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# TREES & SEAWATER (Part I): Flood, Surge, Rise

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Note: This publication concerns seawater inundation and intrusion onto tree sites in coastal communities. The tree salt stress discussed here is not associated with dry-land or semi-arid saline or sodic soils, although some saline soil citations provide insight into seawater salt stress on trees. Some tree and site impacts, and associated treatments, might be similar, but this publication is targeted at only tree health care providers along coastal areas.

The world's oceans currently cover ~70.8% of Earth's surface (Rumble 2017), and contain ~97% of the global water supply. (Wright & Colling 1995) The world's oceans have about 372,000 miles of interface (coastline) with the land, using conservative course measurements. Ten nations with the most coastline length account for 90% of all coastline on Earth. Figure 1. Some coasts have no people and no trees. Other coastlines have concentrated people and their trees. Coastal areas comprise 20% of the global land surface and contains >40% of global population.

Coastal areas of the world are changing due to risks of sea level rise and associated climate variability problems. Figure 2. Along these coastlines, annual variation of world ocean levels have traditionally been about four (4) inches. (Rumble 2017) But, sea level rise is currently about +2.2X to +3.1X times greater than expected. It is estimated 40% of world's population live within 62 miles of the coast with most relying upon freshwater aquifers for drinking water. (Tully et.al. 2019; UN data) Small changes in salinity (~0.5ppt) can make freshwater undrinkable and medically damaging. (Tully et.al. 2019) Another estimate suggests three billion of the world's population live within 124 miles of the coast. (National Public Radio data)

Too Close To Change

More than 630 million of the world population (~1/10th of the globe) live within 33 feet above current sea level. (National Public Radio data) Of these people, roughly 590 million live within 10 feet above sea level. Low-lying island nations are extremely vulnerable to sea level rise. Currently around the world, coastal areas of community forests and landscapes are experiencing flooding, saltwater intrusions, storm surges, and sea level increases. (Ury et.al. 2021; Zhai et.al. 2018)

Coasts are being impacted by sea level rise and extreme events which are delivering higher soil water salinities and saltwater inundation of tree sites. (Paudel et.al. 2018) Rising sea levels are causing waterlogging of tree soils and temporary submergence. (Choudhury et.al. 2022) Trees along coasts are declining and dying from salinity stress. (Zhai et.al. 2018) Saltwater intrusion into tree sites represents a leading edge of sea level rise, preceeding the more visible symptoms from tidal inundation. (Tully et.al. 2019) Northern Europe, Chile, Australia and southeast Asia will experience the most coastal tree loss, with an estimated 30% of all current coastal wetland sites lost by 2100. (Ury et.al. 2021) The southeastern United States is not immune to these changes.

Salt Water Wall

Global elevation of the sea surface has increased +2.8-3.6mm (+0.11 - 0.14 inches) per year over the last 30 years. Coupled with erosion, and land surface subsidence of -1-3mm (-0.04 - 0.12 inches) per year which is occurring in some coastal areas, as in parts of the eastern North American coastal plain for example, sea level rise is presenting coastal areas with major tree issues. Storm driven surges and flooding, and higher peak tidal inundation are all associated with sea level rise. Seawater salts can be delivered slowly to tree sites by ground water exchange, surface water mixing, and tidal movements, or can be deposited rapidly during storm surges driven by hurricanes. (Tully et.al. 2019)

Predicted intensification of saltwater problems can be divided into chronic salinity (permanent sea level rise), acute salinity (temporary storm surges and tidal flooding), and compounding desiccation stress (episodic drought). (Paudel et.al. 2018) Salinity changes initiate a cascade of ecological changes on tree soils driven by dessication, ionic strength, alkalinization, and sulfidation. (Tully et.al. 2019) Figure 3 provides a set of salt water descriptions and concentration definitions. (Coder 2022a)

