A SunCam online continuing education course

Water Reuse Applications

by

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Course Outline:

What is Water Reuse?

Water reuse is utilizing treated wastewater as the water source for a useful application. Typically, the wastewater comes from municipal or industrial treatment systems. The original clean water is used once, becomes wastewater, is treated, and then is used a second time. Hence the water is “reused.” The reused water is also called “reclaimed” or “recycled” water.

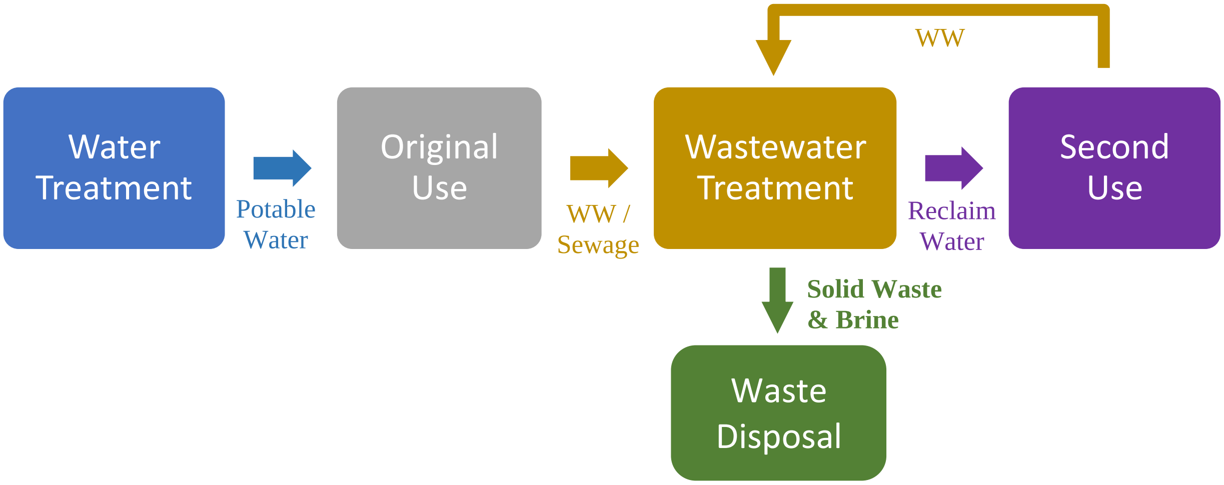


Figure 1: Water to wastewater flow diagram with water reuse in purple.
Source: Author

Applications for reclaimed water include the following:

- Agricultural
- Industrial
- Urban
- Landscaping
- Potable
- Environmental
- Groundwater

See Figure 2 for a depiction of different forms of reclaimed water.

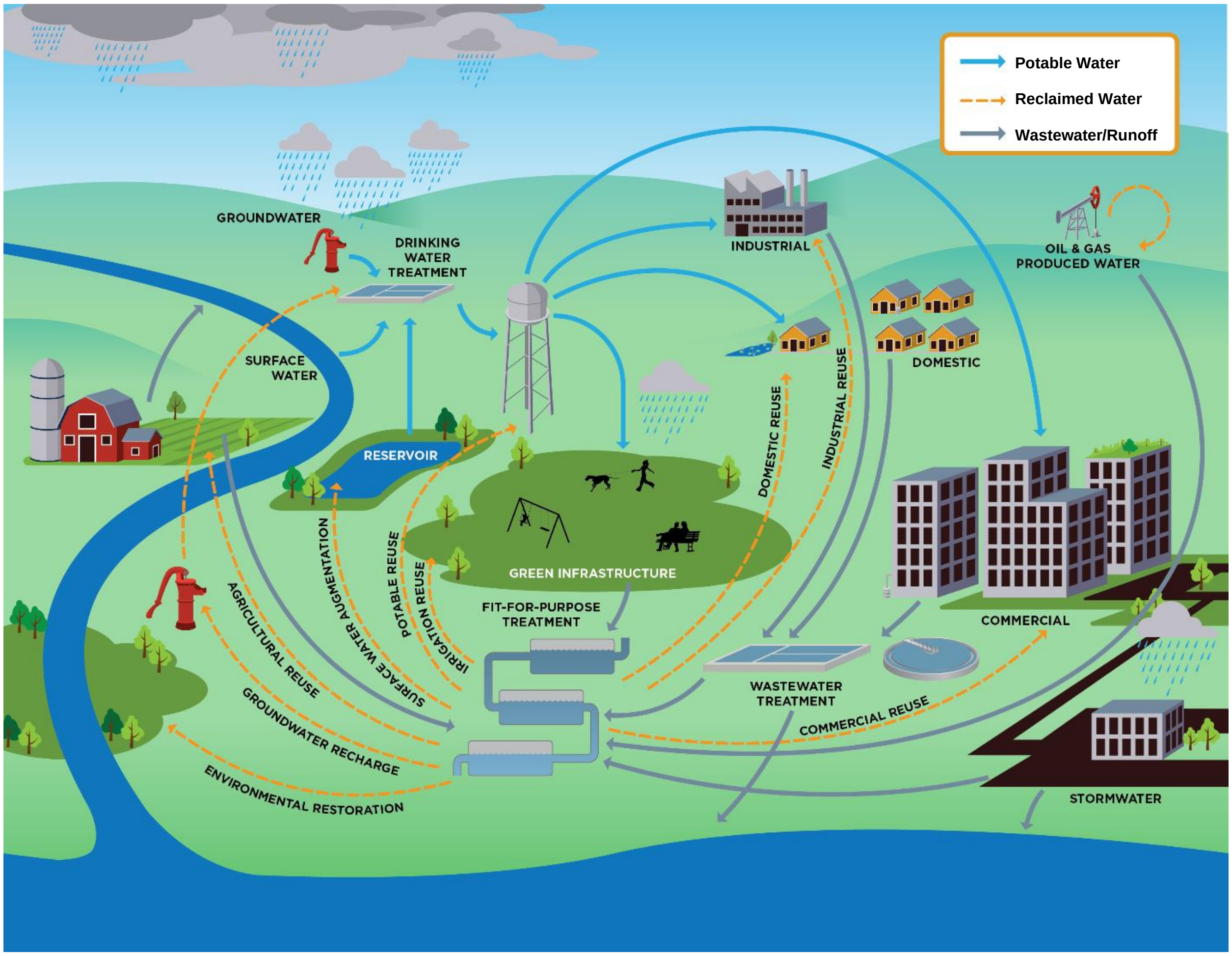


Figure 2: Sustainable anthropomorphic water cycle with potable water (blue), reused/reclaimed water (orange dashed), and wastewater or runoff (grey).

Source: www.epa.gov/waterreuse/basic-information-about-water-reuse, public domain

History

Early humans were hunter gatherers in families or small tribes. As large tribes and permanent communities formed, agriculture was practiced to support the food needs of the communities. People quickly learned that soil conditions determine the success of the plants. Watering and fertilizing the soil was found to increase crop yields. Some early communities started covering farmland with wastewater containing discarded water, food remains, human excreta, and animal excreta. This is the earliest known water reuse application.

Archeological discoveries show that wastewater for irrigation and fertilization was used by the Minoan civilization and Indus Valley civilization, both in the Bronze Age around 3,000 BCE. See Figures 3 and 4 for examples of the sewer lines built to carry the wastewater out of the cities. Often, these sewers routed to farmlands or cisterns where the wastewater would be carried in jars to spread at the crops.

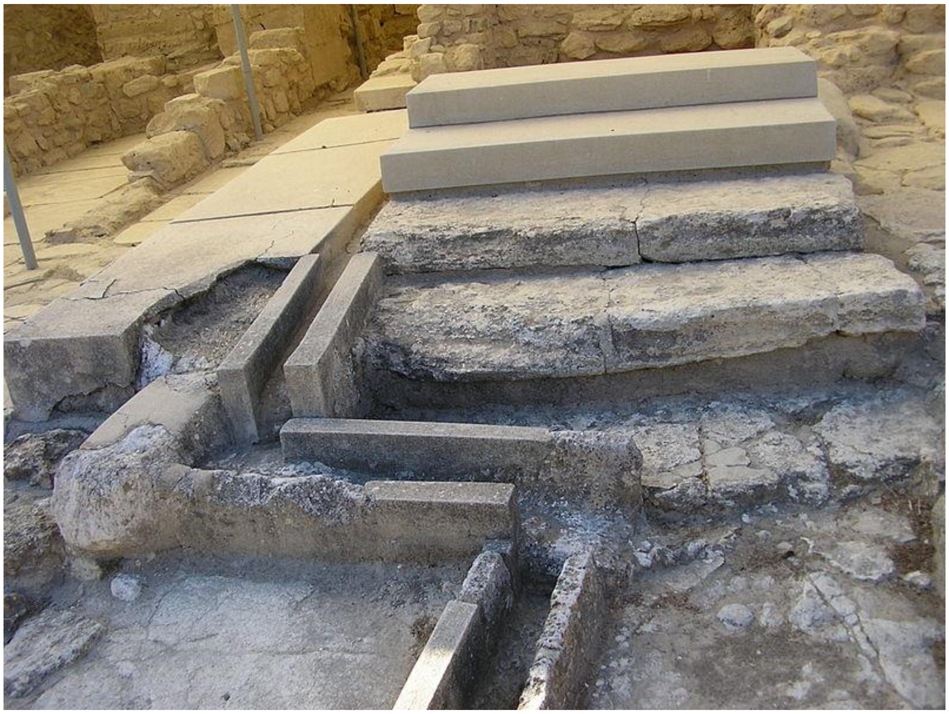


Figure 3: Remains of a sewer channel at a Minoan city.

