DESIGNING ADVANCED TREATMENT SYSTEMS TO PERFORM AT HIGH ELEVATIONS

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Abstract

The dissolved oxygen concentration in water is determined by a combination of three environmental parameters; temperature, salinity and barometric pressure. Warm water contains less dissolved oxygen than cold water. Another way of describing this relationship is that gas solubility decreases with increasing temperature. Fresh water holds more dissolved oxygen than salt water. Another way of describing this relationship is salinity negatively affects the solubility of oxygen in water. The solubility of dissolved oxygen in water is also influenced by pressure. As barometric pressure increases, the amount of oxygen that can be dissolved in the water also increases. This relationship happens because higher pressure forces more oxygen molecules to enter into water's molecular spaces. (Source: The Engineer's Toolbox, accessed 2 6 2026).

A fundamental concept in fluid mechanics is the inverse relationship between elevation and barometric pressure. The higher the elevation is above sea level, the lower the barometric pressure will be, with a corresponding decrease in dissolved oxygen concentration.

Oxygen solubility in water has an upper limit, called the saturated dissolved oxygen concentration. Elevations significantly higher than sea level depress the saturated dissolved oxygen concentration compared to oxygen concentration dissolved in water bodies found at sea level. Designers must recognize and quantify the dissolved oxygen shortfall at the elevation, salinity and record high temperature found at the site, and ensure their designs compensate for elevation, salinity and climate effects when circumstances dictate these adjustments.

Introduction

The field of onsite wastewater is more multidisciplinary than most other disciplines. Sherman (2008) called this field a crossroad discipline. By using this term, the author drew attention to the fact that the field of onsite wastewater requires multiple inputs from the academic disciplines of Biology (including microbiology), Chemistry, Engineering, Geology (including soil science), Physics and Public/Environmental Health. The purpose of this paper is to focus on the relationship between site elevation, highest site temperature, and salinity on the water's saturated dissolved oxygen concentration.

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NOTE: readers do not need to have prior experience or knowledge about any of these topics to understand this talk. We will begin with basic, easily understood concepts and build on them as the document unfolds. The author will reinforce important concepts by using analogies linking the concept to experiences readers likely have already witnessed. The approach will be step by step.

Temperature impacts dissolved oxygen saturation concentration. Have you ever experienced this scenario? (Analogy 1)

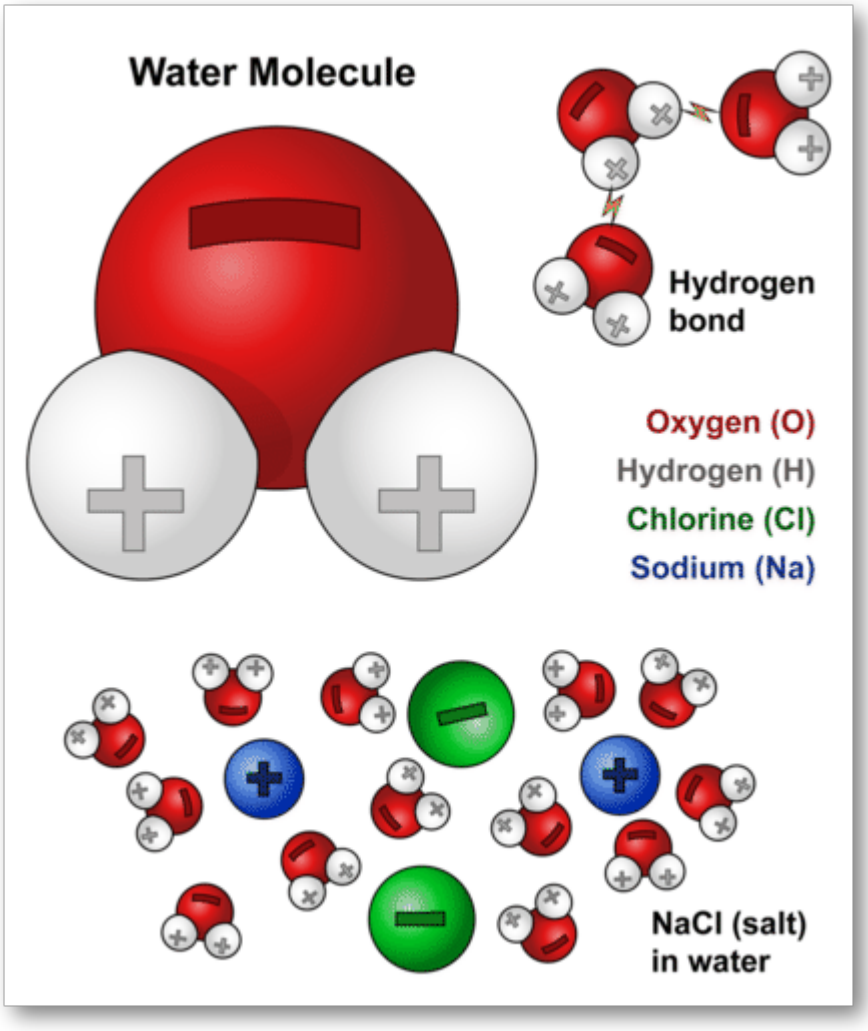
A customer sits down for a meal in a diner. They ask the server if they have **sweet** iced tea. They say no, but there is sugar on the table. The customer then brings to the server's attention that salt, pepper, and napkins are also on the table. The customer then states to the server that all of the above items have the same ability to make **iced** tea sweet, and that ability is zero.