Salinity in ocean surface waters at mid-latitudes is about 34-36 ppt (parts per thousand). (Rumble 2017) If coastal rivers under tidal influence are examined, salinity levels (beginning farthest from the ocean) can be categorized as: <0.5ppt (<1.4% seawater concentration) considered tidal freshwater; 0.5-3.0ppt (<10% seawater concentration) considered intermediate salinity; 3.0-7.0ppt (<23% seawater concentration) considered brackish salinity; 7.0-18.0ppt (<60% seawater concentration) considered sub-saline or high salinity; and, the ocean edge with >30ppt (>86% seawater concentration). (Conrads et.al. 2013)

## Defining Seawater

Seawater is salt water. Geological evidence suggests its composition has not changed for several hundred million years. (Wright & Colling 1995) Seawater is 96.5% water and 3.5% salts with traces of dissolved organic and inorganic materials, particulate matter, and gases. Figure 4 shows concentrations of primary gasses dissolved in seawater. Note $CO_2$ is only a small portion of dissolved gas present, but its two carbonate ions are present at relatively large concentrations. Ocean salinity is roughly 35 ppt or 35 g/kg, of which 30 ppt are provided by sodium ions — $Na^+$ (11ppt) and chlorine ions — $Cl^-$ (19ppt). (Wright & Colling 1995)

Salinity of ocean water varies. Salinity of surface ocean water is greatest in tropical and sub-tropical latitudes (up to 38ppt salinity) where evaporation is great. (Wright & Colling 1995) High latitude ocean water tends to be slightly less salty (30-33ppt) due to melting ice. (Wright & Colling 1995) Protected coastal bays with freshwater river inputs can have much less salinity than seawater. In one case over 14 years, average surface salinity of bay water was <21ppt. (Celik et.al. 2021) Figure 5 shows the top eight (8) components of salinity in seawater at three different total salt contents. Note the number of sulfur containing materials present.

Rain – River – Sea

There is a chemical and material gradient among rain water (pH5.7 with dissolved gases CO2 and SO2, and elements from chemical weathering), river water (with Ca++ and HCO3-), and seawater (pH8.0 with >300X more dissolved salts than river water). (Wright & Colling 1995) River water is not concentrated rain water, and seawater is not concentrated river water – but coastal rain water is a dilute form of seawater because of marine salt aerosols carried by the wind inland. (Wright & Colling 1995) Salt spray from the ocean surface and wave / beach interactions can be carried long distances (>45 miles) inland, while significant accumulation of salt from salt spray can be measured more the 2 miles inland. (Kozlowski et.al. 1991) Figure 6.

Seawater is a complex solution having roughly 400X times more salt than freshwater. Roughly 44% of seawater salt ions are composed of cations calcium, magnesium, sodium and potassium. (Tully et.al. 2019) The measured salinity is generated by soluble salts: NaCl, Na2SO4, CaCl2, CaSO4, MgCl2, and MgSO4. (Goyal et.al. 2022) Seawater salts originally come from weathering of rocks (both on land and on the seabed), hydrothermal vent circulation, and chlorides, sulfates, and other volatiles from volcanic gas. (Wright & Colling 1995)

Elemental

There are 81 elements found in seawater, with the top twenty highest concentrated elements shown in Figure 7. (Wright & Colling 1995) Note some of the largest concentrations of elements in seawater are tree essential elements. Eleven (11) major ions >1ppm make up 99.9% of dissolved constituents (listed in order from highest concentration to lowest): Cl-, Na+, Mg++, SO4- -, Ca++, K+, Br-, HCO3-, Sr++, H2BO3-, and F-. (Wright & Colling 1995) Negative ions in seawater account for ~21.9 ppt as chloride, sulphate, bicarbonate, bromine, borate, and fluorine (Figure 8), while positive ions account for ~12.7 ppt as Na+, Mg++, Ca++, K+, and Sr++. (Wright & Colling 1995)

