

WATER AND WASTEWATER TREATMENT

C9 1B

TITLE: WATER RESOURCES AND MANAGEMENT

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Global Water Cycle and Sources of Supply

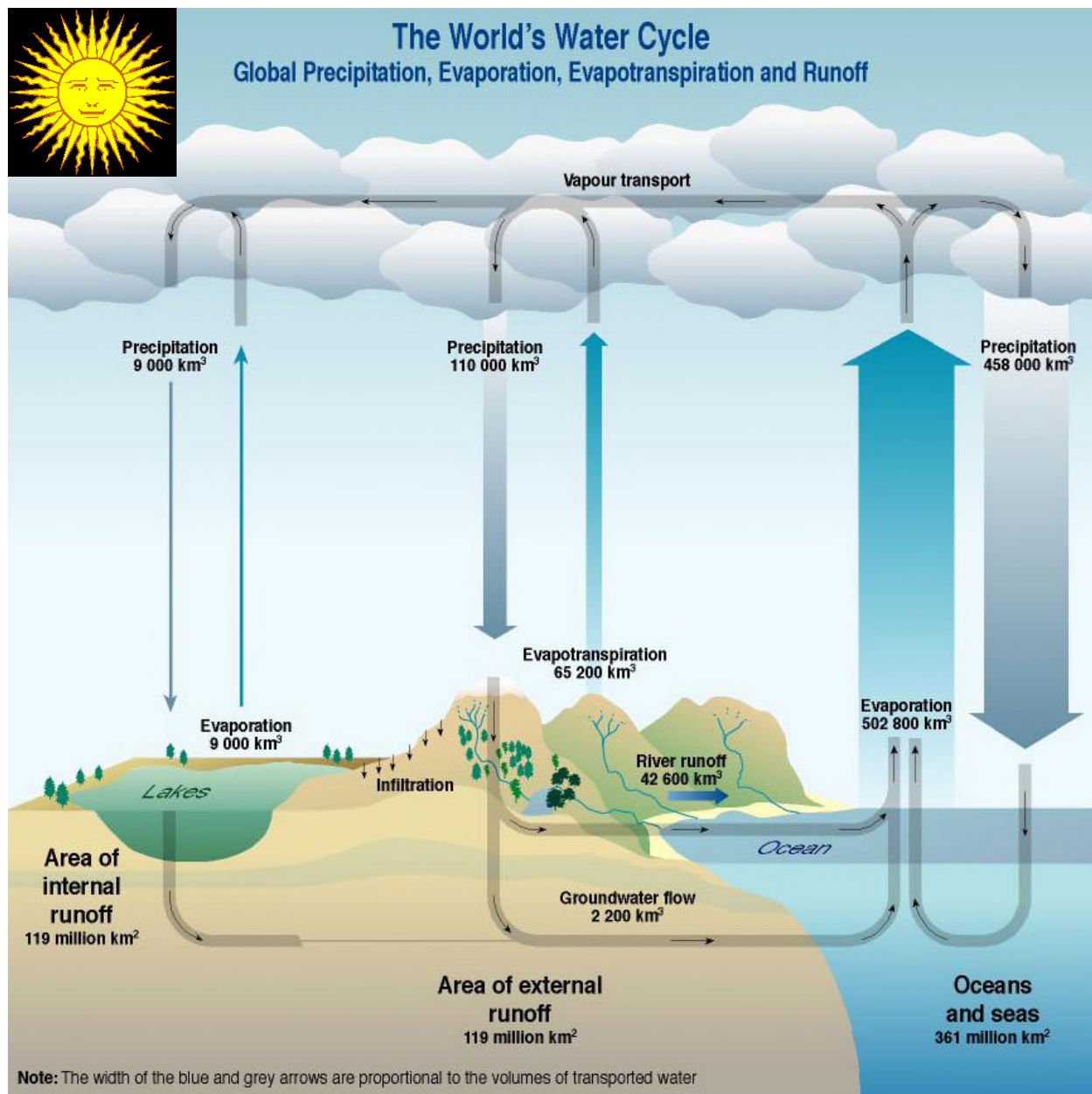
Facts & Figures about the World's Freshwater

- Water covers 71% of the Earth's surface. The total amount of water on Earth remains about the same from one year to the next, as it circulates between the oceans, land and atmosphere in a cycle of evaporation and precipitation. This hydrological cycle is fundamental to the functioning of the Earth as it recycles water, and has a role in modifying and regulating the Earth's climate.
- Nearly 97% of the Earth's water is in the oceans. Freshwater makes up less than 3% of water on earth, and over two-thirds of this is tied up in polar ice caps and glaciers. Freshwater lakes and rivers make up only 0.009% of water on Earth and groundwater makes up 0.76%.
- Water is essential for all life forms. For example, it makes up 60 to 70% by weight of all living organisms and is essential for photosynthesis. The viability of all life on Earth is determined chiefly by the presence of water.

Source:BBC Science & Nature Homepage.

(<http://www.bbc.co.uk/nature/environment/conservationnow/global/freshwater/>)

Water cycle



The driving force for the global water cycle is the Sun.

The Sun lifts the water into the atmosphere by *evaporation* and *transpiration* (evapotranspiration)

Water returns to the earth by *precipitation* (e.g. rains, snows).

Water either runs over the ground into streams and rivers as *runoff* or percolates into the ground to form the *groundwater*.

Global water stocks

Major stocks of water on earth (thousand cubic kilometres)

	Volume (1000 km ³)	Percentage of total water	Percentage of total fresh water
Saltwater stocks			
Oceans	1 338 000	96.54	
Saline/brackish groundwater	12 870	0.93	
Saltwater lakes	85	0.006	
Total salt water stocks	1 350 955	97.476	
Freshwater stocks			
Glaciers, permanent snowcover	24 064	1.74	68.7
Fresh groundwater	10 530	0.76	30.06
Ground ice, permafrost	300	0.022	0.86
Total frozen and underground freshwater stocks	34 894	2.522	99.62
Freshwater lakes	91	0.007	0.26
Soil moisture	16.5	0.001	0.05
Atmospheric water vapour	12.9	0.001	0.04
Marshes, wetlands*	11.5	0.001	0.03
Rivers	2.12	0.0002	0.006
Incorporated in biota*	1.12	0.0001	0.003
Total not frozen or underground freshwater stocks	135	0.0103	0.389
Total freshwater stocks	35 029	2.5323	100
TOTAL WATER ON EARTH (1000 km³)	1 385 984	100	

Source:
Adapted from
Peter H. Gleick,
*The World's Water
2000-2001*,
Washington, D.C.
Island Press, 2000.

