive withdrawal of groundwater from aquifers in coastal regions. Compaction of an aquifer as a result of excessive rates of withdrawal of groundwater can not usually be reversed because closed pore spaces cannot be reopened by pumping water back into an aquifer. Thus the storage capacity and permeability of the aquifer are likely to have been permanently reduced.

Extension of existing water resources in a region is best achieved by conservation. Micro-irrigation techniques are available for delivery of water directly to plant roots for uptake, in contrast to present irrigation practices which involve spraying and result in large losses through evaporation. A micro-irrigation delivery system costs more to set up than a conventional system, but is more cost-effective in the long term, if water is purchased by consumers at an unsubsidized price. For coastal regions, human use of ocean water purified by desalination, is an expensive option because it requires considerable energy. This is especially the case for strongly saline ocean waters as distillation methods must be used instead of less energy-intensive filtration methods. The use of surface water, particularly from lakes, needs to be carefully controlled if lake levels are not to drop dramatically leading to serious environmental degradation. Inter-basin transfer involving the movement of water from one drainage basin to another has been suggested as a solution to the water needs of some of the drier states. However, grand schemes proposed in the 1960s to divert the Columbia River in Washington southwards to join the Colorado River, or to transfer water from rivers in British Columbia to thirsty US states south of the border, have faded as support for engineering on a massive scale has waned. An additional factor has been the recognition of the value of water resources by states with abundant fresh water. As an example in recent years the governors of the Great Lakes states signed an agreement ruling out any interbasin transfers of Great Lakes water. Use of other sources of surface water carries different penalties. Extraction of water from swamps and wetlands is ill-advised because such areas are important places for recharge of aquifers and are also important habitats for unique ecosystems. Loss of wetlands results in a reduction in biodiversity.

Diversion of river water for human use also requires good management, particularly if the end user is a consumer of water rather than a temporary user. The Aral Sea is an inland sea in Turkmenista in central Asia. During the Soviet era water in rivers draining into the Aral Sea were diverted for irrigation purposes. As a result, evaporation rates exceeded recharge rates and the lake shrank dramatically. The fishing industry collapsed as the sea became increasingly salty and coastal ports were left high and dry, several kilometers from the retreating shoreline. Groundwater is a good source of water for human use as long as rates of extraction do not exceed rates of recharge. Excessive pumping leads to problems described above. A rational water policy would emphasize conservation and discourage growth and settlement and agricultural activity in areas lacking a renewable water supply that could be provided without significant environmental degradation in surrounding areas.

The largest aquifer in the US is the Ogalalla aquifer which underlies the southern Great Plains states of NE, KS, and parts of CO, and TX. Farming employing irrigation techniques
in these areas has led to a precipitous drop in the level of the water table in the aquifer. Recharge is slow because the only areas of recharge are on the eastern margin of the aquifer by water coming off the Rocky Mountains. At present rates of pumping the aquifer will be dry within thirty years. Farming will have to revert to dry crop farming, which will only be able to support a small number of the farmers currently working the land in the area. Loss of ground cover following the abandonment of farming threatens increased wind erosion with the potential of a repeat of the dust bowl era of the 1930s. To date no rescue plan for the farmers has been put in place to redirect surface water to replace the dwindling groundwater. This is in contrast to action taken seventy years ago when a similar situation faced farmers in California’s central valley. In the central valley the aquifer was pumped dry in the space of about 30 years, and subsidence of 10 feet or more occurred as a result. The Central Valley Project (CVP) run by the US Bureau of Reclamation involved construction of numerous dams, such as Shasta Dam, in northern California, and aqueducts to bring water to the Central Valley, which is naturally a very dry place between the California coast to the W and the Sierra Nevada to the E. Today 25% of US production of fruit and vegetables is from the central valley thanks to irrigation with water from the CVP.

Excessive extraction rates are not the only cause of declining water quality. Pollution which results from intentional or accidental release of contaminants into the environment is also a major factor. If the source of pollution can be identified and then shut down, a contaminated water resource, whether above or below ground will take time to dissipate to safe levels. The time required depends on the residence time, which is the average length of time a particular entity, e.g., a molecule spends in a particular reservoir. The residence time can be calculated by dividing the stock by the input flux, or by dividing the stock by the output flux. For most contaminants introduced by human activity residence times are measured in years or decades. This compares with much longer times for many solids that occur naturally as dissolved species. For example the residence time of sodium in the world’s oceans is 100 million years because the size of the stock is very large and the rate of input (principally in rivers) is very small. One problem with contamination of lake waters is that even though contaminants may have been removed from lake waters they may remain in lake sediments, from where they may remobilized into the lake water if the sediment is disturbed.