Salinity of seawater is measured in various ways. Seawater salinity is around 550-600 mMol/l with an 8% error depending upon location. Seawater salinity is roughly 35 grams/liter, 35 ppt (parts per thousand), 35 psu (practical salinity unit), 3.5% salt by weight, and ~48 mS/cm electrical conductivity (EC). Figure 9. Here salinity measures will be given in parts-per-thousand (ppt) and percent of seawater concentration. Seawater is alkaline with a pH of 8.0 - 8.3, with a tenth pH point higher in tidal pools, lagoons, and estuaries where evaporation is significant. (Wright & Colling 1995)

Trees & Salt

Significant salinity which causes damage and death to trees is considered to begin at >0.5ppt (>1.4% seawater concentration) up to >2ppt (5.7% seawater concentration), or >1ppt (>2.9% seawater concentration) flooding a site for more than 25% of the time. (Noe et.al. 2021) The largest impacts on tree health and mortality occurs beyond >12ppt (34% seawater concentrations), which is considered a high level of salinity. (Abobatta 2020; Paudel et.al. 2018) Most trees are not tolerant of salt and do not survive moderate or high levels of salinity.

In two studies, salt stress equal to 8.7ppt (25% seawater salinity) and 6.0ppt (17% seawater salinity) caused a large drop of -0.68MPa (-6.8 bars) and -0.48 MPa (-4.8 bars), respectfully, in osmotic (water) potential. (Lambers & Oliveira 2019; Zhang et.al. 2019) These salt stress levels initiate major water uptake problems for trees. Brackish water ranges from 0.5 to 30ppt (1.4% to 86% seawater concentrations). In some locations, tree soil water can become brackish (>8ppt or 22.9% seawater concentration) during summer dry seasons. (Noe et.al. 2021) Artificially increased salt concentrations, or "salt lake" accumulations of salts, greatly increase (make more negative) osmotic potential. Figure 10.

# Sea Level Rise

Sea level rise and associated salt water inundation and intrusion are killing trees and allowing marshland to spread. (Chen & Kirwan 2022; Conner et.al. 2022) For example, coastal forests decreased by 22% over 35 years in parts of the mid-Atlantic region of the United States due to sea level rise. (Chen & Kirwan 2022) Increased salt water flooding and decreased flushing are the greatest threat to trees as sea levels rise. (Conner et.al. 2022) Storm and drought events are also increasing tree impacts from saltwater inundation and intrusion farther inland. (Ury et.al. 2021) Sea-level rise is generating tree stress similar to desertification, but with added ionic toxicity. (Ury et.al. 2021)

What <u>HAS</u> Happened !

Historically, sea level has always changed. Over time-scales of millions of years up to the last few decades, sea levels have always been rising or falling. Figure 11 shows global sea level changes in the last portion of the ice ages leading up to today. Note sea level has been down almost 400 feet in the last 30,000 years. Using a finer resolution in looking at sea level rise, the last 130 years have seen an increase of >7 inches and an acceleration in changes. Figure 12. Since around 1934, sea level rise rates at seven gage stations along the southeastern seaboard of the United States have averaged +2.7mm (0.11 inches) per year. (Conrads et.al. 2013) Between 1990 and 2020 sea level rise has occurred at different levels based upon measured location and measurement system employed. Figure 13. All measures show a minimum increase in sea level rise across 30 years of at least 3.5 inches.

What <u>WILL</u> Happen !

Based upon what has happened in the past and new models, projections into sea level futures can be made. Figure 14 shows the range of estimates from six (6) different sea level rise models to the year 2100 measured in feet. All have significant variability in their estimates. Note all models project sea level rise at least 2.5 feet by 2100. On average these six models project an average sea level rise of 3.2 feet, with three models suggesting a sea level rise of six (6) feet by 2100. In another projection, sea level is predicted to increase a minimum rise of +1.6 feet by 2100. (DeSedas et.al. 2020) New information on flooding extent and duration which will impact trees are shown increasing along the coasts with sea level rise accelerating from 3mm (0.12 inches) per year to more than 10mm (0.4 inches) per year by the end of the century. (Conrads et.al. 2013; Haaf et.al. 2021) NOAA projections of sea level rise for regional planning purposes show mid-level intermediate sea level rise between 2.0 and 4.1 feet by 2100. Figure 15.