What has the server forgotten, or never knew? Water is called the universal solvent (USGS.gov, 2018 accessed 7 26 2026). Water is a three-element compound, consisting of one central oxygen atom flanked on either side by a hydrogen atom (see Fig 1).

Solids, other liquids and gasses will dissolve into water **if** the correct environment is present. In the case of the sweet iced tea analogy, the tea's temperature is too cold to dissolve sugar. In this analogy, the sugar crystals gently descend to the floor of the glass undissolved and then silently mock the customer as they stir the crystals with no sweetness improvement.

Water earned the title "universal solvent" because it is capable of dissolving more substances than any other liquid. This capability is important to every living thing on earth. It means that wherever water goes, either through the air, the soil, or through our bodies, it takes along valuable dissolved chemicals, minerals, and nutrients with it.

It is water's chemical composition and physical attributes that make it such an excellent solvent. Water molecules have a polar arrangement of oxygen and hydrogen atoms—one side (either hydrogen) has a positive electrical charge and in the center (oxygen) has a negative charge. This arrangement allows water molecules to become attracted to many other molecules. Water can become so heavily attracted to some compounds, for example, common table salt (NaCl), that it can disrupt the attractive forces that hold the sodium and chloride in the salt compound together and, thus, dissolve it.



IN: USGS.gov water is a universal solvent, 2018

Figure 1. Diagram showing the positive and negative parts of water molecules. It also depicts how a charged element, such as a cation (Na^+) or anion (Cl^-) salt can interact with water molecules. Source: Mariana Ruiz Villarreal, CK-12 Foundation

Henry's Law.

Most gasses are slightly soluble in water. Environmental conditions are crucial to maximize the dissolution of gasses into water. Gasses dissolve into water in accordance with Henry's Law (Krauskopf & Bird, 1995).

Henry's law, first formulated by English chemist William Henry in 1802, describes the relationship between gas solubility and pressure. The law states that the amount of a gas dissolved in a liquid is directly proportional to the partial pressure of the gas above the liquid. Mathematically, it is

expressed as **C = kP**, where **C** is the concentration of the dissolved gas, **P** is the partial pressure of the gas above the liquid, and **k** is the Henry's law constant specific to each gas-liquid pair and the ambient temperature. Henry's Law recognizes that the amount of gas dissolved in a liquid is proportional to its partial pressure and inversely proportional to temperature (i.e. there is more oxygen dissolved in cold water than in warm water).

At the molecular level, gas molecules collide with the liquid surface and dissolve. At equilibrium, the rate of gas molecules entering the liquid equals the rate of molecules escaping back into the gas phase above the liquid. Increasing the gas pressure increases the number of molecules striking the liquid surface per unit of time, raising the equilibrium concentration of a dissolved gas.

Analogy 2 (Blowing bubbles)

Imagine blowing bubbles into a glass of water using a straw. The harder the person blow (i.e. at a higher pressure), the more gas molecules enter the water per unit of time. At equilibrium, the rate at which gas molecules enter the liquid equals the rate at which they leave. This balance is described by Henry's Law.