Source: commons.wikimedia.org/wiki/File:Knossos_sewers_PA067399.JPG, public domain

Figure 4: Remains of a washroom drainage channel at an Indus Valley city.
Source: commons.wikimedia.org/wiki/File:The_drainage_system_at_Lothal_2.JPG, Abhilashdvbk, CC-BY-SA-3.0

Another early practice of water reuse was for aquaculture, which is when water-based creatures are grown for food. In the Shang Dynasty (now China) around 1,100 BCE, wastewater and solid waste was sent to ponds to feed carp. The carp became a staple in the diets of many communities.

In the antiquity era, efforts were made to find clean water sources and to separate sewage from these water sources. This era includes the first documented practice for boiling water to decrease the likelihood of getting sick from drinking questionable water.

Around 600 BCE, natural hydrological processes were identified and documented by Anaximander and later around 350 BCE by Aristotle, both Greek philosophers. It was realized that water recycles between the clouds, rain, lakes, rivers, ocean, etc. The ancient Greeks developed engineered sewage collection systems including settling basins for removing solids and large cisterns for storage. The practice of using wastewater for irrigation spread throughout the Mediterranean Sea area.

During the Roman period, 100 BCE to 330 CE, large cities like Rome had engineered sewage collection systems with farmlands being important destinations for the wastewater. It appears that other forms of water reuse within the city were not attempted due to sanitary concerns. For example, the streets in Rome were washed down with surface water brought in through the elaborate aqueduct system rather than attempting to treat and reuse the wastewater. The priority was to protect the public from potential illness due to exposure to sewage.

Mesoamerican agriculture practices included gardens called Chinampas. Chinampas are constructed over wetlands and do not need irrigation. The original soil is made from a mixture including manure, compost, food waste, and household wastewater. The origin of Chinampas is unknown, however they appear in Aztec paintings dated from 1200 to 1500 CE. Chinampas are still used today in Mexico, as shown in Figure 5.

Figure 5: Example of a modern Chinampa.

Source: commons.wikimedia.org/wiki/File:Camas_chinampas.jpg, Kristinoller, CC-BY-SA-3.0

In Europe during the Middle Ages, some cities and towns would transport sewage out to farms. These farms became known as sewage farms. Documentation has been found for sewage farms in the following cities with starting dates provided:

- Bunzlaw, Poland, 1531
- Edinburgh, UK, 1650
- Croydon-Beddington, UK, 1860
- Barking, East London, UK, 1868 (See Figure 6)
- Leamington, UK, 1870
- Berlin, Germany, 1874
- Wroclaw, Poland, 1882
- Braunschweig, Germany, 1896

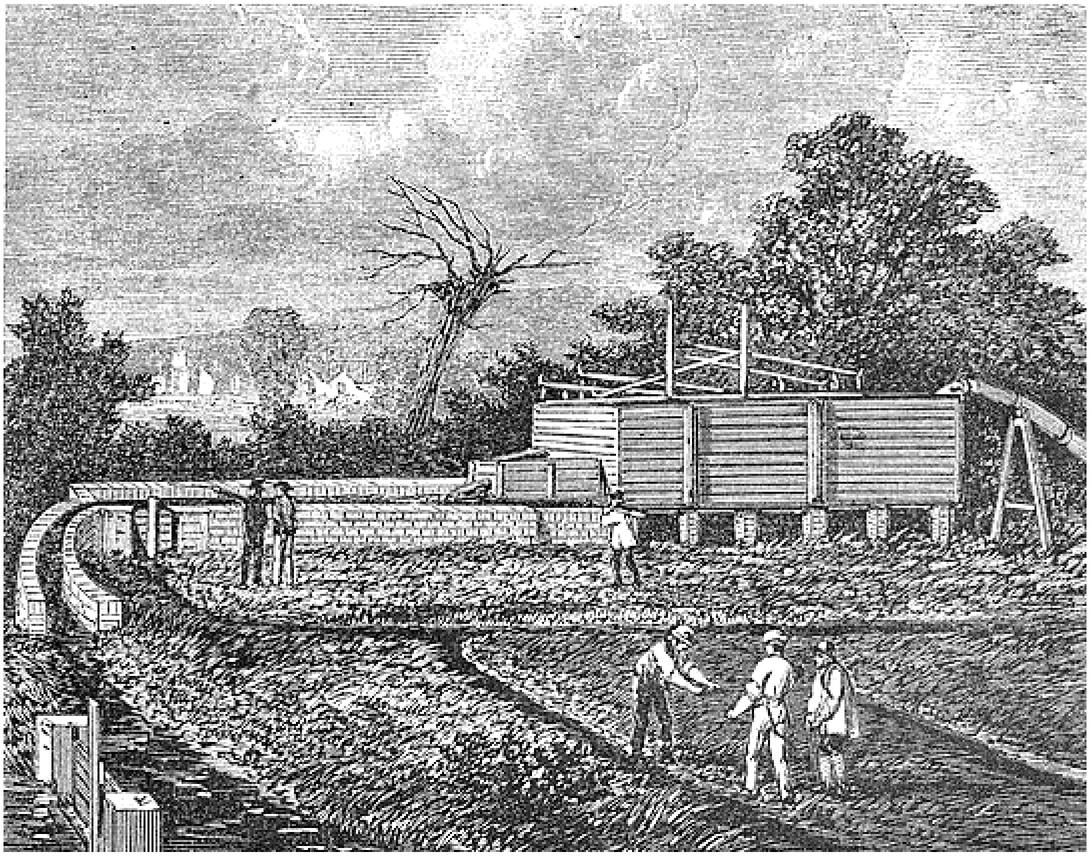


Figure 6: Wastewater storage tank and land application channels at a sewage farm, near Barking in East London, UK, in 1868.

Source: commons.wikimedia.org/wiki/File:Sewage_farm_near_Barking,_19th_century_Wellcome_L0001123.jpg, public domain

In the 19th century, modern water supply and sanitation systems were implemented across Europe and in some cities in the United States and Australia. Indoor plumbing systems and bathroom fixtures were invented and quickly grew in popularity. But even more important was the scientific discovery of the role of drinking water in the transmission of several important diseases, such as cholera, dysentery, and typhoid fever. The microbes causing these diseases were finally discovered and identified, thereby giving engineers new insights into how to eliminate them from public water systems.

Following the numerous scientific discoveries in the late 1800's, several important advances occurred for both drinking water and wastewater management:

- Water quality was monitored by chemical and microbiological examination, in addition to the traditional sensory methods.
- Public water supplies were filtered before distribution. The design of large-scale water treatment systems soon followed.
- Systematic chlorination of drinking water started in the early 20th century. Soon after, disinfection by chlorination became the primary means of eliminating waterborne diseases all around the world.
- Wastewater treatment systems were implemented to protect surface waters from contamination and thereby protect downstream drinking water sources.

Awareness grew of the health risks associated with sewage handling and concerns grew for growing edible food with human excreta. Thus, the first water reuse regulations were adopted in 1918 by the California State Board of Public Health. Sewage farms required treatment prior to land application. Most sewage farms found it more economical to use cow manure for fertilizer and other water sources for irrigation. Today, there are very few known sewage farms using human excreta.

Since the Clean Water Act of 1972 and other regulations, modern wastewater treatment systems produce effluent wastewater that is clean enough for reuse applications beyond traditional farmland irrigation and fertilization. By the end of the 20th century, water reuse had expanded to several new applications around the globe.

Industrial demand for water grew throughout the Industrial Revolution and demand continues to grow to this day. Typical water sources for large industrial facilities include surface water, groundwater, and municipal drinking water. After the water is used, the resulting wastewater is normally returned to the environment or municipal sewer system. The negative impact of industrial pollution was revealed in the 1950's and 1960's, and the Clean Water Act of 1972 required wastewater treatment for nearly all industries throughout the United States. And now around the world, treatment is required for municipal and industrial wastewater to prevent point source pollution, as shown in Figure 7. It is now recognized that reusing wastewater can reduce negative impacts to the environment by reducing discharge flow rates.

Figure 7: Industrial wastewater (grey) being discharged into the Calumet River (cyan).
Source: oceanservice.noaa.gov/education/tutorial_pollution/03pointsource.html, public domain

In last few decades, water sources have become scarcer, especially in urban areas, and drinking water costs have increased faster than inflation for many years in a row. Water reuse is now a viable way to decrease water supply demands and minimize wastewater discharges. Most applications require the reclaim water to be cleaner than typical plant effluent, as shown in Figure 8.

Figure 8: Visual comparison of the color and turbidity differences in raw municipal wastewater (left), treated effluent (center), and advance treated reclaim water (right).

Source: commons.wikimedia.org/wiki/File:Reclaimed_Water_Jars.jpg, Wateralex, CC-BY-SA-4.0

Applications

Agricultural reuse continues to be the most popular application for water reuse based on volume of reclaim water per year. Landscaping and golf course irrigation applications for reclaimed water are also very common. New applications for urban reuse, industrial and commercial reuse, environmental reuse, and groundwater recharge have been developed in recent decades and are continuing to grow in applications each year. See Figure 9 for a breakdown of water reuse applications in California.

