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WATER, REUSE

An essentially constant supply of water is available for utilization by all living creatures; however, it is necessary to manage the water resources of a region in such a way that the available water meets all legitimate needs.

Use dictates the quality required. Potable water must be bacteriologically safe, and toxic substances must be present at levels that are accepted as safe (1–3) (see Table 1). In addition, the water must be aesthetically acceptable. Water that is suitable for drinking may be inadequate for many industrial processes. On the other hand, many industrial processes can use water that is not pure enough to drink.

Water consumption is constantly increasing. In 1950, U.S. industry consumed 290×10^6 m^3 H_2O/d (7.7×10^7 gal/d). By 1970, consumption had increased to 624×10^6 m^3/d (1.65×10^8 gal/d), and in 1980, to 964×10^6 m^3/d (2.55×10^8 gal/d) (4).

Formerly, water was accepted by a second user for reuse while it was still under control of the first user (5). Today, the used water is treated in such a manner that it can be used again before ultimate disposal. Furthermore, a distinction can be made between direct reuse, where the water is reclaimed without dilution or natural purification, and indirect use, where treated used water is returned to the environment for subsequent utilization as a raw water supply.

A notable example of controlled water reuse was utilization of secondary sewage effluent from the Back River Wastewater Treatment Plant in Baltimore by the Sparrows Point Works of Bethlehem Steel (6). The Sparrows Point plant was supplied primarily by wells located near the brackish waters of Baltimore harbor. Increased draft on the wells had led to saltwater intrusion. Water with chloride concentration as high as 10 mg/L is unsuitable for many steelmaking operations. Rollers, for example, are pitted by such waters. However, treated effluent from the Back River Plant can be used for some operations, such as coke quenching, and $>4 \times 10^5$ m^3/d (10^8 gal/d) are piped 13 km to Sparrows Point. This arrangement has proved economical to both parties for >40 yr.

Water can seldom be reused directly. The treatment required depends on the intended second use. Disposal costs of the wastewater must be included in any economic analysis, and additional treatment for reuse may be justified when this expense is included. Costs of reclamation depend on the location, water scarcity, availability of public water supplies, and the intended reuse.

Owing to increased public awareness of water pollution, stringent waste-disposal regulations have been introduced, and best available technology (BAT) had to be applied to industrial wastewater treatment by the mid-1980s (7). The cost–benefit analyses in BAT applications are controversial. Whereas three decades ago waste disposal was indicated only by an arrow in the process flow diagram, today it is a significant part of the operating costs. Pure water is expensive, and high quality sources are becoming more scarce. It is frequently necessary to accept lower quality water and subject it to costly treatment. Used water as a source of raw water supply has long been permitted by public health authorities in water-poor areas. However, in regions with an ample supply of fresh drinking water, there is resistance to the inclusion of reused water. A Gallup Poll indicated a 50% opposition to the use of reclaimed water in drinking water (8).

Conventional secondary wastewater treatment does not produce an effluent suitable for direct reuse, and a tertiary treatment step is required. Secondary treatment reduces BOD, COD (chemical oxygen demand),

Table 1. Maximum Allowable Concentrations of Significant Constituents in Municipal (Domestic) Water Supplies[a]

Constituent	μg/L	Constituent	μg/L
arsenic	50	manganese	50
barium	1,000	mercury	2
cadmium	10	methoxychlor	100
chromium	50	nitrate (nitrogen)	10,000
copper	1,000	phenol	1
endrin	0.2	selenium	10
iron	300	silver	50
lead	50	toxaphene	5
lindane	4		

[a] Ref. 2.

and $\geq$90% of suspended solids. Microbial concentrations are greatly reduced, and remaining organic material in the effluent is further decomposed by natural processes. Some nitrogen and phosphorus compounds are not removed and may cause eutrophication in the receiving waters. Contaminants that cannot be removed by conventional means are termed refractory, and they range from simple inorganic salts to complex organic substances such as pesticides, herbicides, and surfactants. Recycling of effluents from wastewater treatment plants in an essentially closed system normally would result in unacceptably high concentrations of many undesirable substances. The components of typical tap water are compared with those of a secondary effluent in Table 2 (9).