Note:
Totals may not
add due to rounding

*Marshes, wetlands
and water
incorporated in
biota are often
mixed salt and
fresh water.

Globally seems enough water, but locally a serious problem.

Increased global water stress: > 2.8 billion people in 48 countries will face water stress, or scarcity conditions by 2025.

Most of the world still does not have centralized water supply with connections to individual households According to the World Health Organization roughly 1 billion of the world's 6 billion people do not have access to an improved water supply.

(JMC, 2000. Global Water Supply and Sanitation Assessment 2000 Report. WHO and UNICEF Joint Monitoring Programme for Water Supply and Sanitation, World Health Organization and United Nations Children's Fund,

http://www.who.int/docstore/water_sanitation_health/Globassessment/Global2.1.htm).

Access to water-supply services is defined as the availability of at least 20 litres per person per day from an "improved" source within 1 kilometre of the user's dwelling. An "improved" source is one that is likely to provide "safe" water, such as a household connection, a borehole, etc.

(JMC, 2004. The Joint Monitoring Programme: definitions. WHO and UNICEF Joint Monitoring Programme for Water Supply and Sanitation, World Health Organization and United Nations Children's Fund, http://www.wssinfo.org/en/122_definitions.html)

Only 48% of the world's population is connected at the household level. (JMC, 2004. Water supply data at global level. WHO and UNICEF Joint Monitoring Programme for Water Supply

and Sanitation, World Health Organization and United Nations Children's Fund,
http://www.wssinfo.org/en/22_wat_global.html).

How much water do we need?

For survival 5 litres/person/day
For modern lifestyles 40 litres/person/day
For current lifestyles 80 litres/person/day

Where does all our water go?

35% down the loo
15% in the bath
5% in the shower
15% down the kitchen sink
12% through the washing machine
8% down the wash basin
6% on our gardens and over our cars
4% as drinking water!
 NB all this is drinking quality water

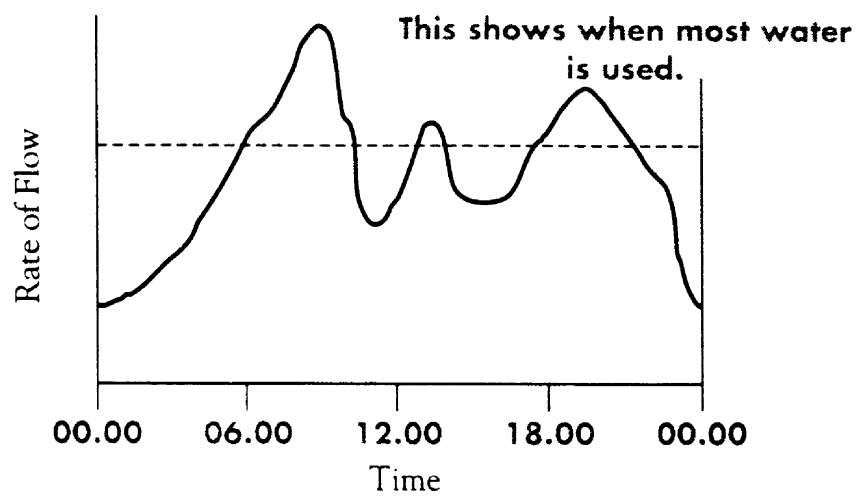
Product	Water required/litres
fresh meat – beef	16 000
fresh meat – lamb	10 000
poultry meat	6000
Rice	3000
palm oil	2000
cereals	1500
citrus fruit	1000
pulses, roots and tubers	1000

Possible solutions to water stress:

- Transport water over long distance, from water abundant regions to water stress region;
- Virtual water trade;
 - Instead of transport water itself, import food and industrial goods which produced from water abundant region
 - The weight of traded goods is 1/100-1/1000 of the weight required to produce the goods
 - However, the economy of water stress region may be weak to afford the trades
- Advanced technology, e.g. more efficient way to produce food and goods, desalination;
- Management, recycle water, e.g. 80% water used in industrial sectors in Japan is recycled.

Average water consumption

Average water consumption



Sources of Supply

Rainfall

Streams and rivers

Groundwater aquifers

Storage

Rivers and Lakes

Groundwater aquifers

Reservoirs

Microbiological, Chemical and Indicator Characteristics of Raw and Treated water

Introduction

The chemical examination of a water can indicate the possible past history and whether it has been, or is now polluted. Certain criteria are required for waters intended for human consumption so that the final product going into supply is pure and wholesome: Substances that are potentially harmful to the consumer have to be limited and substances and properties which affect the general acceptability of the water have to be controlled. The World Health Organisation,(WHO) Guidelines for Drinking Water of 1993 is used universally and is the basis for both EU and USA legislation. The revision of the WHO guideline led to the revision of the EC Drinking Water Directive and the adoption of a completely new Directive (98/83/EEC)

The following four categories are used to describe drinking water quality:

Physical: Physical characteristics are usually associated with the appearance of water, its colour or turbidity, temperature, taste and odour.

Chemical: Chemical characteristics are identified by observing chemical reactions, such as hardness. Most often, they are not visible.

Microbiological: Microbes in water are very important to human health.

Radiological: Radiological factors must be considered, especially in areas where water resources may have possibility to contact with radioactive materials.

Physical Parameters

Taste and Odour

Taste, like odour, is a subjective test, which relies upon description rather than quantitative results. There are many potential causes of tastes and odours in water, the principal ones being algae, decaying vegetable matter, products resulting from chlorination, such as chlorophenols, excessive iron and manganese in solution and stagnant water in dead ends of the distribution system.

Turbidity

Turbidity is an indication of the clarity of a water and is defined as the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through a sample of water.