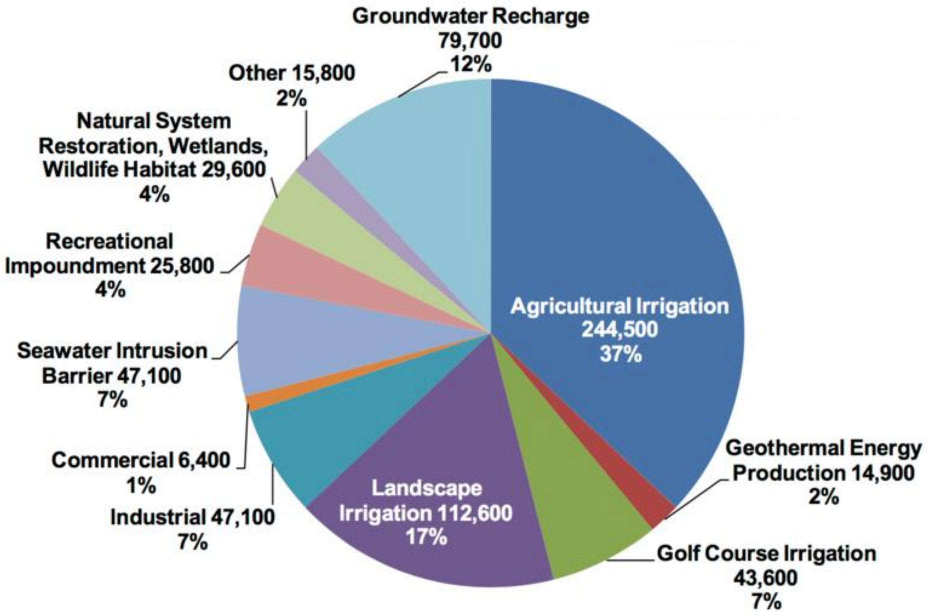


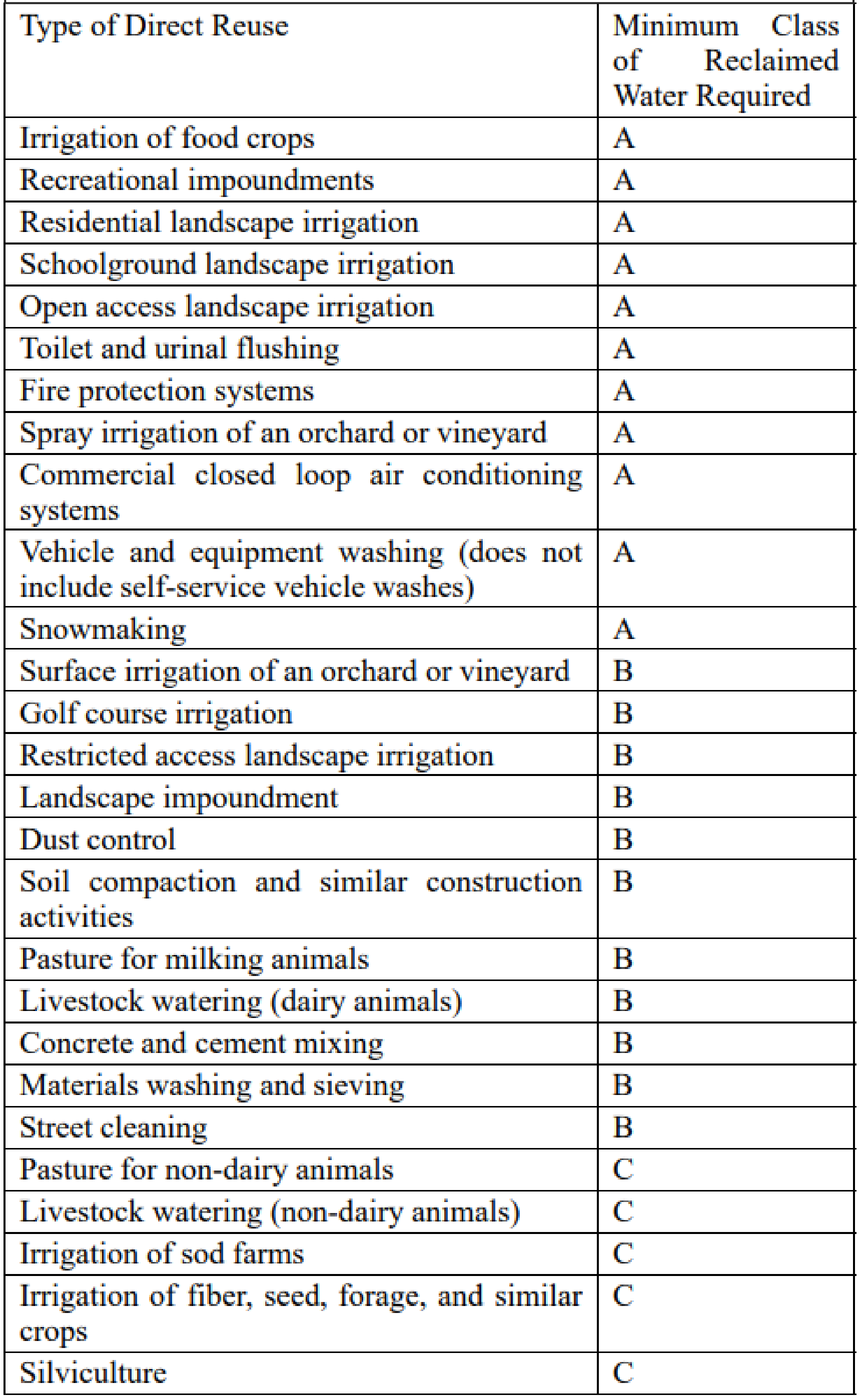
Figure 9: Water reuse applications in California with units of acre-feet per year.

Source: commons.wikimedia.org/wiki/File:Uses_of_recycled_water_in_California.tiff, SWRCB, CC-BY-SA-4.0

Some state and local regulations require different levels of water treatment depending on the reuse applications. See Table 1 for different types/applications with assigned classes of A, B or C, with A being the most stringent and C the least stringent:

- Class A reclaimed water requires secondary treatment, tertiary filtration, disinfection, and has turbidity and disinfection criteria.
- Class B requires secondary treatment, disinfection, does not have turbidity limits, and has more relaxed disinfection requirements.
- Class C requires secondary treatment, which can be with aerated ponds, and does not require disinfection.

Table 1: Water Reuse Types and Classes per Arizona Administrative Code



Type of Direct Reuse	Minimum Class of Reclaimed Water Required
Irrigation of food crops	A
Recreational impoundments	A
Residential landscape irrigation	A
Schoolground landscape irrigation	A
Open access landscape irrigation	A
Toilet and urinal flushing	A
Fire protection systems	A
Spray irrigation of an orchard or vineyard	A
Commercial closed loop air conditioning systems	A
Vehicle and equipment washing (does not include self-service vehicle washes)	A
Snowmaking	A
Surface irrigation of an orchard or vineyard	B
Golf course irrigation	B
Restricted access landscape irrigation	B
Landscape impoundment	B
Dust control	B
Soil compaction and similar construction activities	B
Pasture for milking animals	B
Livestock watering (dairy animals)	B
Concrete and cement mixing	B
Materials washing and sieving	B
Street cleaning	B
Pasture for non-dairy animals	C
Livestock watering (non-dairy animals)	C
Irrigation of sod farms	C
Irrigation of fiber, seed, forage, and similar crops	C
Silviculture	C

Most Stringent

Agricultural Reuse

Water reuse for agricultural purposes has a long history, as explained in the previous section. Historically, raw (untreated) sewage was applied directly to the land for fertilization and irrigation of crops. However, municipal wastewater is now treated prior to land application due to concerns for the spread of disease. Industrial wastewater is also treated prior to being used as irrigation due to concerns for pollutants that can spread into the earth and contaminants that can impact food crops.

The level of treatment highly depends on the agricultural application and type of crop. The following are major categories:

- Aquaculture (growing water-based organisms and fish)
- Flowers
- Food crops, non-commercial
- Food crops, commercial
- Grass for fodder
- Greenhouses
- Hydroponics (growing plants in water)
- Pasture for livestock
- Plant-based fibers
- Seed crops
- Viticulture (growing grapes)

A greater level of treatment is required for food crops than for growing grass for fodder. Many plants are more sensitive to specific parameters. For example, a lettuce crop requires a very low sodium concentration while seaweed requires a high sodium concentration. In this way, wastewater is treated to the level required by the specific crop(s).

One benefit of using wastewater for irrigation is that it tends to have nitrogen and phosphorus, which are essential nutrients for plant growth. The use of fertilizer can be reduced or eliminated by irrigating with wastewater. However, some wastewater may have too much phosphorus which in combination with high pH soil (above 6.5), can result in deficiencies of zinc and iron.

Often wastewater is mixed with clean water (potable, surface, or well water) for irrigation purposes. In such cases, the following *Mixing Formula* is utilized to calculate the resulting concentration (see formula 2). The volume of water (V_2) can be increased until the mixed concentration (C_M) is below the maximum required (limit).