Continued recycling of effluent would soon give an unusable product, and tertiary treatment, although expensive, is essential. In some instances, considerable amounts of water can be saved by careful housekeeping and process change.

In many cases, the quality of a stream or another water source can be adequately improved by removing more BOD or suspended solids. In other instances, the effluent is prepared for groundwater recharge which may require only the removal of nutrient. A classification of wastewater treatment processes is given in Table 3. Table 4 summarizes water quality criteria for various industrial uses (10).

1. Tertiary Treatment

1.1. Chlorination

Chlorination kills bacteria and is routinely included in secondary treatment. For some special uses, it gives a water quality that is acceptable for blending with other water in storage reservoirs.

1.2. Chemical Precipitation

When applied after conventional secondary treatment, chemical precipitation removes heavy metals and gives a high quality effluent. In this process, an insoluble compound is formed and the resulting precipitate allowed to settle. Charges on colloidal particles are neutralized, and particles agglomerate. The resulting floc sweeps other material, including bacteria, from suspension. Phosphates are removed by addition of soluble aluminum or iron salts. Insoluble aluminum phosphate or ferric phosphate are formed, but the removal may require adsorption on hydroxide floc. Addition of lime is the cheapest and most easily controlled method. At high pH, lime, in addition to removing hardness, forms a precipitate of hydroxyapatite, $Ca_5(OH)(PO_4)_3$. Lime also assists in removing sulfides and fluorides. The sludge is putrescible and a nuisance source, and disposal is difficult.

Table 2. Increase of Tap Water Components in Wastewater[a]

Component	Tap water, mg/L	Secondary wastewater, mg/L	Difference, mg/L
BOD	2	20	18
COD	12	100	88
alkylbenzenesulfonates	0.4	6.8	6.4
cations			
Na^+	50	125	75
K^+	3	13	10
NH_4^+	0.1	16	15.9
Ca^{2+}	42	60	18
Mg^{2+}	16	19	3
anions			
Cl^-	66	143	77
NO^{-3}	5	12	7
NO_2^-	0.15	1.5	1.3
HCO_3^-	198	296	98
CO_3^{2-}	0.1	1	1
SO_4^{2-}	56	84	28
SiO_3^{2-}	29	43	14
PO_4^{3-}, total	8.1	25	17
PO_4^{3-}[b]	0.3	25	25
hardness[c]	158	235	77
alkalinity[c]	164	242	78
total dissolved solids	382	700	318
pH	8.0	7.4	−0.6

[a] Ref. 9.

[b] Other than orthophosphates.

[c] As $CaCO_3$.

Table 3. Wastewater Treatments[a]

Process	Substance treated or removed
Biological	
conventional secondary treatment	suspended solids, BOD, bacteria
conventional process modifications	suspended solids, BOD, bacteria, nutrients
anaerobic denitrification	nitrates
algae harvesting	nitrates and phosphates
Chemical	
ammonia stripping	ammonia nitrogen
ion exchange	nutrients
electrodialysis	salts
chemical precipitation	suspended solids and phosphates
Mechanical	
activated carbon adsorption	organic matter and suspended solids
sedimentation	suspended solids and bacteria
filtration	suspended solids and bacteria
microstrainers	very small particles
reverse osmosis	salts
distillation	salts
foam separation	detergents
vapor-compression evaporation	concentration of wastewater
wasteheat evaporation	concentration of wastewater
steam stripping	hydrogen sulfide and ammonia

[a] Ref. 7.