All Along The Interface

With current sea levels rising, and projections of these changes to continue or accelerate, the interface between fresh and salt water will impact the ecology of community tree and tree site systems. Six major sea level rise impacts include: ocean level and fresh water-table rises; interface boundary of saltwater and freshwater pushed farther inland; local freshwater and tidal stream flow increases; coastal well water becoming more salty; and, ecological viable volume supporting trees and tree sites declining. Figure 16. (Hine et.al. 2016)

Figure 17 represents a current interface between ocean and fresh water along the coast. Note two items in this example – one is the ecologically viable volume in which trees can grow, and second is the fresh water well depth. Figure 18 represents the same land area under rising sea level. Note the ecological viable space for trees is diminished and thinned, and the well is now into brackish or salt water. (Hine et.al. 2016)

Additional Changes

One consequence of sea level rise in community tree areas is an attempted prevention of over-land sea water flooding coupled with drainage systems. Figure 19. With sea level rise, hardscape meant to exclude overland flooding can also prevent drainage if over-topped. In addition, storm sewers and field drainage system must have an adequate drop to be effective. In coastal areas, sea level rise may prevent or back-up water drainage. (Hine et.al. 2016) In addition, for many coastal communities, some legal land ownership and public jurisdiction issues will arise due to sea level changes. For example, if private land ownership runs down to the average high water point on the beach, and sea level rise pushes this line farther inland, total ownership acreage, taxable land base, and ownership or jurisdictional boundaries will change. Figure 20. (Titus et.al. 2009)

Surrounded

Anther concern is community trees and tree sites on barrier islands and hammocks. Figure 21 represents trees and their ecological viable volume needed for survival and growth. Trees are sustained by a floating freshwater lens beneath an island surface which is surrounded by seawater. Figure 22 represents the same island with sea level rise. Note the fresh water lens is pushed higher into the landscape and shrinks the ecological viable volume. (Hine et.al. 2016) Tree mortality is the result.

To summarize, sea level rise will impact coastal and barrier island community trees. Figure 23 lists the progression of impacts which cause community trees to decline and die. The process of seawater inundation and intrusion causes beach and bluff retreat inland and shoreline recession. Islands are thinned and washed over by a rising sea. Coastal wetlands are converted from a tree dominated system to marsh. Increasing salinity causes community tree and forest mortality. (Hine et.al. 2016)

Ocean Surging

Storm flooding events represent an acute deposition of salt water onto tree sites. Hurricane storm surge is not based solely upon storm energy, but is influenced by wind direction and strength, coastal underwater topography, beach height, tide phase and height, and lateral marsh distance. (Coder 2022a) Hurricane surges can be tall and quickly come-up around community trees. Figure 24 shows the time-line of a storm surge for hurricane Camille, a category 5 storm at landfall which occurred in 1969. As this large storm approached and made landfall, day 2 saw a storm surge of about 25 feet rising up and around tree sites, and over-topping flood control structures.

Hurricane surges can deposit large salt water loads onto tree sites. Figure 25 provides a selection of maximum storm surge levels since 1957 for the Gulf and Atlantic coasts of Eastern North America. Many storms can generate seawater surges, especially if these arrive at high tide and in the correct location for building surge volumes. Note hurricanes Katrina, Opal and Camille recorded surges of greater than 24 feet of seawater. Few locations have flood prevention structures to resist these surges. (Coder 2022a)

If storm surge projections are made into the future under both a two (2) feet and three (3) feet sea level rise with no increase in storm energy, the time between catastrophic storm surges becomes shorter and events more common. Figure 26 shows the number of years historically between moderate, major, and record breaking storm surges. This figure also provides the time in years between these intensity of storm surges under two sea level rise scenarios. Under a two feet rise in sea level, record storm surges increases from once every eight (8) decades to once every seven (7) years.