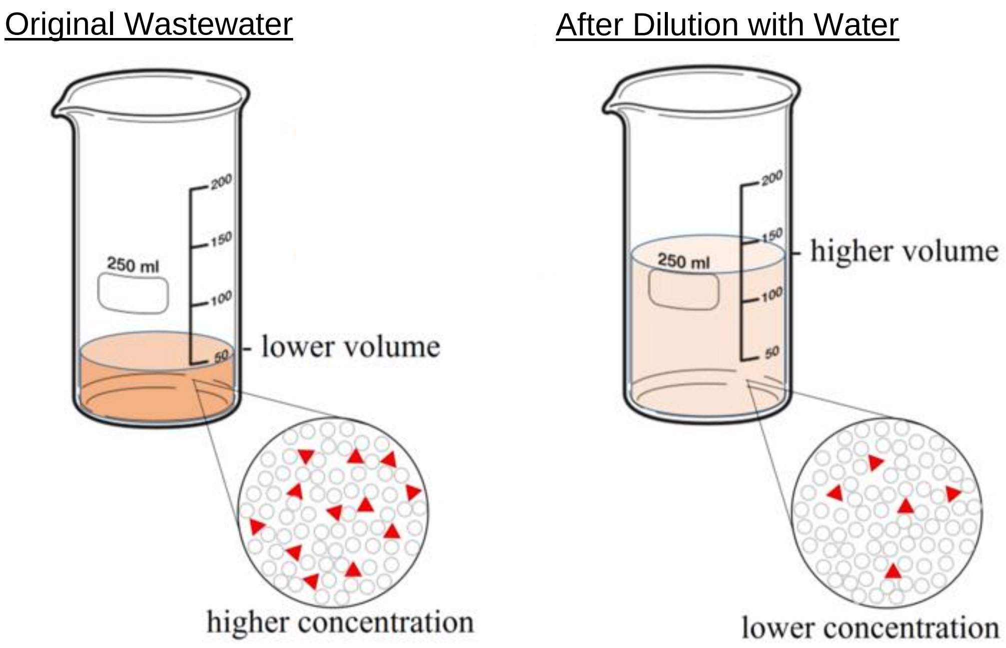
1) $C_1 * V_1 + C_2 * V_2 = C_M * (V_1 + V_2)$

or

2) $C_M = (C_1 * V_1 + C_2 * V_2) / (V_1 + V_2)$

3) Mix Ratio (Wastewater to Water) = V_1 / V_2

C_1 is the concentration of the starting solution (wastewater)
V_1 is the volume of the starting solution (wastewater)
C_2 is the concentration of the final solution (water)
V_2 is the volume of the final solution (water)
C_M is the concentration of the final solution (wastewater + water)
V_M is the volume of the final solution (wastewater + water)


Original Wastewater

After Dilution with Water

Figure 10: Depiction of pollutant concentration reduction by mixing with clean water.
Source: commons.wikimedia.org/wiki/File:Dilution.png, Theislikerice, CC-BY-SA-4.0

Example Problem 1

An agricultural company is considering watering a crop of watermelons with a mix of groundwater from a well and effluent wastewater from a local municipal wastewater treatment plant. Table 2 lists the water quality parameters for the wastewater (WW) and groundwater (GW) as well as the maximum allowable values for watering watermelons. Find an acceptable mix ratio of wastewater to groundwater (rounded to nearest 0.5) that maximizes water reuse.

Table 2: Parameters (mg/L) for Problem 1
Values in Red Indicate WW Effluent is over the Limit

Parameter	WW Effluent (mg/L)	Groundwater (mg/L)	Allowable Limits for Irrigation (mg/L)
Chloride	80	30	100
Copper	0.3	0.1	0.5
Hardness ($CaCO_3$)	120	180	200
Iron	0.8	0.5	1.0
pH (s.u.)	7.0	7.5	5 to 8
Phosphorus	5.1	0.2	6
Sodium	50	20	100
Sulfate	20	40	250
Sulfides	**8.0**	0.3	5
Total Dissolved Solids (TDS)	500	100	900
Total Suspended Solids (TSS)	**15**	1	10

Solution

The following parameters are above the irrigation limits for the watermelon crop:

- Sulfides: 8 mg/L is over the 5 mg/L limit (60% over)
- TSS: 15 mg/L is over the 10 mg/L limit (50% over)

The Dilution Formula 2 is used to calculate the final concentration (C_M) with wastewater to groundwater mix ratios (V_1:V_2) of 1:1, 1.5:1 and 2:1:

$$C_M = (C_1 * V_1 + C_2 * V_2) / (V_1 + V_2)$$
$$C_{M\_1:1} = (C_1 * 1 + C_2 * 1) / (1 + 1) = (C_1 + C_2) / 2$$
$$C_{M\_1.5:1} = (C_1 * 1.5 + C_2 * 1) / (1.5 + 1) = (C_1 * 1.5 + C_2) / 2.5$$
$$C_{M\_2:1} = (C_1 * 2 + C_2 * 1) / (2 + 1) = (C_1 * 2 + C_2) / 3$$
$$C_{M\_2.5:1} = (C_1 * 2.5 + C_2 * 1) / (2.5 + 1) = (C_1 * 2.5 + C_2) / 3.5$$
$$C_{M\_3:1} = (C_1 * 3 + C_2 * 1) / (3 + 1) = (C_1 * 3 + C_2) / 4$$

These formulas are applied to sulfides and TSS, with the results summarized in Table 3.

Table 3: Final Concentration Calculation Results for Problem 1
Values in Red are above the Limit

Ratio (WW:GW)	Final Concentration, C_M (mg/L)		Acceptable?
	Sulfides (Limit 5)	TSS (Limit 10)	
1:1	4.2	8.0	Yes
1.5:1	4.9	9.4	Yes
2:1	**5.4**	**10.3**	No

Based on the results in Table 3, the greatest acceptable mix ratio of WW:GW is **1.5:1**. This means that every 1.5 gallons of wastewater must be mixed with 1 gallon of groundwater.

Sludge as Fertilizer

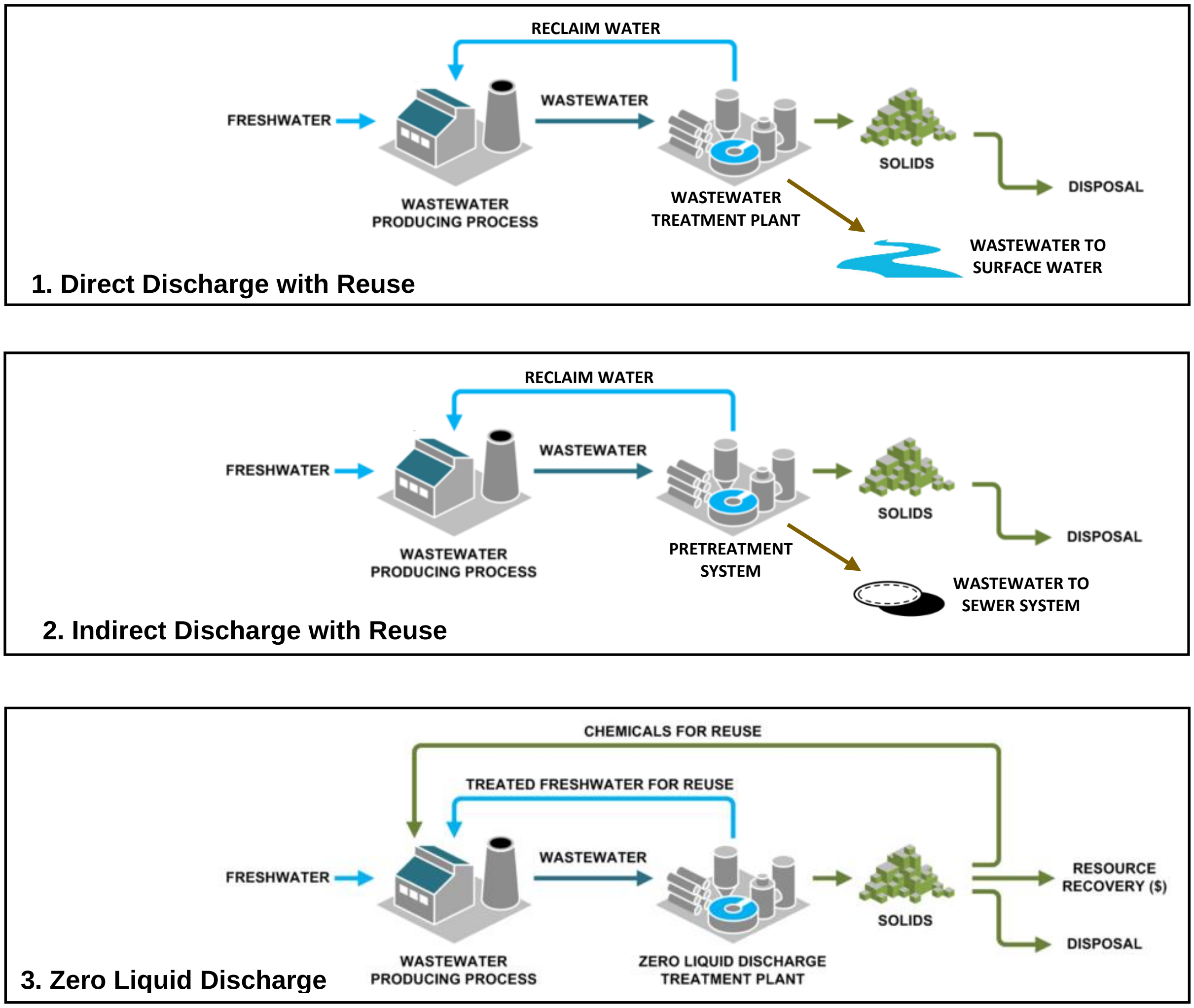
A byproduct of wastewater treatment is sludge, which is a thick, soft, mud like mixture of water and solids. Biological treatment processes product a sludge called biosolids that contains degraded cells from micro-organisms which is rich in nutrients. This biosludge can be directly land applied or dried into a dry fertilizer that is sometimes sold in bags at stores. See Figure 11 for an example.