Table 4. Industrial Water Quality Limits[a]

Industry	Turbidity, units	Color, units	Hardness	Temperature, °C	pH	TDS	SS	SiO_2	Fe	NaCl	Cl	SO_4	Alkalinity
textiles (SIC 22)	0.3–5	0–5	0–50			100–200	0–5	25	0–0.3	0.01–0.05	100	100	50–200
pulp and paper (SIC 26)													
fine paper	10[b]	5	100			200		20	0.1	0.03			75
kraft paper													
bleached	40[b]	25	100			300		50	0.2	0.10	200		75
unbleached	100[b]	100	200			500		100	1.0	0.50	200		150
groundwood papers	50[b]	30	200			500		50	0.3	0.10	75		150
soda and sulfite paper	25[b]	5	100			250		20	0.1	0.05	75		75
chemicals (SIC 28)		500	1,000	[c]	5.5–9.0	2,500	10,000	[c]	10	2.00	500	850	500
petroleum (SIC 2911)		25	900		6.0–9.0	3,500	5,000	85	15		1,600	900	500
iron and steel (SIC 33)				38	5.0–9.0		100[d]						
food canning (SIC 2032, 2033)		5	250		6.5–8.5	500	10	50	0.2	0.20	250	250	250
tanning (SIC 3111)													
tanning processes	[e]	5	150		6.0–8.0				50		250	250	[c]
finishing processes	[e]	5	[f]		6.0–8.0				0.3	0.20	250	250	[c]
coloring	[e]	5	[e]		6.0–8.0				0.1	0.001			[c]
soft drinks (SIC 2086)		5	[g]		[g]	[g]			0.3	0.05	500	500	85

[a] From Ref. 10; units are mg/L unless otherwise specified. Abbreviations: TDS, total dissolved solids; SS, suspended solids.
[b] Units in mg/L as SiO_2.
[c] Not considered a problem of concentrations encountered.
[d] Settleable solids.
[e] Not detectable by test.
[f] Lime softened.
[g] Controlled by treatment for other constituents.

1.3. Filtration

Filtration is usually a misnomer for tertiary processes that remove particulate matter. Small particles are removed by adsorption rather than by physical straining. If secondary effluents contain a high concentration of solids, filter beds clog and binding occurs at the bed surface. Energy losses become high, and short circuiting passage of dirty water. Sand, mixed media, and diatomaceous earth are the most common filter materials.

Rapid sand filters have a limited use in tertiary wastewater treatment. Suspended solids accumulate in the filter bed, and BOD in the water is reduced. Adsorbed foreign matter is removed by backwashing; frequency depends on the surface application rate and concentration of suspended material. For backwashing, water may be used alone at a rate of 100–120 mL/$(\text{cm}^2{\cdot}\text{min})$ (25–30 gal/$(\text{ft}^2{\cdot}\text{min})$), or a combination of air and water may be used, with water applied at a rate of 40–60 mL/$(\text{cm}^2{\cdot}\text{min})$ (10–15 gal/$(\text{ft}^2{\cdot}\text{min})$) and air at ca 120 mL/$(\text{cm}^2{\cdot}\text{min})$ (30 gal/$(\text{ft}^2{\cdot}\text{min})$). Air serves to thoroughly agitate the filter. Particle range of the medium is 0.5–0.8 mm, bed depth is ca 60 cm, and the application rate of raw water is 8–10 mL/$(\text{cm}^2{\cdot}\text{min})$ (2–2.5 gal/$(\text{ft}^2{\cdot}\text{min})$). Most of the particles are removed in the upper part of the filter, and bed porosity in this region decreases rapidly as the filtration progresses, excessive head loss results, and the filter clogs. Effective filter depth can be increased by mixed media, with the lightest and coarsest material at the top and the heaviest and least porous at the bottom. This is the opposite of the case where the bed contains material of constant density. In a mixed-media filter, three or more materials are used, including coal, sand, and garnet, with specific gravities of 1.65, and 2.65, and 4.00, respectively. Coal has the greatest porosity and garnet the least. After backwashing, where the filter acts as a fluidized bed, the filter materials stratify and the coal is on top. The resulting particles are graduated from ca 1 mm at the top to 0.15 mm at the bottom, and the entire filter bed is utilized for particulate removal. The garnet at the bottom forces the water to pass a much finer barrier than that provided by sand alone, whereas the coal layer does not clog as readily. Filter depths are 60–75 cm, and application rates of 4–120 $\mathrm{mL/(cm^2{\cdot}min)}$($1$–$30\ \mathrm{gal/(ft^2{\cdot}min)}$) are common.