Colour

Colour in an un-polluted water can be caused by humic and peaty material and by naturally occurring metallic salts; usually of iron and manganese. Waters subject to industrial pollution can also contain a wide variety of coloured material. The colour of a water is usually expressed in Hazen units, which are the same as the platinum-cobalt scale.

Conductivity

Conductivity is a measure of water's ability to conduct an electric current. This is linked to the concentration of mineral salts in solution. It is controlled by the degree to which these salts dissociate into ions, the electrical charge on each ion and temperature. Often used as a measure of pollution in raw water.

Chemical Parameters

Hardness

Total hardness consists of carbonate, or temporary hardness and non-carbonate, or permanent, hardness. Temporary hardness is precipitated by boiling and forms the scale found inside kettles. Permanent hardness is due to calcium and magnesium sulphates and chlorides, which are not precipitated on heating. Hardness is usually expressed in mg/l as CaCO_3 .

Total hardness is determined by titration with a standard solution of the disodium salt of ethylenediamine tetra acetic acid (EDTA). Temporary hardness is determined by titration using methyl orange or phenolphthalein.

The problems caused by excessive hardness are mainly economical in terms of scale formation in boilers and hot water systems. Conversely, waters softer than 30-50mg/l tend to be corrosive and should always be examined for plumbsolvency (liability to take lead into solution).

Nitrite and Nitrate

Nitrite (NO_2) and nitrate (NO_3) are usually expressed in terms of nitrogen, i.e.N. The total oxidised nitrogen is the sum of nitrite and nitrate nitrogen. Nitrite is an intermediate oxidation state of nitrogen in the biochemical oxidation of ammonia to nitrate and in the reduction of nitrates under conditions where there is a deficit of oxygen.

Nitrate is the final stage of oxidation of ammonia and the mineralization of nitrogen from organic matter.

Whilst the presence of nitrites in a groundwater may be a sign of sewage pollution, it may have no hygienic significance.

Waters containing high nitrate concentrations are potentially harmful to infants and young children.

Chlorine

Chlorine gas is used as a biocide and disinfectant in water. The maximum amount of residual chlorine, which may be permitted in a water going into supply, depends upon the taste, odour and corrosion that may result.

Fluoride

Fluoride may occur naturally in a water or it may be added in controlled amounts during the treatment process. It is now generally accepted that fluoridation of water supplies to a level of 1 mg/l F is both safe and effective in substantially reducing dental caries.

Fluoride levels have to be closely controlled as excessive amounts can lead to fluorosis with resultant mottling of the teeth and even skeletal damage in both children and adults.

Lead

Lead is rarely found naturally in concentrations greater than 10 µg/l but in many areas where soft acidic water resources are used high values of lead are common. This is because most houses built before 1964 will have some lead pipes. Plumbsolvency (the ability of water to dissolve lead) increases rapidly as water becomes more acidic.

Lead attacks the nervous system. Those most at risk are young children, unborn babies and people with kidney diseases who need to use dialysis.

Mercury

Along with many other inorganic and organic chemicals, mercury is a toxic material. High safety factors are used in setting the allowable level of concentration as the long term effects of very low levels of exposure are not easily quantifiable.

Other toxic compounds include arsenic, cyanide, lead, pesticides and trihalomethanes.

Microbiological Parameters

Sampling is done exclusively at consumer's taps and the water must be free from any diseases-producing organisms (*pathogens*). These organisms include virus, bacteria, protozoa, and helminths (worms), which constitute a potential danger to human health.

Total Coliform Test: A main test, which is for *coliform* group (*Escherichia Coli* (*E. coli*) and *Aerobacter aerogenes*)

E.coli is usually associated with animals;

Aerobacter aerogenes are common in the soil, leaves, and grains; they may cause urinary tract infections.

The most common water-borne protozoa are *Giardia cysts* and *cryptosporidium oocysts*, which are associated with animals.

Two techniques are principally used, *membrane filtration* and *multiple tube* methods. The EC drinking water directive specifies that total and faecal coliforms, and faecal streptococci must be isolated using the membrane filtration method, while the multiple tube method is used for clostridia.

Membrane filtration

Known volumes of water are passed through a sterile membrane filter with a pore size of just 0.45 µm to retain all the bacteria present. The membrane filter is placed onto a special growth medium, which allows the individual bacteria to grow into colonies. For total coliforms the membrane filter is placed onto a membrane-enriched teepol medium which contains the detergent teepol to inhibit non-intestinal bacteria from growing. The membrane filter on the culture medium is then incubated. During this incubation period the nutrients diffuse from the culture medium through the membrane and the coliform bacteria are able to multiply and form recognisable colonies which can be counted. Membranes are incubated at 30°C for 4 hours followed by 14 hours at 37°C for total coliforms or 14 hours at 44°C for *E. coli*.

Faecal streptococci are determined using the same technique except that different culture media and incubation conditions are required.

Multiple tube

The principle of the test is that various volumes of sample water are inoculated into a series of tubes containing a liquid medium that is selective for coliform bacteria. From the pattern of positive and negative growth responses in the dilution series, a statistical estimate of the number of coliforms and subsequently *E. coli* can be made. This is called the most probable number (MPN) estimate, which is calculated by reference to probability tables. The MPN is expressed as the number of cells per 100 ml of sample.

Radiological Parameters

The development and use of atomic energy as a power source, mining of radioactive materials, naturally occurring radioactive materials could contaminate drinking resources.

Indicator Parameters

Aluminium

Aluminium occurs in many natural waters in detectable amounts. The most usual sources of aluminium in drinking water, however, come from corrosion of aluminium utensils, tanks or pipes or from the incorrect dosing of aluminium sulphate as a coagulant at the treatment works. The concentration of aluminium in drinking water is of importance for sufferers of kidney diseases who have to use dialysis.

Ammoniacal Compounds

Ammonia is one of the forms of nitrogen found in water and is usually expressed in terms of Mg/l N. Free ammonia, which is the same as free and saline ammonia or ammoniacal nitrogen. It is so called because it exists either in the free state or as saline ammonium ion depending upon pH value. Albuminoid ammonia is the additional fraction liberated from organic material in the water by strong chemical oxidation. Ammoniacal compounds are found in most natural waters. They originate from various sources, some of which are completely harmless, for example decomposing vegetation. Deep well waters which are of good organic quality can contain high levels of free ammonia caused by the reduction of nitrates, either by bacteria or by the surrounding geological strata. However, ammonia can also indicate recent pollution by either sewage or industrial effluent. The amount of ammonia in a raw water is of importance in determining chlorine doses for disinfection.