Figure 11: Bag of biosolids based fertilizer (left) and the sludge handling building where it is produced, at the Jones Island Water Reclamation Facility in Milwaukee (right).
Source: commons.wikimedia.org/wiki/File:Milorganite_building_(1177320933).jpg, Michael Pereckas, CC-BY-2.0

Industrial Reuse

Most industrial processes require water and produce wastewater. There are three basic options for wastewater discharge as shown in Figure 12:

1. Treat and directly discharge to the environment with reuse optional,
2. Pretreat and indirectly discharge to the sewer system public-owned treatment works (POTW) with reuse optional, and
3. Treat, reuse, and evaporate wastewater such that there is no wastewater discharge, only solids disposal. This is called Zero Liquid Discharge.



1. Direct Discharge with Reuse

2. Indirect Discharge with Reuse

3. Zero Liquid Discharge

Figure 12: Industrial Wastewater Disposal Options.

Source: https://en.wikipedia.org/wiki/File:What_is_Zero_Liquid_Discharge_Diagram.png, Saltworks Technologies, Modified, CC-BY-SA-4.0

The industrial and commercial opportunities for water reuse abound. Each industrial process has unique water quality requirements, so an engineer is needed to design a water reclamation systems that meet the needs of the specific application.

A few examples of industrial reuse are as follows:
- Cooling tower water,
- Power generation cooling water,
- Other cooling applications,
- Boiler feed water,
- Steam generation,
- High-purity water for electronics manufacturing,
- Seal water for pumps and moving equipment,
- Washdown and rinse water,
- Pump and paper production,
- Chemical make-up water
- Coating mix water,
- Plating and galvanizing,
- Fire suppression,
- Dyes and textile manufacturing water,
- Wastewater treatment utility water, and
- Landscaping and irrigation.

Some processes require potable water, such as when water goes into a consumable product. For these applications it is unusual to use reclaimed water due to health risks, treatment costs, and public discomfort. However, turning wastewater into potable water can be done and, in some cases, is currently being done, as explained in the Potable Reuse section of this course.

Resource Recovery

In addition to being able to reuse the water, wastewater treatment process can salvage lost products, ingredients, or energy (heat). This is called resource recovery. Many industries lose a percentage of product ingredients or other valuable assets down the drain in the wastewater. Advanced separation processes can salvage the valuable constituents for reuse along with producing reclaim water. The net savings is equal to the avoided disposal cost plus the material cost savings minus the treatment cost.

Example Problem 2

A magnet manufacturer uses iron, boron, and the rare earth element (REE) neodymium ($Nd_2Fe_{14}B$) to produce high-strength magnets for hard disks. Potable water and high-purity water is used in the manufacturing process and the resulting waste streams contain heavy metals. Currently, pollutants are removed in a sludge that is incinerated. The resulting fly ash is then sent to a special landfill. Based on the information in the below table, determine which elements are economical to extract and reuse and the total savings per day for reuse of just those elements.

Table 4: Waste and Reuse Information for Problem 2

Element	Waste Load (lb/d)	Percent Extractable	Disposal Cost ($/lb)	Material Savings ($/lb)	Treatment Cost ($/lb)
Iron	500	80%	$1	$0.10	$5
Boron	20	60%	$50	$1,000	$50
Neodymium	50	90%	$50	$80	$10

Solution

For each element, calculate the disposal cost, material savings, and treatment cost per day for the portion with reuse potential by using the percent extractable values (the remaining portion will have to be wasted).

For iron:

Disposal cost = 500 lb/d * 0.8 * $1/lb = $400/d
Material savings = 500 lb/d * 0.8 * $0.1/lb = $40/d
Treatment cost = 500 lb/d * 0.8 * $5/lb = $2,000/d

Next, the net savings is equal to the disposal cost plus the material savings minus the treatment cost.

For iron:

Net savings = $400/d + $40/d - $2,000/d = -$1,560/d (a loss)

The following table provides the calculated values for each element. The net savings for Iron is negative, so it is not selected for reuse.

Table 5: Calculated Values for Problem 2

Metal	Disposal Cost ($/d)	Material Savings ($/d)	Treatment Cost ($/d)	Net Savings ($/d)	Savings for Selections ($/d)
Iron	$400	$40	$2,000	-$1,560	-
Boron	$600	$12,000	$600	$12,000	$12,000
Neodymium	$2,250	$3,600	$450	$5,400	$5,400
				Total Savings	**$17,400**

Boron and Neodymium result in positive savings, with a total savings of $17,400 a day.

Phosphorus Recovery

Phosphorus is common in wastewater. It can be removed with a recovery rate of around 50% and sold as raw material. Phosphorus removal and reuse is advantageous for the following reasons:

- The discharge of excessive phosphorus into surface waters often leads to eutrophication, which is the excessive growth of algae and aquatic plants which upon decay decrease dissolved oxygen and produce algal toxins.
- Phosphorus is a valuable and limited resource which cannot be replaced by other elements.
- Phosphate rock reserves are only found in Morocco, China, Egypt, Algeria, and Syria. Domestic phosphorus supplies are often protected to avoid dependance on these countries and minimize geo-political risks.

Urban Reuse

Some utilities deliver treated wastewater in pipes routed through the community for various purposes with the goal of reducing potable water demands. Often these reclaimed water pipes are colored purple/lavender and routed in parallel with potable water pipes, as shown in Figure 13.

Figure 13: Upper left: A purple pipe in Mountain View, CA. Upper right: Reclaimed pipes with labels. Lower left: Portable main (blue), reclaim main (lavender), & force main (green).

Upper left: commons.wikimedia.org/wiki/File:Nonpotable_water_pipeline_in_Mountain_View.gk.jpg, Grendelkhan, CC-BY-SA-3.0
Upper right: www.ppic.org/publication/alternative-water-supplies/purple-pipe-on-grass-horizontal/ (public domain)
Bottom: Maps Data: Google, ©2022 Google

Care must be taken not to cross-connect reclaim pipes with potable water pipes or force main pipes. Pipes are given special labels and signs are often posted in areas where reclaim water is utilized so it is not mistaken for potable water.

A few examples of urban reuse are as follows:

- Fire protection systems,
- Sporting facilities,
- Street cleaning,
- Vehicle washing,
- Toilet flushing,
- Laundry use,
- Airport runway and plane cleaning,
- Water fountains,
- Cooling water such as power plants,
- Hydraulic fracturing (fracking),
- Dust control,
- Concrete mixing,
- Soil compaction,
- Other construction activities,
- Artificial ponds and lakes,
- Artificial snow,
- Ice rinks,
- Vertical farming, and
- Landscaping and irrigation (see next section).

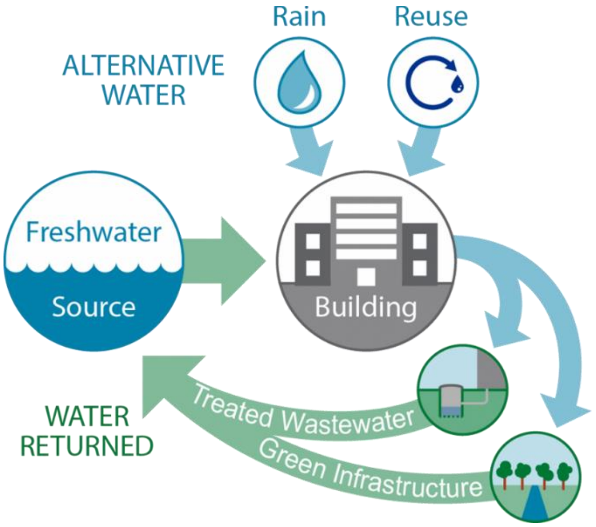
LEED Water Efficiency

For obtaining LEED certification of a building, water efficiency initiatives must be incorporated into the design with the goal of reducing potable water consumption. LEED points can be obtained for minimizing potable water consumption, including using reclaimed water where possible, such as for irrigation and cooling tower make-up water.

Net Zero Water

Net Zero Energy, Water, and Waste are strategies from the US Department of Energy, Federal Energy Management Program. These strategies are intended for federal buildings; however, they can be applied to any building.

A Net Zero Water designation means the amount of alternative water used plus the water returned to the original water source is equal or greater than the building's total freshwater (utility/potable water) consumption. This is depicted in Figure 14.



Alternative Water Use
+
Water Returned
≥
Freshwater Consumption

Figure 14: Left, depiction of major elements to achieve Net Zero Water.
Right: Water balance equation for achieving Net Zero Water.
Source: www.energy.gov/eere/femp/net-zero-water-building-strategies

Example Problem 3

For the building shown in Figure 15, write the water balance equation and indicate if Net Zero Water is achieved.

Solution

Water balance equation:

Alternative Water Use + Water Returned ≥ Utility Water Use
18kgal/yr Rainwater + 12kgal/yr Gray + 26kgal/yr Recharge ≥ 26kgal/yr Potable Water
56kgal/yr ≥ 26kgal/yr

The equation is true; therefore, Net Zero Water is achieved.