In diatomaceous-earth filtration, the powdered filter aid is built upon a relatively loose septum to screen out suspended solids. The filter becomes clogged, and pressure losses become excessive; backwashing is then necessary. The smallest removable particle is 0.5–1 μm (see Diatomite).

Both vacuum and pressure filters are used. Turbidity is more easily removed by vacuum filters, usually at 85% efficiency. Flow rates are low, ca 4 $\mathrm{mL/(cm^2{\cdot}min)}$ [1 $\mathrm{gal/(ft^2{\cdot}min)}$]; these filters are not practical for treating large volumes.

1.4. Microstrainers

Microstrainers are rotating steel screens with extremely fine stainless steel mesh (85–170 perforations per square centimeter (13–26/in.^{2})). The flowing liquid enters the open end of the drum and passes through the mesh to the effluent end. The mesh traps solid impurities and rotates with the drum. A wash-water spray washes the trapped solids into a hopper for final disposal. The mesh is washed with filtered effluent discharged from jets fitted into the drum and then exposed to uv radiation to inhibit microbial growth. The mesh is washed with chlorine water at intervals of 7 to 28 days in order to control slime growth; removal efficiencies are 30–55% of the applied BOD and 40–60% of suspended solids.

1.5. Effluent Polishing

The term polishing is sometimes applied to the preparation of effluents of exceptional clarity. Plant effluent is collected in a sump and pumped through a tube-settling unit, followed by mixed-media filtration. Filter effluent is collected in a storage tank, which also serves as a reservoir for backwash water. The tank further acts as a chlorine-contact chamber. The tube settler is a supplemental solids-separation device which allows the filter to operate efficiently during severe operational upsets, such as excessive loading of organic matter or increased hydraulic loading. In such instances, the bulk of the suspended solids in the plant effluent is removed in the tube settler and the filter is not overloaded. These installations produce an effluent low in BOD and suspended solids. The polishing units continue to function well when suspended solids are loaded at a rate of 2 g/L (0.12 oz/gal). The tube settler and mixed media can be used for phosphate removal after suitable treatment for coagulation and flocculation.

1.6. Foam Separation

Conventional secondary treatment cannot remove detergents that resist biological treatment such as alkylbenzenesulfonates. Although ABS has been almost completely replaced by linear alkylbenzenesulfonates in household detergents, foam (qv) continues to be a problem. Foam-separation techniques have been applied for removing refractory matter such as organic hydrates and nitrogen compounds (11). A sparger disperses small bubbles of gas, usually air, throughout the waste. The rising gas collects suspended solids and surface-active substances while the foam collects at the liquid–liquid interface. It is removed and collapsed to yield a waste concentrate.

For small installations, column foam separators are more suitable. Waste flows downward in the column whereas gas spargers, located at the bottom, give countercurrent flow. The foam generated is carried upward to a foam breaker and collector.

Through-type separators are more effective for larger municipal and industrial treatment facilities. The operating principles are the same, but flow is through a trough rather than a column.

1.7. Activated-Carbon Adsorption

Treatment of waste by activated-carbon adsorption has shown promise of becoming an important tertiary treatment process. It has long been applied for the removal of tastes, odor, and color but has not been suitable for treatment of effluents containing high concentrations of organic matter because of rapid decrease of surface area. As the surface of the carbon becomes coated with adsorbed material, less surface area is available for further adsorption. Activated carbon is available either as fine powder or granules. Use of the latter is preferred for wastewaters. In a packed-bed installation, water is passed through a column filled with activated-carbon particles, and the organic content of the water is reduced along the path of flow. However, the carbon at the influent end becomes exhausted and must be regenerated. A fluidized bed gives more uniform concentration gradient throughout the bed. Packed beds accumulate solids more rapidly than fluidized beds. Activated-carbon adsorption can remove 80% of the COD and 70% of BOD. Regeneration of carbon is accomplished in multistage hearth furnaces in a steam–air mixture at 76°C. Approximately 5% of the carbon is lost in regeneration.