Oxygen solubility in water

Oxygen dissolving in water is the opposite of sugar dissolving in tea. More oxygen dissolves in cold water than in hot water. Does that statement make sense to you based on your experiences? The analogy this time is more accurately stated as observations. Consider an energetic fresh-water fish. Trout are active fish, and live in a highly oxygenated environment. Where do you typically find Trout? Each species of trout has their own specific preferences. Generally speaking, they thrive in cold, fast-moving streams. In whitewater streams, bubbles generated by the turbulent water flow make the dissolved oxygen concentrations even higher than laminar flows produce.

At the molecular level, when water cools, its molecules move more slowly. This allows dissolved oxygen molecules to remain in solution because the forces holding them in the water are not easily overcome. As water heats, molecules gain more kinetic energy. They move faster, and vibrate more vigorously. This increased motion makes it easier for oxygen molecules to break free from the liquid and escape into the air. This is a general property of gases in liquids; higher temperature reduces gas solubility (scienceinsights.org accessed 8 8 2026).
Warmer water has a lower solubility for oxygen, so even if the air's oxygen partial pressure is the same, less oxygen stays dissolved. (Davis & Dykstra, 2012).

Warm water has less dissolved oxygen because rising temperature increases molecular motion, reduces gas solubility, and speeds oxygen escape, while also increasing oxygen demand from aerobic (oxygen requiring) organisms living in that water.

Another observation of gas being soluble under some condition and not in others is by carefully observing how water boils. As the temperature increases in a pan of water on a heated stove, bubbles first form on the floor of the pan. Eventually air bubbles rise quickly out of the pan. This phenomenon demonstrates that gases that once were dissolved in a cold pan of water, now have to leave as water vapor or steam once the temperature of the water equals the boiling point of water.

Salinity's impact on dissolved oxygen saturation concentration.

Salinity is another environmental parameter that depresses oxygen saturation. Let's explore table salt with the chemical formula NaCl. When salts dissolve, the positively charged cation, sodium (Na^+) is physically separated from the negatively charged anion chloride (Cl^-). An analogy may help understanding this effect.

Cocktail party analogy

Imagine water molecules as party hosts and oxygen molecules as guests at a cocktail party. When salts are introduced to the party, their positively charged cations and negatively charged anions also become "guests" that compete for the water molecules' attention. As more salt ions enter the water, fewer water molecules are now available to "host" oxygen gas. This competition directly reduces water's capacity to dissolve oxygen, leading to lower dissolved oxygen levels in high-salinity environments, such as the earth's oceans. This inverse relationship consistently affects oxygen availability across various aquatic systems. (source:Biologyinsights.com accessed 7 28 2026).

Practically speaking, saltwater (with a salinity of 36 g/kg or 36‰) holds about from 18% to 22% less saturated dissolved oxygen concentration than freshwater under the same temperature and pressure (Atlas Scientific What is the relationship between dissolved oxygen and salinity? Posted July 30, 2025 accessed 7 28 2026).

Barometric pressure impacts dissolved oxygen saturation concentration.

The third parameter that influences the dissolved oxygen is barometric pressure. The solubility of oxygen in water is directly related to barometric pressure. As barometric pressure increases, the solubility of oxygen in water also increases. This is because higher pressure allows more gas molecules to dissolve in the water. Conversely, lower barometric pressure results in decreased oxygen solubility.

Results

A mountain can have several peaks but only the tallest peak in a mountain is called it's summit. Table 1 lists the 20 tallest summits in North American mountains in order from highest summit elevation to lower.

Table 1. North America's 20 highest elevation summits (Wikipedia, accessed 7 28 2026)

Name	Location	Summit Elevation (ft)	Notes
Denali	USA Alaska	20,310	7th highest on planet
Mount Logan	CAN Yukon	19,551	
Pico de Orizaba	MEX Vera Cruz	18,491	
Mount St. Elias	USA Alaska	18,009	
Popocatépetl	MEX Morelos/Puebla	17,749	
Mount Foraker	USA Alaska	17,400	
Mount Lucania	CAN Yukon	17,257	
Volcán Iztaccihuatl	MEX Puebla	17,108	
King Peak	CAN Yukon	16,972	
Mount Bona	USA Alaska	16,550	
Mount Steele	CAN Yukon	16,470	
Mount Blackburn	USA Alaska	16,390	
Mount Sanford	USA Alaska	16,237	
Mount Wood	CAN Yukon	15,945	
Mount Vancouver	CAN Yukon	15,787	
Mount Slaggard	CAN Yukon	15,558	
Nevado de Toluca	MEX Toluca	15,387	
Mount Fairweather	CAN British Columbia	15,325	
Sierra Negra	MEX Puebla	15,059	
Mount Hubbard	USA Alaska & CAN Yukon	14,951	