Chloride

High values indicate natural solution from rocks, pollution from domestic sewage or infiltration from seawater.

Hydrogen Ion Concentration (pH)

The pH value or hydrogen ion concentration, is a measurement of the acidity or alkalinity of a water. It is one of the most important determinations in water chemistry since many of the processes involved in water treatment are pH dependent.

An acid water is one, which has a pH value of less than 7.0. Acidity in an unpolluted water is usually from dissolved carbon dioxide which produces weak carbonic acid. There is no defined limit for acidity in water, the main requirement being that the water is non-corrosive. Alkalinity is almost entirely due to the bicarbonate, carbonate and hydroxide ions in the water, usually in association with calcium, magnesium, sodium and potassium.

Iron and Manganese

Both are extremely common metals and are found in large amounts in soil and rocks. Solubility depends largely on pH and redox potential and when brought into solution cause problems with taste and staining of laundry.

Suspended and Total Solids

Tested in raw water only as should be absent in treated water. Total solids give a good correlation with electrical conductivity.

Taste and Odour

Turbidity

EU quality standards

Extracts from Council Directive 98/83/EC, 1998 on the quality of water intended for human consumption Annex 1

Part A Microbiological parameters

Parameter	Parametric value (number/100ml) tap water	Parametric value (number/250ml) bottled water
Escherichia coli (E. coli)	0	0
Enterocci	0	0

Part B Chemical parameters

Parameter	Parametric value	Unit
Arsenic	10.0	µg/l
Cadmium	5.0	µg/l
Cyanide	50.0	µg/l
Fluoride	1.5	mg/l
Lead	10.0	µg/l
Mercury	1.0	µg/l
Nitrate	50.0	mg/l
Nitrite	0.5	mg/l
Pesticides - total	0.5	µg/l
Trihalomethanes	100.0	µg/l

Part C Indicator Parameters

Parameter	Parametric value	Unit
Aluminium	200	µg/l
Ammonium	0.5	mg/l
Chloride	250	mg/l
Colour	Acceptable to consumers and no abnormal change	
Conductivity	2500	µS/cm at 20°C
Hydrogen ion concentration	≥6.5 and <9.5	PH units
Iron	200	µg/l
Manganese	50	µg/l
Odour	Acceptable to consumers and no abnormal change	
Taste	Acceptable to consumers and no abnormal change	
Turbidity	Acceptable to consumers and no abnormal change	

RAW WATER CHARACTERISTICS

	CHALK BOREHOLE	LOWLAND RIVER	UPLAND RESERVOIR	
			Peaty catchment	rock catchment
Colour	None	Varies	Brown colour	Slight
Taste and odour	None	Bad	None	None
pH	Slightly alkaline	Neutral or slightly alkaline	Acidic	Neutral
Hardness	Very hard	Moderate to very hard	Soft	soft
Ammonia	Low	High	Low	Low
Mineral nutrients	High	High to very high	Low	Low
Man-made pollution	Normally absent	High	Low	Low
Bacteriological Quality	Good	Very poor	Fairly good	Fairly good

CHANGE IN WATER QUALITY DUE TO STORAGE

	River Thames at Oxford		River Great Ouse at Diddington	
	Raw water	Stored water	Raw water	Stored water
Colour (°hazen)	19	9	30	5
Turbidity	14	3.2	10	1.5
Ammoniacal Nitrogen (mg/l)	-	-	0.3	0.06
Nitrite N, (mg/l)			0.1	0.01
Nitrate N (mg/l)			0.1	0.01
BOD (mg/l)			4.5	2.5
Total hardness (mg/l)	300	259	430	280
E.coli MPN per 100ml	20000	100	1700	10

Water Pollutants and Their Resources

Water Pollutants Sources

Point sources:

Domestic sewage, Industrial wastes,

Non-point sources:

Agriculture runoff, Urban runoff

For examples:

Sewage, manure

nitrogen, phosphorus

pathogenic organisms

biodegradable chemicals – consume O₂

Fertilizers

nitrogen, phosphorus

Pesticides, oil

Toxic chemicals

Water pollutant category

Pathogenic organisms

Oxygen demanding materials

Nutrients

Suspended solids/sediments

Salts

Toxic metal

Toxic organic compounds

Endocrine disrupting chemicals

Heat

Water Management in Rivers

DO (dissolved oxygen): the amount of molecular oxygen dissolved in water

- Typical DO=8-15 mg/L
- Minimal recommendation >5 mg/L for healthy fish population