We distinguish point source pollutants, which are released from a single discrete source, and therefore hopefully relatively easy to identify, and non-source pollutants which are released from a broad, highly dispersed set of contributory sources. Example of point sources include sewage outlets, individual chemical plants, septic tanks, and leaks from upper sections of very deep waste injection wells. Non-point sources include surface run-off of fertilizer from fields, road salt applied to winter roads, acid mine drainage from sulfide minerals disturbed by mining activities.

Once a contaminant has entered surface waters, its concentration will be gradually reduced by dilution with uncontaminated water. In the case of a river this will occur further downstream as additional unpolluted run-off from overland flow or tributaries joins the water in the main channel. In the case of a lake this can occur when the contaminant spreads out through the lake, with part leaving the lake at any outflow points. In the case of groundwater contaminant concentration decreases more slowly because groundwater flow rates are slow. A contaminant plume will be created in the downstream direction. The plume widens from a narrow cross-sectional area immediately adjacent to the pollution point source to a broad cross-sectional area distant from the source. Concentration in the plume will also decline both along its length from source to propagating tip, and also across its width from center to margins. The cause of dispersion is the fact that flowing water carrying the contaminant must travel through a tortuous series of interconnected pore spaces. At any point some water will flow one side of a grain while other water will flow on the other side. The net effect is dispersal into a contaminant plume lessening in concentration levels but widening in dimension downstream.
The important types of pollutant include industrial, agricultural and municipal/residential pollution. Industrial pollutants include: (1) Heavy metals such as cadmium, mercury, plutonium which are toxic at low concentrations, but accumulate in the body when their intake occurs over a prolonged period. Heavy metals are also amplified within a food chain such that concentrations found in complex organisms at the top of a food chain are far in excess of the concentrations in the simplest organisms at the base; (2) Acid mine drainage from weathering of pyrite exposed by coal mining activities; (3) Oil spills from oil drilling and transportation; (4) Organic chemicals such as TCE (trichloroethane), vinyl chloride, and PCBs -poly chlorinated biphenyls (used as electrical insulators); (5) thermal pollution from warm water used as a coolant in turbine circuits in power. Agricultural pollution includes animal waste produced in feedlots, and not recovered for use as a natural fertilizer, fertilizers spread on arable land, herbicides and pesticides such as DDT, which like heavy metals are accumulative, and lastly sediment that ends up in streams following removal from plowed fields by water and wind erosion. Municipal pollution includes untreated, or partially treated sewage. Untreated sewage may contain pathogens such as amoebae, bacterial and viruses which cause disease and death in humans. In the US all municipal sewage is treated to remove such pathogens, typically by filtration through beds of gravel, sand and silt (which remove progressively smaller micro-organisms). Treated sewage, although cleaned of pathogens may still contain high levels of dissolved nitrates and phosphates, which may cause eutrophicication problems (see below).

Besides containing pathogens, untreated sewage may also contain organic matter. Organic matter is also provided from food processing operations. Organic matter in surface waters will decay as a result of bacterial action. Biochemical oxygen demand is the total amount of oxygen required for aerobic decomposition of all organic matter within a particular volume of water. If organic matter is released into a river, from a point source, as the river flows downstream from the entry point, bacteria will decompose the organic matter aerobically. In doing so the bacteria will consume oxygen and reduce the concentration of oxygen. Eventually there will be insufficient oxygen for continued aerobic decomposition and anaerobic bacterial decomposition will take over. Once decay of the organic matter is complete, as the river flows further downstream, oxygen will return to the water from the atmosphere. Oxygen concentration falls with increasing distance downstream from the pollutant source, reaches a low point, and then begins to rise again to return to normal levels (a sag curve).

Phosphates from detergents and nitrates from fertilizers can cause eutrophicication. Eutrophication is undesirable because it lowers water clarity, produces toxins, increases BOD and results in death of organisms dependent on the presence of dissolved oxygen in the water. Eutrohypication is a dramatic increase in biological productivity, notably the growth of so-called algal blooms which form a green scum on the water surface. When the algae die they will contribute to the load of organic matter in the water column, and will increase the BOD.

Groundwater pollution is either cleaned up through in situ techniques such as immobilization of contaminants or aeration in which oxygen is added to accelerate breakdown by microorganisms, or by decontamination after extraction. Extraction requires identifying the location of the contaminant and then drilling a deep well to extract the material. This technique is appropriate for liquid pollutants that are dissolve little in water. Such liquids will pond on the top of the water table if less dense than water (e.g., leaking gasoline from underground storage tanks) or at the base of an aquifer above an underlying impermeable layer. Extraction is most effective when the amount of dispersal of the contaminant has been small. Surface water pollution may be cleaned up using dredging of contaminated bottom sediments, isolating bottom sediments with an impermeable barrier (e.g., a plastic covering or covering with impermeable clay layers) or aeration involving the bubbling of oxygen into the surface water to counteract oxygen deficiency as a result of increased BOD.