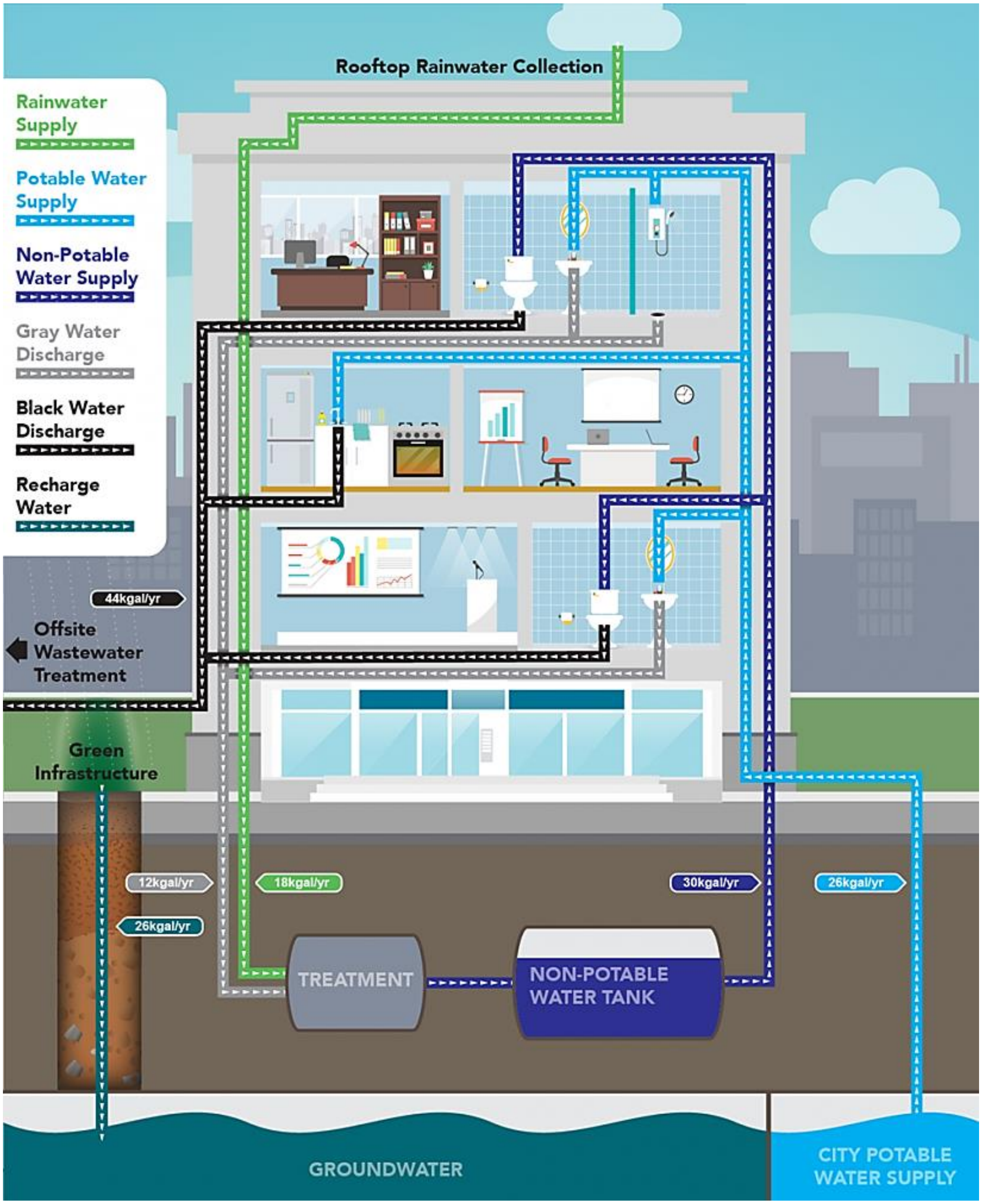


Figure 15: Depiction and water balance for Example Problem 3.

Source: www.energy.gov/eere/femp/scenario-2-mainstream-net-zero-water-building

Landscaping Reuse

Landscape irrigation with reclaimed water is very common. Here are few examples:

a) An industrial facility sprays treated wastewater on a large field that is fenced in with signs indicating irrigation with reclaimed water,
b) A commercial facility uses condensate, cooling tower blowdown, and boiler blowdown to irrigate lawns, bushes, trees, and flowers,
c) Residential houses use reclaimed water from purple pipes to irrigate their yards and personal gardens,
d) A golf course uses City wastewater effluent to irrigate the course,
e) A County uses reclaimed water for irrigation of several parks and ball fields,
f) A City uses reclaimed water to irrigate road medians and flower beds at each of the welcoming signs, and
g) A State Department of Transportation uses reclaim water for landscape features.

Figure 16: Left: Landscape irrigation at an office park. Right: Irrigation of a natural field.
Source: commons.wikimedia.org/wiki/File:Recycled_Water_irrigation_sign_in_Sunnyvale,_California.jpg, Grendelkhan, CC-BY-SA-3

The reclaimed water properties should be compared to the maximum limits for the plants that will receive the irrigation. See Table 6 for an example comparison of reclaim water properties to common landscaping plant groups, with high values in red.

Table 6: Example Reclaim Water Quality Compared to Plant Requirements					
Parameter	Reclaim Water Limit (ppm)	Turfgrass	Trees	Bushes, Hedges	Flowers
Boron	2	Ok	High for Some	High for Some	**High**
BOD5	20	Ok	Ok	Ok	Ok
Chloride	80	Ok	Ok	High for Some	High for Some
Chlorine, Residual	0.2	Ok	Ok	Ok	Ok
Conductivity (mS/m)	500	Ok	Ok	High for Some	**High**
Copper	0.2	Ok	Ok	Ok	High for Some
Fecal Coliform (CFU/100 mL)	<200	Ok	Ok	Ok	Ok
Hardness ($CaCO_3$)	150	Ok	Ok	Ok	Ok
Iron	1	Ok	Ok	Ok	Ok
Nitrogen	30	Ok	Ok	Ok	Ok
Oil & Grease	15	Ok	Ok	Ok	Ok
Oxygen, Dissolved	2	Ok	Ok	Ok	Ok
pH (s.u.)	6 to 9	Ok	Ok	Ok	Ok
Phosphorus	3	Ok	Ok	Ok	High for Some
Sodium	50	Ok	Ok	High for Some	High for Some
Sulfate	30	Ok	Ok	Ok	Ok
Sulfides	8.0	Ok	Ok	Ok	Ok
Total Dissolved Solids (TDS)	500	Ok	Ok	Ok	Ok
Total Suspended Solids (TSS)	20	Ok	Ok	Ok	Ok
Turbidity	10	Ok	Ok	Ok	Ok

Potable Reuse

Turning wastewater into drinking water is called potable water reuse. There are three main types of potable water reuse:

1. *Indirect potable reuse:*
    - Treated wastewater is discharged through an environmental buffer, such as a lake, river, or groundwater aquifer, and then collected and treated as potable water.
2. *Direct potable reuse:*
    - Wastewater is treated with precise engineered processes (without an environmental buffer) to produce potable water.
3. *Unplanned potable reuse:*
    - Treated wastewater is discharged and unintentionally drawn in by a downstream water treatment facility.
    - Also called “de facto” or unacknowledged potable reuse.
    - Common along large rivers with multiple cities. The upstream city discharges wastewater into the river and the downstream city draws raw water from the river which includes some remnants of the wastewater.

Indirect Potable Reuse

Indirect potable reuse is relatively common and accepted practice for water management. Groundwater and surface water supplies are diminishing for many communities. A solution is to discharge the wastewater into the ground such that it passes through natural filtration of the earth prior to being drawn for water treatment.

The mixture of treated wastewater and groundwater can have better water quality values than either of the waters on their own. For example, the wastewater may have high phosphorus and sulfides, while groundwater is low in these parameters. And the groundwater may have high hardness and metals, while wastewater is low in these parameters. When combined, the resulting water quality is better than either source on its own.

Rapid infiltration basins (RIBs) are engineered ponds where wastewater passes through layers of sand where pollutants and organisms are filtered out before the wastewater enters the groundwater. These RIBs can be designed so the filtered wastewater is directed towards a raw water inlet. To do this it is essential to understand the bedrock depth, slope, and natural groundwater flow.

Another indirect potable reuse approach is to inject the wastewater into a confined aquifer at a location where the wastewater will natural flow through the earth towards a raw water source. This approach is also a form of groundwater recharge which is discussed in a subsequent section.

Direct Potable Reuse

Direct potable reuse is a relatively new approach made possible by advanced technology, such as reverse osmosis. The main concern with direct potable reuse is that fecal pathogens present in wastewater will survive the treatment process and contaminate the drinking water. Therefore, the focus of treatment is the reliable removal of microorganisms. Direct potable reuse standards require the removal of microorganisms be greater than for other forms of reuse and greater than normal potable water treatment systems. The removal is commonly measured on a log scale.

Log Removal

The level of removal of microorganisms (also called inactivation) is customarily measured on a log scale, as a convenience to avoid long numbers. An easy way to remember the correlation between a log number and percent removal is that the log number equals the number of 9’s in the percent removal. For example:

- 1-log removal = 90% (one 9)
- 4-log removal = 99.99% (four 9’s)
- 6-log removal = 99.9999% (six 9’s)

Typical water treatment systems (without reuse) are required to provide the following removal rates for common pathogens:

- *Crypto*: 2-log (99%)
- *Giardia*: 3-log (99.9%)
- Viruses: 4-log (99.99%)

However, for direct potable reuse, some states require a 99.9999999999% (12 log) removal of viruses. Viruses are the most difficult organisms to remove, so typically calculations are done to show compliance with virus removal only, with the assumption that other larger organisms would be removed to a greater extent.

Removal Credits

Most water and wastewater treatment processes eliminate some portion of microorganisms from the water. These processes can provide reduction credits for attaining compliance with log reduction requirements. The credits are often referred to as log removal value or log reduction value (LRV). See Table 7 for example removal credits for common treatment processes. Regulations often dictate the appropriate credits for different treatment processes.