DISSOLVED OXYGEN CONCENTRATION VALUES AS A FUNCTION OF SALINITY AND BAROMETRIC PRESSURE*

SALINITY										
TEMP, °C	DISSOLVED OXYGEN CONCENTRATION, mg/L									
	SALINITY, PARTS PER THOUSAND									
	0	5	10	15	20	25	30	35	40	45
0	14.60	14.11	13.64	13.18	12.74	12.31	11.90	11.50	11.11	10.74
1	14.20	13.73	13.27	12.83	12.40	11.98	11.58	11.20	10.83	10.46
2	13.81	13.36	12.91	12.49	12.07	11.67	11.29	10.91	10.55	10.20
3	13.45	13.00	12.58	12.16	11.76	11.38	11.00	10.64	10.29	9.95
4	13.09	12.67	12.25	11.85	11.47	11.09	10.73	10.38	10.04	9.71
5	12.76	12.34	11.94	11.56	11.18	10.82	10.47	10.13	9.80	9.48
6	12.44	12.04	11.65	11.27	10.91	10.56	10.22	9.89	9.57	9.27
7	12.13	11.74	11.37	11.00	10.65	10.31	9.98	9.66	9.35	9.06
8	11.83	11.46	11.09	10.74	10.40	10.07	9.75	9.44	9.14	8.85
9	11.55	11.19	10.83	10.49	10.16	9.84	9.53	9.23	8.94	8.66
10	11.28	10.92	10.58	10.25	9.93	9.62	9.32	9.03	8.75	8.47
11	11.02	10.67	10.34	10.02	9.71	9.41	9.12	8.83	8.56	8.30
12	10.77	10.43	10.11	9.80	9.50	9.21	8.92	8.65	8.38	8.12
13	10.53	10.20	9.89	9.59	9.30	9.01	8.74	8.47	8.21	7.96
14	10.29	9.98	9.68	9.38	9.10	8.82	8.55	8.30	8.04	7.80
15	10.07	9.77	9.47	9.19	8.91	8.64	8.38	8.13	7.88	7.65
16	9.86	9.56	9.28	9.00	8.73	8.47	8.21	7.97	7.73	7.50
17	9.65	9.36	9.09	8.82	8.55	8.30	8.05	7.81	7.58	7.36
18	9.45	9.17	8.90	8.64	8.39	8.14	7.90	7.66	7.44	7.22
19	9.26	8.99	8.73	8.47	8.22	7.98	7.75	7.52	7.30	7.09
20	9.08	8.81	8.56	8.31	8.07	7.83	7.60	7.38	7.17	6.96
21	8.90	8.64	8.39	8.15	7.91	7.69	7.46	7.25	7.04	6.84
22	8.73	8.48	8.23	8.00	7.77	7.54	7.33	7.12	6.91	6.72
23	8.56	8.32	8.08	7.85	7.63	7.41	7.20	6.99	6.79	6.60
24	8.40	8.16	7.93	7.71	7.49	7.28	7.07	6.87	6.68	6.49
25	8.24	8.01	7.79	7.57	7.36	7.15	6.95	6.75	6.56	6.38
26	8.09	7.87	7.65	7.44	7.23	7.03	6.83	6.64	6.46	6.28
27	7.95	7.73	7.51	7.31	7.10	6.91	6.72	6.53	6.35	6.17
28	7.81	7.59	7.38	7.18	6.98	6.79	6.61	6.42	6.25	6.08
29	7.67	7.46	7.26	7.06	6.87	6.68	6.50	6.32	6.15	5.98
30	7.54	7.33	7.14	6.94	6.75	6.57	6.39	6.22	6.05	5.89
31	7.41	7.21	7.02	6.83	6.65	6.47	6.29	6.12	5.96	5.80
32	7.29	7.09	6.90	6.72	6.54	6.36	6.19	6.03	5.87	5.71
33	7.17	6.98	6.79	6.61	6.44	6.26	6.10	5.94	5.78	5.63
34	7.05	6.86	6.68	6.51	6.33	6.17	6.01	5.85	5.69	5.54
35	6.93	6.75	6.58	6.40	6.24	6.07	5.92	5.76	5.61	5.46
36	6.82	6.65	6.47	6.31	6.14	5.98	5.83	5.68	5.53	5.39
37	6.72	6.54	6.37	6.21	6.05	5.89	5.74	5.59	5.45	5.31
38	6.61	6.44	6.28	6.12	5.96	5.81	5.66	5.51	5.37	5.24
39	6.51	6.34	6.18	6.03	5.87	5.72	5.58	5.44	5.30	5.16
40	6.41	6.25	6.09	5.94	5.79	5.64	5.50	5.36	5.22	5.09

Oxygen demand: the amount of oxygen required to oxidize a waste

- Indirect measurement of the amount of organic (or carbon-containing) impurities in a water
- Most common

Biochemical oxygen demand (BOD): The amount oxygen required for microbes to degrade the wastes. Most useful for assess strength of organic pollution

Chemical oxygen demand (COD): The amount of oxygen required for chemically oxidizing the wastes

Theoretical oxygen demand (ThOD): The amount of oxygen required for completely oxidizing a organic matter to carbon dioxide and water.

Since some organic carbon are transferred into cellular materials, BOD is usually less than ThOD and COD.

Biochemical Oxygen Demand Measurement

- Take sample of waste; dilute with oxygen saturated water; add nutrients and microorganisms (seed)
- Measure dissolved oxygen (DO) levels over 5 days
- Temperature 20° C
- In dark (prevents algae from growing)
- Final DO concentration must be > 1.5 mg/L
- Need at least 2 mg/L change in DO over 5 days

$$BOD_t = \frac{(DO_i - DO_f) - (B_i - B_f)(1 - p)}{p}$$

$$p = \frac{V_s}{V_b}$$

BOD_t = biochemical oxygen demand at t days [mg/L], usually t=5 days

DO_i and DO_f = initial and final dissolved oxygen in the sample bottle [mg/L]

B_i and B_f = initial and final dissolved oxygen in blank water sample bottle [mg/L]

V_b = sample bottle volume, usually 300 or 250 mL [mL]

V_s = sample volume [mL]

BOD_5 : 5-day analysis

Usually $B = B_f$ if use pure water as blank water, the BOD5 can be simplified to

$$BOD_5 = \frac{(DO_0 - DO_5)}{p}$$

$$p = \frac{V_s}{V_b}$$

DO_0 and DO_5 = initial and day-5 dissolved oxygen in the sample bottle [mg/L]

$BOD_u (L_a)$: ultimate test of 20 to 30 days

Modeling BOD Reactions

Assume rate of decomposition of organic waste is proportional to the waste that is left in the flask, DO depletion is first order

$$\frac{dL_t}{dt} = -kL_t$$

where L_t = amount of oxygen demand left after time t

t = time

k = the BOD reaction rate constant (time^{-1})