Between Life & Death

A coastal tree line defines where salinity issues reach a threshold between trees and marsh. In many places this threshold is visualized as ghost forests (dead standing trees). Figure 27. (Chen & Kirwan 2022) Ghost forests are becoming more widespread along the Gulf and Atlantic coasts of North America due to sea level rise and soil salinization. (Hall et.al. 2022) In some locations, the living coastal tree line fell back roughly 15.4 feet per year over 20 years. Coastal tree line retreat can be as much as 180 feet per year in some areas depending upon topography. Accelerating rates of change for forest (-17.3% loss) conversion to marsh (+15.8% gain) over the last 20 years is twice (2X) the rate of change for the previous 15 years due to sea level rise. (Chen & Kirwan 2022) One study site of forest trees saw a tree loss of 29% over 60 years due to sea level rise and increasing salinity. (Conner et.al. 2022)

Climate change is driving tree health problems in low relief coastal areas due to sea-level rise, salinization, storm surge flooding, and tidal inundation. (Ury et.al. 2021) More frequent and longer tidal flood exposures generate soil salinization and water saturation in excess of what is tolerated by most trees. (Haaf et.al. 2021) Salt stress damage to tree growth due to salinity increases often precede visible evidence of sea-level rise. (Ury et.al. 2021)

In some locations, sea-level rise impacts have been accelerated by soil surface subsidence caused by oxidation of anaerobic soils, drainage of soils, and long term settling of land surfaces since the last glaciation. (Ury et.al. 2021) Over the next 80 years, sea-level rise and soil surface fall may inundate up to 76,000 square kilometers (29,344 square miles) of coastal landscape in the continental United States. (Ury et.al. 2021)

Losing Balance

Changes in streamflow patterns will change salinity intrusions along coastal rivers with rising sea level. (Conrads et.al. 2013) Salinity is constantly responding to changing streamflow and tidal conditions represented by the position of a sea-water / fresh-water interface. This interface is balanced between upstream freshwater river flow and downstream tidal interactions. Saltwater pushes upstream driven by average sea level and tidal range changes. Seawater flows beneath the less dense freshwater, as freshwater flows toward the ocean gliding over the top of salt water beneath. (Conrads et.al. 2013) Seawater sinks below fresh water when not actively mixed because seawater density is 3% heavier than freshwater. (Wright & Colling 1995)

During low stream flows, salinity intrudes upstream farther and the sea-water / fresh-water interface is pushed upstream powered by increasing seawater levels and increased tidal ranges. (Conrads et.al. 2013) During neap tides when the tidal range is smallest, the decreased energy and less mixing at the interface allows fresh water to flow over the top of salt water while salt water still intrudes farther upstream. Figure 28. Salinity intrusions are also present when tidal energy is greatest, as during the new moon period, tropical storms, and high winds. (Conrads et.al. 2013) During high volume freshwater stream flows, salinity does not intrude far upstream and the seawater / fresh-water interface is pushed downstream.

At one municipal water gage and intake station located inland along a river, salt water intrusion has occurred 5.4% of the time. It is projected with a one foot rise in sea level, salt water intrusions will increase to 11.0% of the time, and with a two feet sea level rise intrusions will occur 17.6% of the time. (Conrads et.al. 2013) Coupled with periodic low stream flow and drought, the current one (1) salt water intrusion event with a duration of 73 days at one intake, would increase to four (4) intrusion events with one foot of sea level rise having a total duration of 121 days, and five (5) intrusion events with a two feet sea level rise having a total duration of 161 days. (Conrads et.al. 2013)

## Conclusions

Trees along coasts will have more stress and strain placed upon them as climate variability and sea level changes occur. Expanding salt stress impacts will require more careful management of community trees and their sites. Salt water inundation and intrusion onto community tree sites will cause many soil and tree impacts, some of which will lead to tree death, as well as a failure to regrow trees on some sites. Tree health care providers will need to be more vigilant in prescribing treatments for salt stressed trees over time as salt water flooding, storm surges, and sea level rise all lead to more damage.