Notice that none of the summits above are located in the 48 contiguous United States. The highest points in the 48 contiguous United States are in California's Mount Whitney at 14,501 ft, Colorado's Mount Elbert at 14,439 ft, and Washington's Mount Ranier at 14,406 ft (Source: Peakbagger.com accessed Aug 2, 2026).

Water found in mountainous regions (such as in a high elevation lake), would likely have a dissolved oxygen concentration lower that the dissolved oxygen concentration of water at sea level. A helpful rule of thumb is for every 1,000 feet of elevation gained; the barometric pressure drops by 26 mm of mercury (Table 2).

Table 2 Barometric pressure in mm Hg versus elevation above sea level in feet

Barometric Pressure	**Elevation above sea level (ft)**
760 mm of mercury	0’ (at sea level)
734 mm of mercury	1,000’
682 mm of mercury	3,000’
630 mm of mercury	5,000’
578 mm of mercury	7,000’
526 mm of mercury	9,000’
500 mm of mercury	10,000’
474 mm of mercury	11,000’
448 mm of mercury	12,000’
370 mm of mercury	15,000’

In: Metcalf, L., Eddy, H. P., Tchobanoglous, G.& F.L. Burton (1991). *Wastewater engineering: treatment, disposal, and reuse* (3rd edition) Appendix B Table B-1 Physical Properties of Air. New York: McGraw-Hill, 1334 pp.

Note that the barometric pressure at 15,000 ft above sea level is less than half of the barometric pressure at sea level (i.e. one half of 760 mm of mercury is 380 mm of mercury).

Although the atmosphere does not have a sharp boundary; it gradually thins with increasing altitude. Most of the atmospheric mass, about 75–80 percent, is concentrated within the troposphere, which extends roughly 47,520 ft above the Earth's surface, depending on latitude and season, and is where nearly all weather occurs and water vapor is found. If a person is climbing a mountain with a summit elevation of 15,000 feet, the remaining barometric

pressure the person will experience is 370 mm of mercury, aka 7.2 psi (pounds per square inch). This pressure can be compared to pressures you may be more familiar with. The tires on your vehicle are inflated with air at 30-35 psi. The pressure a mountaineer experiences is one-fifth (or 20% of pressure in a properly inflated tire.

Other factors influence whether hospitable conditions are found near mountain summits. One of these is where or if a tree-line will be found on a mountainside. The tree line marks a natural boundary where forests give way to open, treeless landscapes. This transition zone often appears as a rugged, windswept frontier. It stands as a testament to the environmental limits that shape plant distribution across the earth's diverse terrains. The abrupt change from towering trees to low-lying vegetation presents an ecological puzzle. Alpine tree lines occur at high altitudes on mountains, primarily limited by cold temperatures.

We need to add common sense to put the collected scientific information in context. Many places in North America have high elevations (see Table 1). The highest elevations are attractive places for experienced hikers and rock-climbing enthusiasts to visit for short time periods (i.e., 10 to 30 minutes at most). High-elevation mountain summits are visited, but they are not used as home sites. Consequently, these places do not need to install an onsite wastewater system. Therefore, states and provinces should recognize the highest elevations on the prior table are uninhabitable. I suggest local regulations limit their oxygen compensation techniques to sites 12,000 feet above sea level or less.

Human physiology begins to be significantly affected human beings at 7,000 feet above sea level, where oxygen saturation in the blood starts to drop rapidly due to reduced atmospheric pressure (Table 2). At 7,000 feet elevation to 12,000 feet, the partial pressure of oxygen in the air is low enough to trigger serious physiological changes. Some of the warning signs include noticeable difficulty breathing, acute mountain sickness symptoms, including headaches, nausea, fatigue, dizziness and sleep disturbances (Source, scienceinsights.org March 18, 2026 accessed August 2, 2026).