Solving this equation yields :

$$L_t = L_a e^{-kt}$$

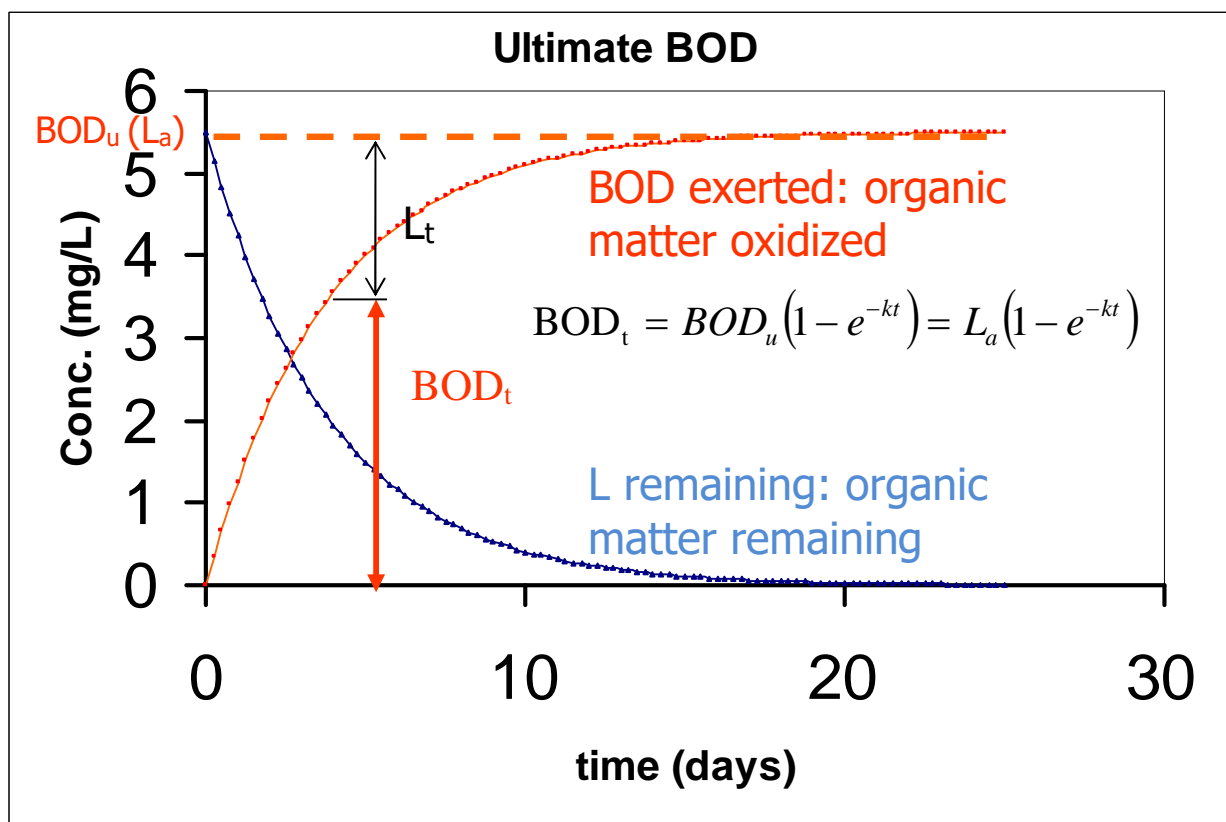
where BOD_u is the ultimate carbonaceous oxygen demand

L_t = amount of O₂ demand left in sample at time, t

L_a = amount of O₂ demand left initially (at time 0, no DO demand has been exerted, so BOD = 0)

At any time, $BOD_u(L_a) = BOD_t + L_t$ (that is the amount of DO demand used up and the amount of DO that could be used up eventually)

$$BOD_t = L_a - L_t = L_a(1 - e^{-kt}) = BOD_u(1 - e^{-kt})$$



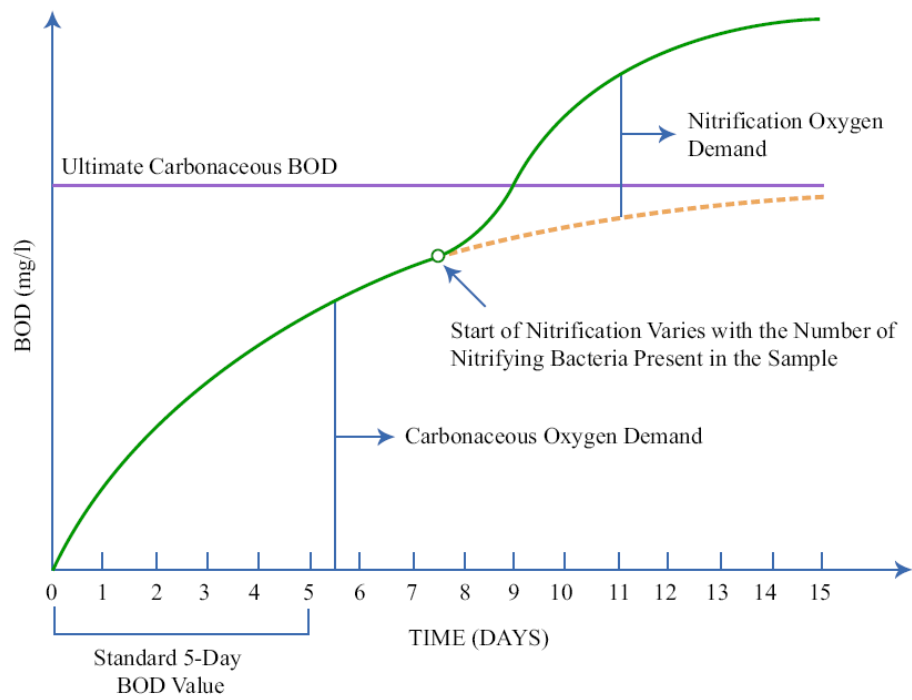
Additional notes on BOD (Nitrogenous Oxygen Demand)

- So far we have dealt only with carbonaceous demand (demand to oxidize carbon compounds)
- Many other compounds, such as proteins, consume oxygen
- Mechanism of reactions are different