1.8. Ion Exchange

Ion exchange (qv) is a method of softening hard water. Calcium and magnesium are exchanged for a cation, usually sodium. Ion-exchange beds can remove 95% of phosphate, 85% of nitrates, 100% of sulfates, and 45% of COD. Color and organic matter are efficiently removed by cationic and anionic mixed beds, but the latter tend to foul the beds. Cost and frequency of regeneration are principal disadvantages of ion exchange.

1.9. Oxidation Ponds

Oxidation ponds, or sewage lagoons, long popular in Europe, now also find wide application in North America. Careful design is necessary for successful operation. Although oxidation ponds are, in essence, large open ponds into which waste is led, careful planning allows natural purification processes to proceed in an orderly manner giving a stable and high quality effluent. The main disadvantage is production of odors offensive to nearby residents. In addition, relatively large areas are required.

Many facilities utilize air diffusers or surface aerators for supplying additional oxygen. The capacity of an oxidation pond is mostly a function of the oxygen transferred from the atmosphere to the pond water but also depends on other physical and biological variables. These ponds, usually designed for 2.2–3.3 gBOD/$(\mathrm{m}^2 \cdot \mathrm{d})$ (6.5–9.7 oz/$(\mathrm{acre} \cdot \mathrm{d})$), are ca 1.2 m deep. Mixing is very important. If waste material were uniformly distributed throughout the pond, the oxygen demand would be constant throughout the pond. This is, however, not the case, and oxygen requirements vary from area to area. The processes involved in waste stabilization are mostly aerobic, but facultative organisms are dominant at the bottom of the pond. Most of the oxygen is transferred from the surface, but additional oxygen may be added by aerators and diffusers; most surface aerators operate intermittently (12). Natural surface agitation is important, and prevailing wind direction must be considered for surface aeration as well as deflection of odors affecting downwind residents. The pond must be deep enough to avoid weed problems but shallow enough to allow sunlight to penetrate. Algae maintain aerobic conditions. The pond functions as a sedimentation basin, and it may be necessary to periodically remove deposited solids.

Current practice is to feed influent at the pond center and withdraw effluent at the periphery. Multiple ponds are used in series (7, 8).

Water discharged from an oxidation pond may be used directly for low quality industrial purposes or mixed with other waters (13).

1.10. Reverse Osmosis

In reverse osmosis (qv), a solution or suspension flows under pressure through a membrane; the product is withdrawn on the other side. This process can treat dissolved solids concentrations ranging from 1 mg/L to 35 g/L (14). The principal constraint is the requirement that the waste material be relatively nonfouling. Recent advances have been mostly in membrane development, and pilot studies are required (15). Energy costs can be significant, and it is frequently necessary to pretreat influent in order to minimize fouling. Reverse osmosis can deal with particles <1 to 600 nm in size.

1.11. Electrodialysis

In reverse osmosis pressure achieves the mass transfer. In electrodialysis (qv), dc is applied to a series of alternating cationic and anionic membranes. Anions pass through the anion-permeable membranes but are prevented from migrating by the cationic permeable membranes. Only ionic species are separated by this method, whereas reverse osmosis can deal with nonionic species. The advantages and disadvantages of reverse osmosis are shared by electrodialysis.

1.12. Vapor-Compression Evaporation and Waste Heat Evaporation

Both of these processes remove water from contaminants rather than contaminants from water. They are better suited for industrial installations where excess energy is available. The water thus produced is of high quality and can be used directly. An important advantage is the concentration of waste-residue volume with attendant economies of handling and transportation (see Evaporation).

The saturation temperature of a vapor rises when it is mechanically compressed and its latent heat is available at a higher temperature. Application of this heat to an aqueous stream evaporates part of the water, producing a distillate of pure water. Application of vapor compression has grown significantly since 1960.

Cooling loads can be transferred from process heat exchangers to a wastewater-evaporation system, thus reducing cooling-water requirements and total wastewater volume.

In both processes, care must be taken in dealing with organic compounds that either steam distill or form azeotropes.

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Related Articles

Water, municipal water treatment; Water, industrial water treatment; Water, Pollution; Reverse osmosis; Activated carbon