Table 7: Common Log Removal (LRV) Credits for Treatment Processes

Technology	Log Removal Credit		
	Crypto	Giardia	Viruses
Bag Filter or Cartridge Filter	2	2	0
Earth Filter	2	2	1
Slow Sand Filter	2	2	2
Conventional Sand Filter	2	2.5	2
Microfiltration (MF)	2	3	0
Ultrafiltration (UF)	2	3	0
Nanofiltration (NF)	2	3	3
Reverse Osmosis (RO)	2	3	3
Disinfection	Varies	Varies	Varies

Disinfection Removal Credits

High levels of removal credits are obtained by disinfection. Disinfection is often the last treatment process before the water is reused. The following are common disinfection methods:

1. Free Chlorine
2. Chloramines
3. Chlorine Dioxide
4. Ozone
5. UV

The most common approach for determining the removal rate of a disinfection system is to calculate the contact time (CT) and compare it to the required contact times listed in the EPA Surface Water Guidance Manual. Contact time is calculated in these steps:

Step 1: Determine the time available in the basin at peak flow. Multiply the storage volume by the baffling factor (see EPA Table 3-2 below) and divide by the peak hourly flow.

$$\text{Time (min)} = \frac{\text{Volume (gal)} \times \text{Baffling Factor}}{\text{Peak Hourly Flow (gpm)}}$$

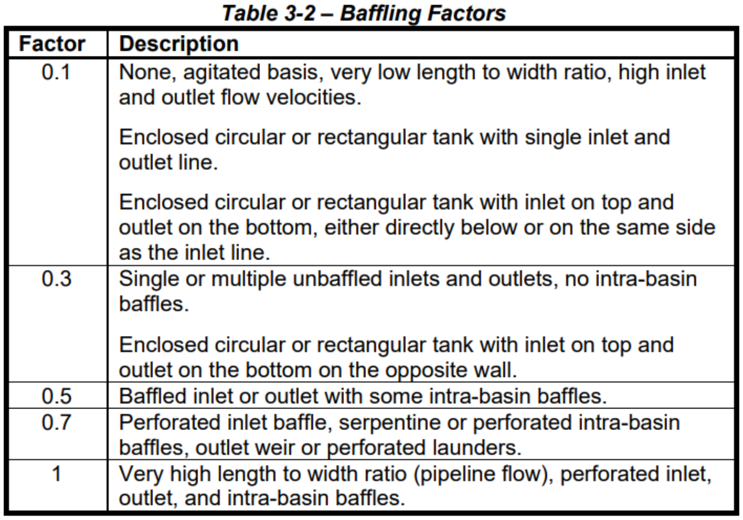
Step 2: Determine the contact time available at peak flow. Multiply the Time (from Step 1) by the chlorine concentration at peak hourly flow.

$$CT_{avail}\ \text{(min mg/L)} = \text{Time (min)} \times \text{Chlorine Conc (mg/L)}$$

Step 3: Find the required contact time (CT_{req}) from the EPA Tables (see Table B-2 below) using the pH, temperature, and chlorine concentration.

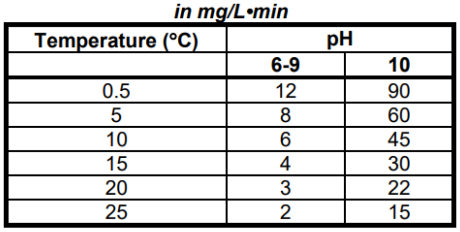
Step 4: Determine if the disinfection system meets the EPA requirements. Compare CT_{avail} to CT_{req}. If CT_{avail} is greater, then the disinfection system met the contact time requirements. If CT_{avail} is less, consider increasing the storage volume or increase the disinfectant concentration, and recalculating.

Table 3-2 – Baffling Factors



Factor	Description
0.1	None, agitated basis, very low length to width ratio, high inlet and outlet flow velocities. Enclosed circular or rectangular tank with single inlet and outlet line. Enclosed circular or rectangular tank with inlet on top and outlet on the bottom, either directly below or on the same side as the inlet line.
0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles. Enclosed circular or rectangular tank with inlet on top and outlet on the bottom on the opposite wall.
0.5	Baffled inlet or outlet with some intra-basin baffles.
0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders.
1	Very high length to width ratio (pipeline flow), perforated inlet, outlet, and intra-basin baffles.

Table B-2 – CTreq values for 4-log virus inactivation of viruses by free chlorine in mg/L•min



Temperature (°C)	pH	
	6-9	10
0.5	12	90
5	8	60
10	6	45
15	4	30
20	3	22
25	2	15

Example Problem 4:
For the direct potable reuse system shown in Figure 17:
a) Does the LRV exceed the minimum regulatory requirement of 12?
b) What is the percent removal of viruses?

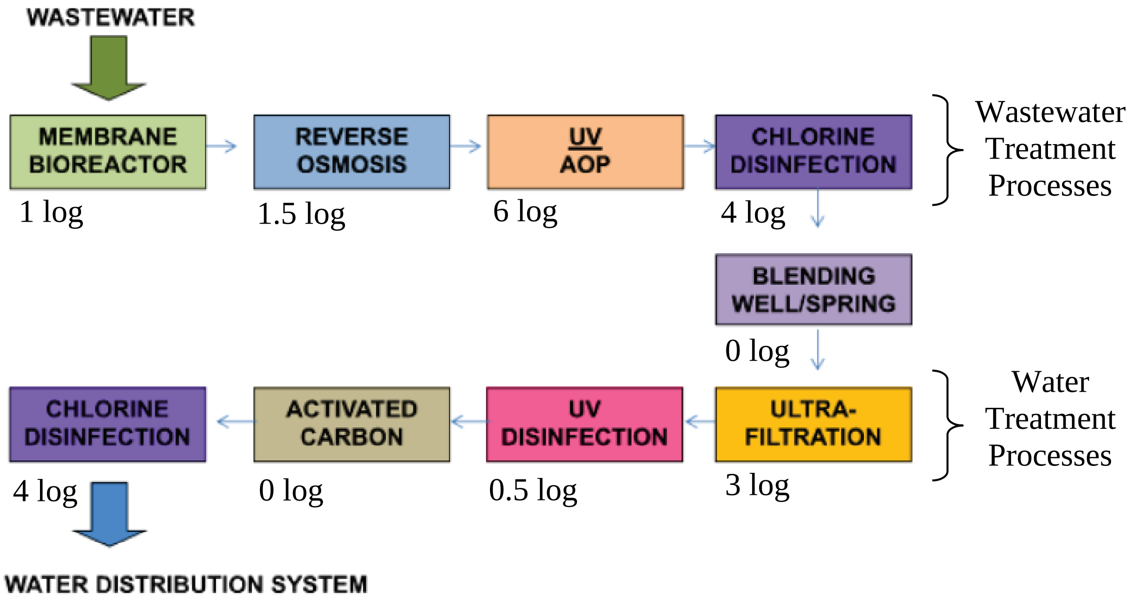


Figure 17: Block flow diagram for Example Problem 4. The virus log removal is stated for each process. Note that AOP stands for Advanced Oxidation Process.
Source: D. Venable, E. Livingston, J. Vandegrift. (2017) Village of Cloudcroft PURe Water Project

Solution:
a) The total log removal of viruses can be found by summing the log removals for each process:

Total log removal = 1 + 1.5 + 6 + 4 + 0 + 3 + 0.5 + 0 + 4 = 20

This is called the log removal value (LRV), and since 20 is greater than 12, it exceeds the regulatory minimum.

b) Log removal is converted to percent removal by entering the number of 9's to be the log removal. Therefore, there should be twenty 9's in the percent removal:

Percent log removal = 20 log = **99.999999999999999999%**

Environmental Reuse

Environmental reuse is releasing reclaimed water into surface water bodies to enhance, sustain, or augment natural water. Examples include the following:

- Create a constructed wetland,
- Support or restore an existing wetland,
- Support aquatic habitats for flora, fauna, and native wildlife,
- Stream flow augmentation,
- Lake water augmentation, and
- Maintaining canal depths.

Example Problem 5

Development has impacted an existing wetland. An assessment was performed which indicated that the wetland could be restored with reclaimed water at an approximate rate of 0.20 MGD in the wet season (165 days) and 1.50 MGD in the dry season (200 days). The nearby municipal wastewater treatment plant (WWTP) can provide a consistent flow of up to 1.00 MGD of reclaimed water. A storage reservoir can be constructed to receive reclaim water and feed it to the wetland at the rates needed for restoration. What is the consistent reclaim flow rate needed (MGD, rounded to two decimal places) and is it below the maximum available from the WWTP?

Solution:
The consistent (or average) reclaim flow rate can be calculated by summing the total volume required over a year (dry and wet seasons) and then dividing that total volume by the number of days in a year, 365:

$$\begin{aligned}\text{Avg Flow} &= \text{Annual Volume} / 365 \text{ days} = (\text{Wet Volume} + \text{Dry Volume}) / 365 \text{ d} \\ &= (200{,}000 \text{ gal/d} * 165 \text{ d} + 1{,}500{,}000 \text{ gal/d} * 200 \text{ d}) / 365 \text{ d} \\ &= (33{,}000{,}000 \text{ gal} + 300{,}000{,}000 \text{ gal}) / 365 = 912{,}329 \text{ gal} = \mathbf{0.91\ MGD}\end{aligned}$$

The required average reclaim flow of 0.91 MGD is less than the maximum flow available of 1.0 MGD from the WWTP, so this reservoir approach appears feasible.