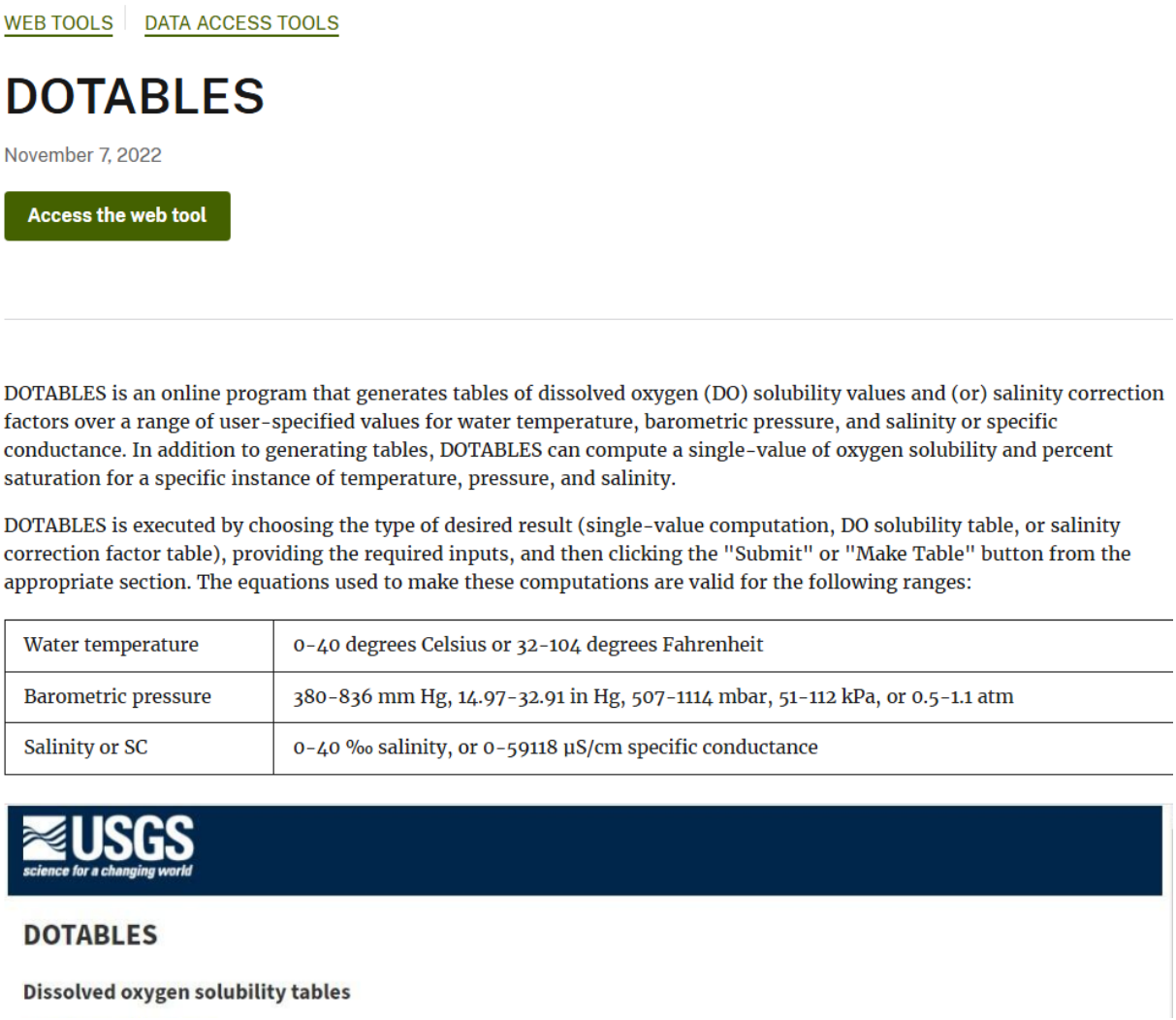
Calculating Dissolved Oxygen concentrations

In my opinion, the easiest way to determine dissolved oxygen concentration is to use the USGS Dissolved Oxygen Solubility Tables, DOTABLES for short. A screen shot of the web tool is shown in figure 2.

If you do not fully understand the USGS program steps, or are not prepared to distinguish between metric and English units, you could be guilty of a GIGO mistake. GIGO is an acronym which stands for garbage in : garbage out. The idea I want to warn you about is the web tool counts on the operator to select the correct units of temperature, salinity or specific conductance, pressure etc. Before a query is submitted, you must be certain that all units are compatible with each other (i.e. there are no mixed units used). If incompatible units are input to the tool, it will

provide incorrect answers, but will **not** warn you of any mistakes. Sometimes the program defaults to original units.