Nitrogenous Oxygen Demand

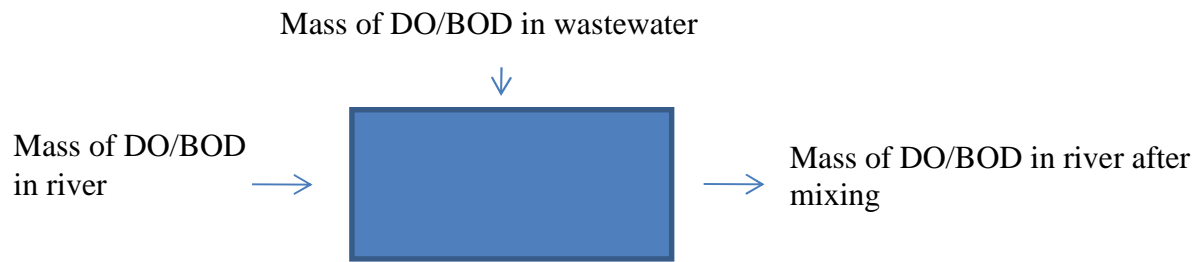
- Nitrification (2 step process)
$$2 \text{NH}_3 + 3\text{O}_2 \rightarrow 2 \text{NO}_2^- + 2\text{H}^+ + 2\text{H}_2\text{O}$$
$$2 \text{NO}_2^- + \text{O}_2 \rightarrow 2 \text{NO}_3^-$$
 - Overall reaction:
$$\text{NH}_3 + 2\text{O}_2 \rightarrow \text{NO}_3^- + \text{H}^+ + \text{H}_2\text{O}$$
- Theoretical NBOD =

$$\frac{\text{grams of oxygen used}}{\text{grams of nitrogen oxidized}} = \frac{4 \times 16}{14} = 4.57 \text{ g O}_2/\text{g N}$$



Hypothetical biochemical oxygen demand reaction curve showing the carbonaceous & nitrification reactions.

Mass balance to understand changes of OD and BOD



$$\text{Mass of DO in wastewater} = Q_w DO_w$$

$$\text{Mass of DO in river} = Q_r DO_r$$

$$\text{Mass of DO after mixing} = Q_w DO_w + Q_r DO_r$$

DO after mixing

$$DO = \frac{Q_w DO_w + Q_r DO_r}{Q_w + Q_r}$$

BOD after mixing

$$L_a = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r}$$

Q_w : Volumetric flow rate of the wastewater, m^3/s

Q_r : Volumetric flow rate of the river, m^3/s

DO_w : Dissolved oxygen concentration in the wastewater, mg/L

DO_r : Dissolved oxygen concentration in the river, mg/L

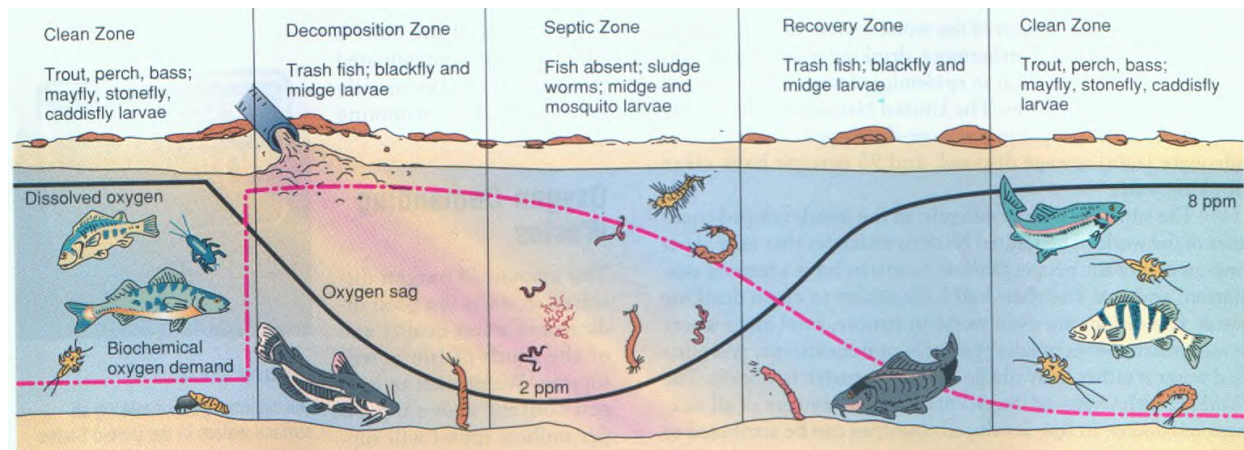
L_w : ultimate BOD of the wastewater, mg/L ;

L_r : ultimate BOD of the river, mg/L ;

L_a : initial ultimate BOD after mixing.