Groundwater Recharge

Groundwater recharge is when water moves downward into an aquifer. There are two forms of recharge:

- Natural recharge occurs as part of the water cycle, and
- Artificial recharge occurs through anthropogenic processes where rainwater or reclaimed water is forced down to the subsurface.

Artificial groundwater recharge is becoming increasingly important for the reasons:

- In agricultural areas, over-pumping of groundwater by farmers has led to a lowering of the groundwater table and increased difficulty to pump clean water from aquifers.
- In urban areas, groundwater tables have dropped due to growing groundwater demands while impervious surfaces have routed rainwater to other areas.
- Climate changed has led to less rainwater and more evaporation, causing a depletion of groundwater in some areas.
- Coastal cities have seen sea levels rise and saltwater intrusion of previously fresh groundwater.

See Figure 18 for a depiction of how the groundwater table can be lowered by a raw water well. In an area with many wells, the overall groundwater table will generally lower over time unless adequate recharge is provided. Increasingly, groundwater tables are being monitored and efforts made to prevent groundwater from becoming depleted. Injecting reclaim water into the earth at select locations is a common approach to maintaining groundwater balance.

Along ocean coastlines, saltwater naturally penetrates below the land. The location of the interface between freshwater and saltwater depends on the depth and distance from the coast. Adding a raw water well near the coast results in unnatural saltwater intrusion. To counter this, reclaim water can be injected at points between the raw water well and coastline, as depicted in Figure 19.

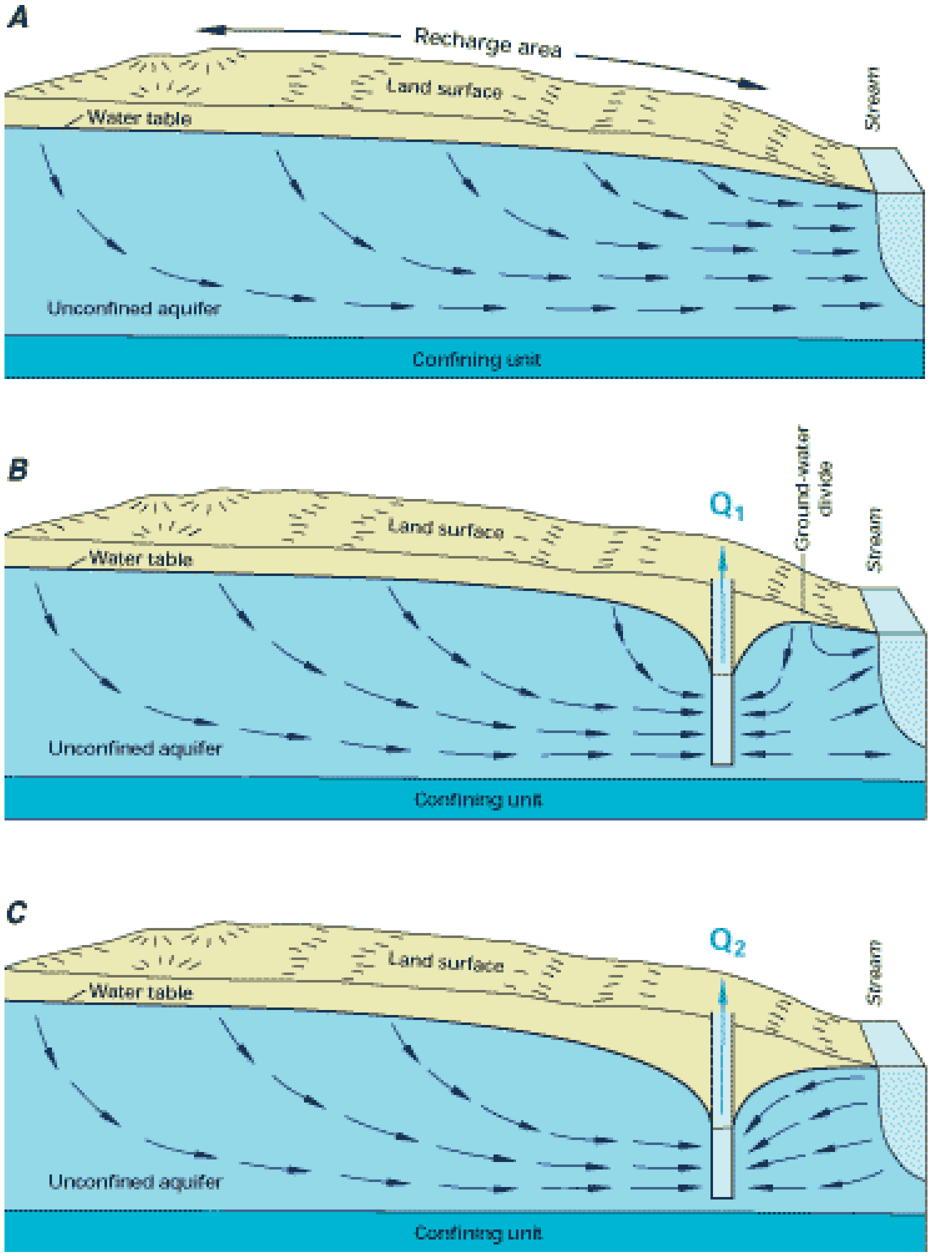


Figure 18: Water table impact of a water well pumping at low flow (B) and high flow (C). At high flow, water from the stream is sucked into the well.
Source: pubs.usgs.gov/circ/circ1186/html/gw_effect.html, public domain

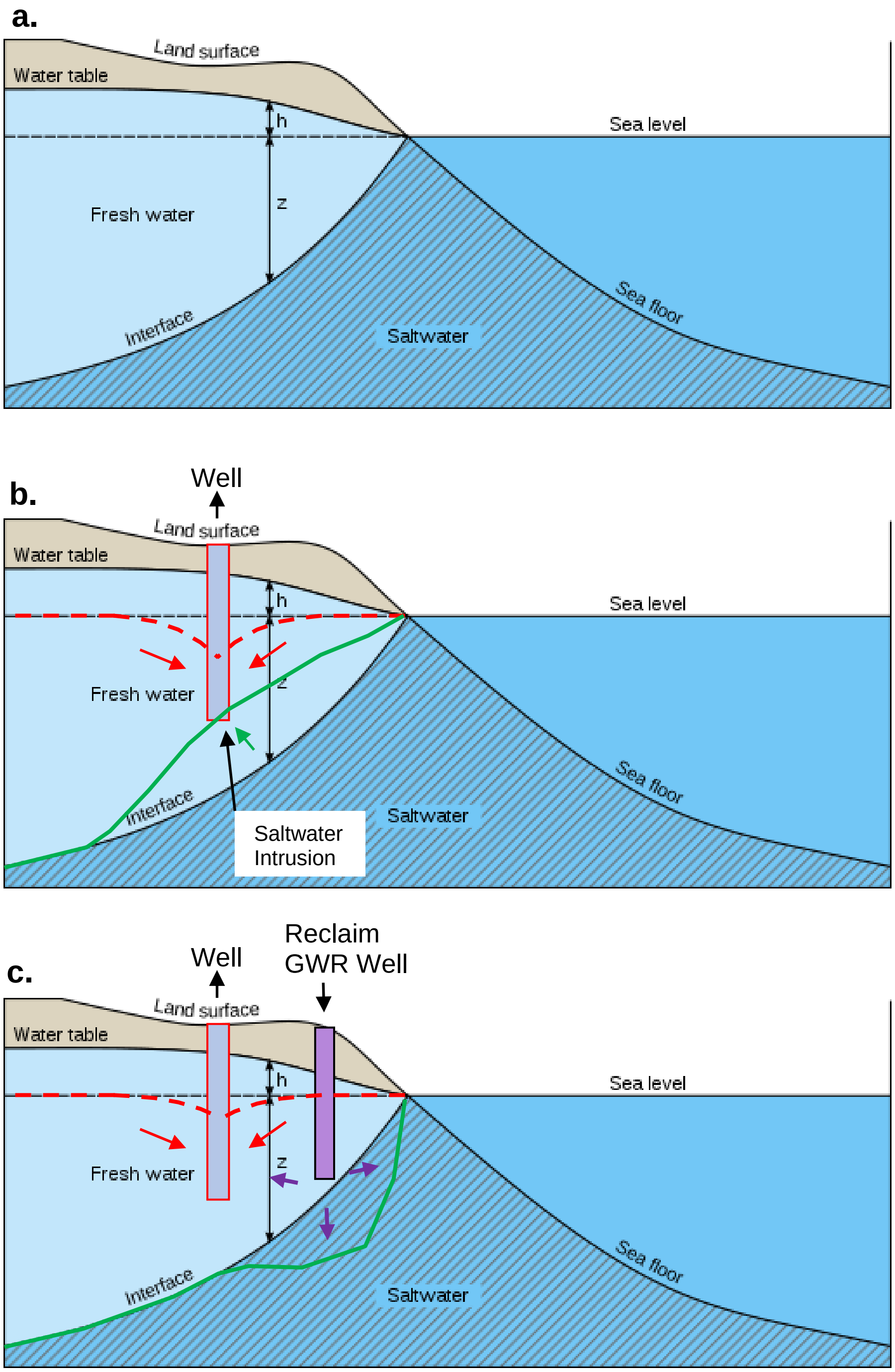


Figure 19: a) Natural saltwater interface. b) Raw water well added with resulting modified saltwater interface in green. c) Reclaim groundwater recharge (GWR) well added, with resulting modified saltwater interface in green.

Source: commons.wikimedia.org/wiki/File:Saltwater_intrusion_en.svg (Modified), Jooja, CC-BY-SA-4.0

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