Figure 2. Screenshot of DOTABLES web tools and data access tools. Accessed July 31, 2026.



WEB TOOLS | DATA ACCESS TOOLS

DOTABLES

November 7, 2022

Access the web tool

DOTABLES is an online program that generates tables of dissolved oxygen (DO) solubility values and (or) salinity correction factors over a range of user-specified values for water temperature, barometric pressure, and salinity or specific conductance. In addition to generating tables, DOTABLES can compute a single-value of oxygen solubility and percent saturation for a specific instance of temperature, pressure, and salinity.

DOTABLES is executed by choosing the type of desired result (single-value computation, DO solubility table, or salinity correction factor table), providing the required inputs, and then clicking the "Submit" or "Make Table" button from the appropriate section. The equations used to make these computations are valid for the following ranges:

Water temperature	0-40 degrees Celsius or 32-104 degrees Fahrenheit
Barometric pressure	380-836 mm Hg, 14.97-32.91 in Hg, 507-1114 mbar, 51-112 kPa, or 0.5-1.1 atm
Salinity or SC	0-40 ‰ salinity, or 0-59118 µS/cm specific conductance

USGS science for a changing world

DOTABLES

Dissolved oxygen solubility tables

Table 3. Data obtained from DO Tables (USGS.gov, 2022). The green cells display saturated dissolved oxygen concentration in fresh water (zero parts per thousand salinity) while temperatire ranges from 32 degree to 86 degrees fahrenheit. The blue cells display saturated disoved oxygen concentration from fresh water all the way to sea water (36 parts per thousand salinity) while temperatire ranges from 32 degrees to 86 degrees fahrenheit.

Saturated Dissolved Oxygen tables

- DO concentration (mg/L) as function of temp & elevation (salinity 0 0/00)
- DO concentration (mg/L) as a function of temp &salinity (elevation sea level)

Temp °F	Sea level	5,000'	9,000'	11,000'	Temp °F	Fresh Water	10 0/00	20 0/00	Sea (36) water
32	14.62	12.11	10.19	9.09	32	14.62	13.69	12.71	11.37
50	11.29	9.33	7.77	6.99	50	11.29	10.59	9.93	8.97
68	9.09	7.50	6.23	5.59	68	9.09	8.57	8.09	7.35
86	7.56	6.21	5.13	4.59	86	7.56	7.15	6.77	6.20

Data source ; USGS DOTABLES

Using the green side of Table 3, at an elevation of 11,000 feet above sea level (right most green column), dissolved oxygen concentrations at room temperature are depressed by ~38 percent. For example, at temperature of 68°F fourth row from the top, note the following information.

DO concentration at 68°F (4th Row from top) is 5.59 mg/L at 11,000' compared to 9.09 mg/L at sea level.

9.09 minus 5.59 equals a 3.50 loss or shortfall due to the high elevation; The percent loss is 9.09/3.05 equals 0.38 or 38 percent. The corresponding salinity impact on oxygen solubility percent losses are less ranging from 22 to 18% loss at a salinity of sea water (36 parts per thousand).

A crucial step is deciding which of the trio of environmental conditions will create the worst-case scenario for dissolved oxygen concentration. The highest elevation, temperature and salinity combine to create the worst case. In most situations, only two of the three conditions are truly challenging.

Case study 1: Nuestra Señora de La Paz, Bolivia; La Paz Bolivia is the seat of government in Bolivia. La Paz is also the third most populous city in the country. La Paz is located in west-central Bolivia. ~42 miles southeast of Lake Titicaca. La Paz is set in a canyon created by the

Choquevapu River and the Andes mountain chain. The average elevation is roughly 11,975 ft above sea level, Due to its location, the city has an unusual subtropical highland climate with rainy summers and dry (snowless) winters. The record highest temperatures in La Paz are typically found in December (68°F).

Using an elevation of 12,000 ft and a record high temperature of 68°F (a cherished concept in design is always round up! It is better to have a little more than you need than to supply less.) DO Tables gives an oxygen solubility of 5.15 mg/L for the Nuestra Señora de La Paz, Bolivia aka Our Lady of Peace.