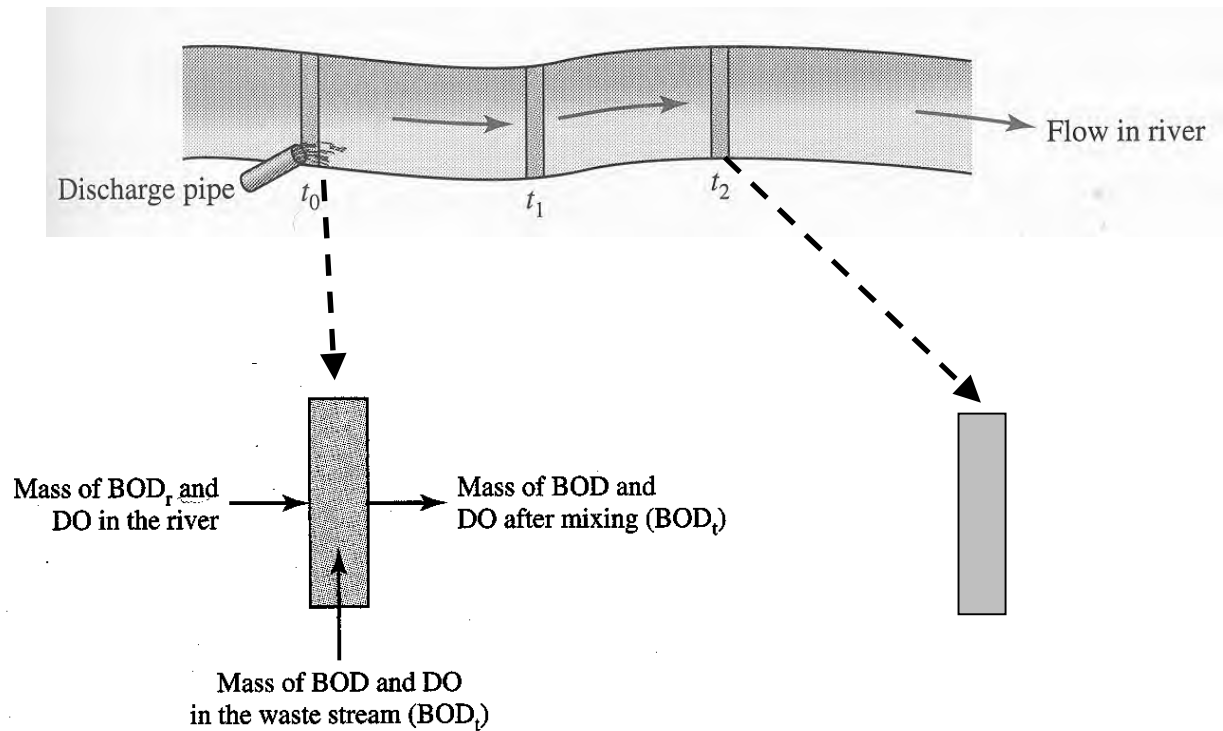
DO sag curve

One of the major tools of water quality management in rivers is to assess the capability of a stream to absorb a waste load. This is done by determining a DO profile downstream from a waste discharge, which is DO sag curve.

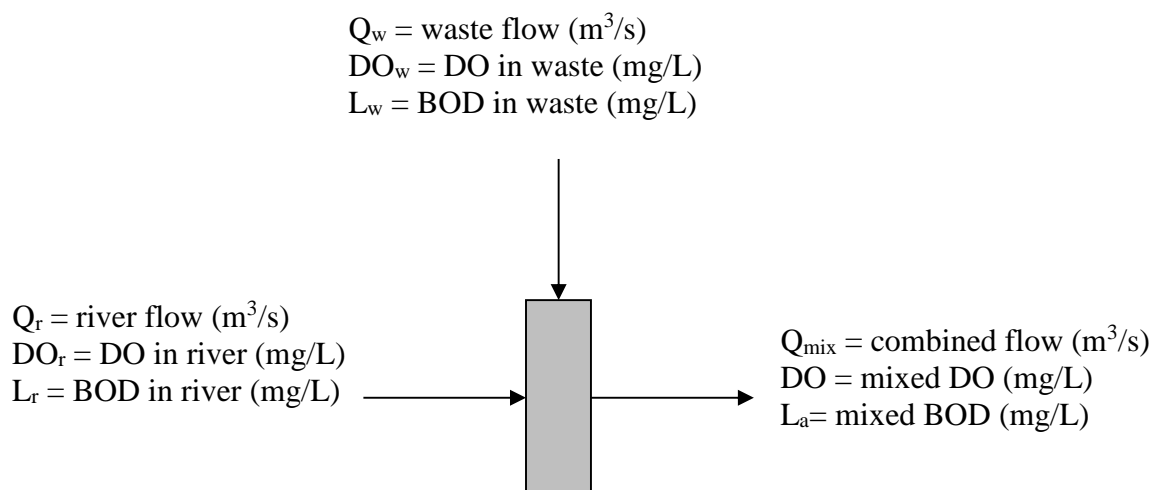


Steps in Developing the DO Sag Curve

1. Determine the initial conditions
2. Determine the reaeration rate from stream geometry
3. Determine the deoxygenation rate from BOD test and stream geometry
4. Calculate the DO deficit as a function of time
5. Calculate the time and deficit at the *critical point*



1. Determine the initial conditions



- a. Initial dissolved oxygen concentration
- b. Initial dissolved oxygen deficit

where D = DO deficit (mg/L)
 DO_s = saturation DO conc. (mg/L)

$$D_a = DO_s - \frac{Q_w DO_w + Q_r DO_r}{Q_{mix}}$$

DOs is a function of temperature. Values can be found in Table.

- c. Initial *ultimate* BOD concentration

$$L_a = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r}$$

2. Determine Reaeration Rate

a. O'Connor-Dobbins correlation

$$k_r = \frac{3.9u^{1/2}}{h^{3/2}}$$

where k_r = reaeration coefficient @ 20°C (day-1)

u = average stream velocity (m/s)

h = average stream depth (m)

b. Correct rate coefficient for stream temperature

$$k_r = k_{r,20} \Theta^{T-20}$$

where $\Theta = 1.024$

3. Determine the Deoxygenation Rate

a. rate of deoxygenation = $kdLt$

where kd = deoxygenation rate coefficient (day-1)

Lt = ultimate BOD remaining at time (of travel downstream) t

b. If k_d (stream) = k (BOD test)

$$L_t = L_a e^{-k_d t}$$

And

$$\text{rate of deoxygenation} = k_d L_a e^{-k_d t}$$

c. However, $k = k_d$ only for deep, slow moving streams. For others,

$$k_d = k + \frac{u}{h} \eta$$

where η = bed activity coefficient (range from 0.1 for stagnant or deep water to 0.6 for rapid flowing water)

d. Correct for temperature

$$k_d = k_{d,20} \Theta^{T-20}$$

where $\Theta = 1.135$ (4-20°C) or 1.056 (20-30°C)

4. DO as function of time

- Mass balance on moving element
- Rate of increase of the deficit = Rate of deoxygenation - Rate of reaeration

$$\frac{dD}{dt} = k_d L_t - k_r D \qquad \frac{dD}{dt} = k_d L_a e^{-k_d t} - k_r D$$

- Solution at time t the deficit D_t and DO_t

$$D_t = \frac{k_d L_a}{k_r - k_d} (e^{-k_d t} - e^{-k_r t}) + D_a (e^{-k_r t})$$

$$DO_t = DO_s - \left[\frac{k_d L_a}{k_r - k_d} (e^{-k_d t} - e^{-k_r t}) + D_a e^{-k_r t} \right]$$

5. Calculate Critical time and DO

To find the critical time t_c , let us differentiate Dt and set to zero, and solve it and obtain

$$t_c = \frac{1}{k_r - k_d} \ln \left[\frac{k_r}{k_d} \left(1 - D_a \frac{k_r - k_d}{k_d L_a} \right) \right]$$

DO at critical point is

$$DO_c = DO_s - \left[\frac{k_d L_a}{k_r - k_d} (e^{-k_d t_c} - e^{-k_r t_c}) + D_a e^{-k_r t_c} \right]$$

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