Case Study 2: My conversation assisting a conscientious WWTP operator at GITMO will give us the chance to use the blue cells in Table 3. Naval Station Guantanamo Bay, Cuba has an elevation of 56 feet above sea level, a seasonal high temperature of ~86°F and a record summer high temperature of 97°F. The distance between Guantanamo Bay and the equator is ~1,400 miles.

The staff responsible for operating and managing the wastewater treatment system were asking for someone to help them understand the low DO concentrations they were experiencing at the plant. I provided an over-the-phone consultation. The officer told me at the plants he operated in the states had much higher DO that what he was measuring in GITMO. I asked what the operator how toilets were flushed. To conserve fresh water, they flush the toilets with seawater. Having that piece of the puzzle in hand allowed me to reassure the operator that the dissolved oxygen he routinely measured was the saturated dissolved oxygen concentration for the environmental conditions at the base.

Using the blue half of Table 3, a temperature 97 °F (fifth row) and ignoring the 56 ft elevations (0.05% of 1000 ft) as a safety factor, saturated dissolved oxygen concentrations is depressed to 5.63 mg/L.

DO concentration at 86 °F (5th Row down) are 7.56 mg/L in fresh water zero parts per thousand of NaCl and 6.20 mg/L in salt water 36 parts per thousand. Using the record high temperature is probably unnecessary as salt water has a higher boiling point than fresh water.

Using DO Table with a salinity of 36 parts per thousand ; 7.56 minus 6.20 equals a 1.36 loss or shortfall; The percent loss is 7.56/1.36 equals 0.18 or 18 percent.

To compensate for potential shortfalls of dissolved oxygen, designers can follow one of many potential solutions. These solutions include installing additional diffusers, increasing the power (Cubic Feet / Minute) of blowers, choosing a larger model, etc. Air compressor selection for higher altitude installations introduces even more considerations (Mejia and Hudson, 2025). These considerations include using a larger air compressor than what would be used at sea level. A larger inlet capacity to minimize friction losses and footprint including specifying high altitude rated motors. High elevation designs have to add a derating factor to compensate for the loss of dissolved oxygen in high elevation installations. The derating factor varies on each site to ensure

the installation will perform optimally at the site's elevation (Manuscript review email - Jim Bell, 8/20/2026).

The inlet pressure to the air compressor at higher elevation is measurably less than that found at sea level. To achieve the same desired discharge pressure found at sea level, the air compressor has to work harder to overcome the increased pressure ratio.

The mathematical formula used for determining the oxygen requirements of a wastewater treatment system is found in Jantrania & Gross 2006, page 77. Oxygen requirements are a combination of oxygen needed by heterotrophic (i.e. carbon eating bacteria) and the oxygen requirements of slower growing autotrophic (self-feeding) nitrifying bacteria. Nitrifying bacteria add oxygen atoms to nitrogen compounds inside their cells and capturing a portion of the energy released from the reactions they facilitate. The equation is

$$O_2 = (0.00000834)\ Qi\ [1.2\ BOD_5 + 4.57\ TKN]$$

Where O_2 = the pounds of oxygen required per day
BOD_5 = 5-day biochemical oxygen demand concentration reduction in mg/L
TKN = total kjeldahl nitrogen concentration reduction in mg/L
Qi = daily flow through the system in gallons per day.

It is imperative that the oxygen supplied to the wastewater at high elevation must exceed the oxygen required. To ensure the system is always supplying more oxygen than required, a safety factor of 1.3 to 1.5 is recommended.

Conclusion

The dissolved oxygen concentration in water is determined by a combination of three environmental parameters; temperature, salinity and barometric pressure. This topic is relevant to wastewater treatment generally. The varied circumstances where systems are placed in high elevations or the effluent is mixed with salty water is a wastewater issue and not a centralized versus decentralized wastewater issue. The references section includes a paper written Baquero-Rodríguez, G. A., Martinez, S., Acuña, J., Nolasco, D., and Rosso, D., 2022. The authors of this paper are associated with central sewer plants in both North America and South America. The issues they have discussed regarding the Andes Mountain chain are very similar to experiences found in North America.

The goal is designing wastewater treatment that completely compensates for the oxygen concentration shortfall created by the temperature, salinity and barometric pressure at the installation site. Using the equation provided by Jantrania and Gross, 2006, calculate the mass of oxygen required in pounds of oxygen.

Acknowledgements

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