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# World Coastal Length

| rank | country | coastline % |
|---|---|---|
| 1. | Canada | 34% |
| 2. | Indonesia | 17% |
| 3. | Norway | 10% |
| 4. | Russia | 6% |
| 5 | Philippines | 6% |
| 6. | Japan | 5% |
| 7. | Australia | 4% |
| 8. | USA | 3% |
| 9. | New Zealand | 3% |
| 10. | China | 2% |
| | total = | 90% |

Figure 1: Countries with the most ocean coastal miles in percent of total world ocean coastline.
(conservative estimate based upon course measurements)
Note 10 nations have 90% of world's ocean coastline.

## POPULATION & COASTAL TREE RISKS

### DISTANCE FROM COAST:

| | |
|---|---|
| 40% world population | = 62 miles. |
| 3 billion people | = 124 miles. |

### HEIGHT ABOVE SEA LEVEL:

| | |
|---|---|
| 630 million people | = 33 feet. |
| 590 million people | = 10 feet. |

### CHANGE IN SEA LEVEL:

Current sea level rise =
~2.7X times greater than expected.
+0.125 inches per year over last 30 years.

Figure 2: Current people, trees, and seawater interactions -- Increasing sea level rise, number of potential climate refugees, and associated potential community tree loss areas.

# SALT WATER TYPES

| type of water | salt content (ppt) |
|---|---|
| brine | >50ppt |
| saline water | 30-50ppt |
| seawater | 35ppt |
| high salinity | 10-35ppt |
| moderate salinity | 3-10ppt |
| slight salinity | 1-3ppt |
| brackish water | 0.5-30ppt |
| irrigation water | <2ppt |
| fresh water | <0.5ppt |
| drinking water | <0.1ppt |

Figure 3: Water types and descriptive names based upon the amount of salt dissolved (measured in parts per thousand (ppt)). (Coder 2022a; Coder 2022b)

## DISSOLVED GASSES -- SEAWATER

| element | form | equilibrium concentration |
|---|---|---|
| nitrogen | $N_2$ gas | 9.0 ml/l |
| oxygen | $O_2$ gas | 5.0 ml/l |
| carbon dioxide | $CO_2$ gas | 0.25 ml/l |
| bicarbonate | $HCO_3^-$ | 40 ml/l |
| carbonate | $CO_3^{--}$ | |
| argon | Ar gas | 0.2 ml/l |

Figure 4: Concentration by volume of four most common gasses dissolved in seawater at ~75°F (24°C). Note $CO_2$ gas is present in small amounts but its carbonate ion products are found in large amounts. (Wright & Colling 1995)

# COMPOSITION OF SEAWATER

| material | 30 ppt | 35 ppt | 40 ppt |
|---|---|---|---|
| Cl- | 16.6ppt | 19.3ppt | 22.2ppt |
| Na+ | 9.0 | 10.5 | 12.0 |
| NaSO4- | 1.0 | 1.3 | 1.5 |
| Mg++ | 1.0 | 1.1 | 1.2 |
| SO4-- | 1.0 | 1.1 | 1.2 |
| MgSO4 | 0.6 | 0.7 | 0.8 |
| K+ | 0.3 | 0.4 | 0.5 |
| CaSO4 | 0.1 | 0.2 | 0.3 |
| total ppt | 99% | 99% | 99% |

Figure 5: Top eight (8) seawater ions and compounds representing 99% of all materials dissolved in seawater at three different salinities (parts per thousand). Note how many sulfur containing compounds are present.
(Rumble 2017)

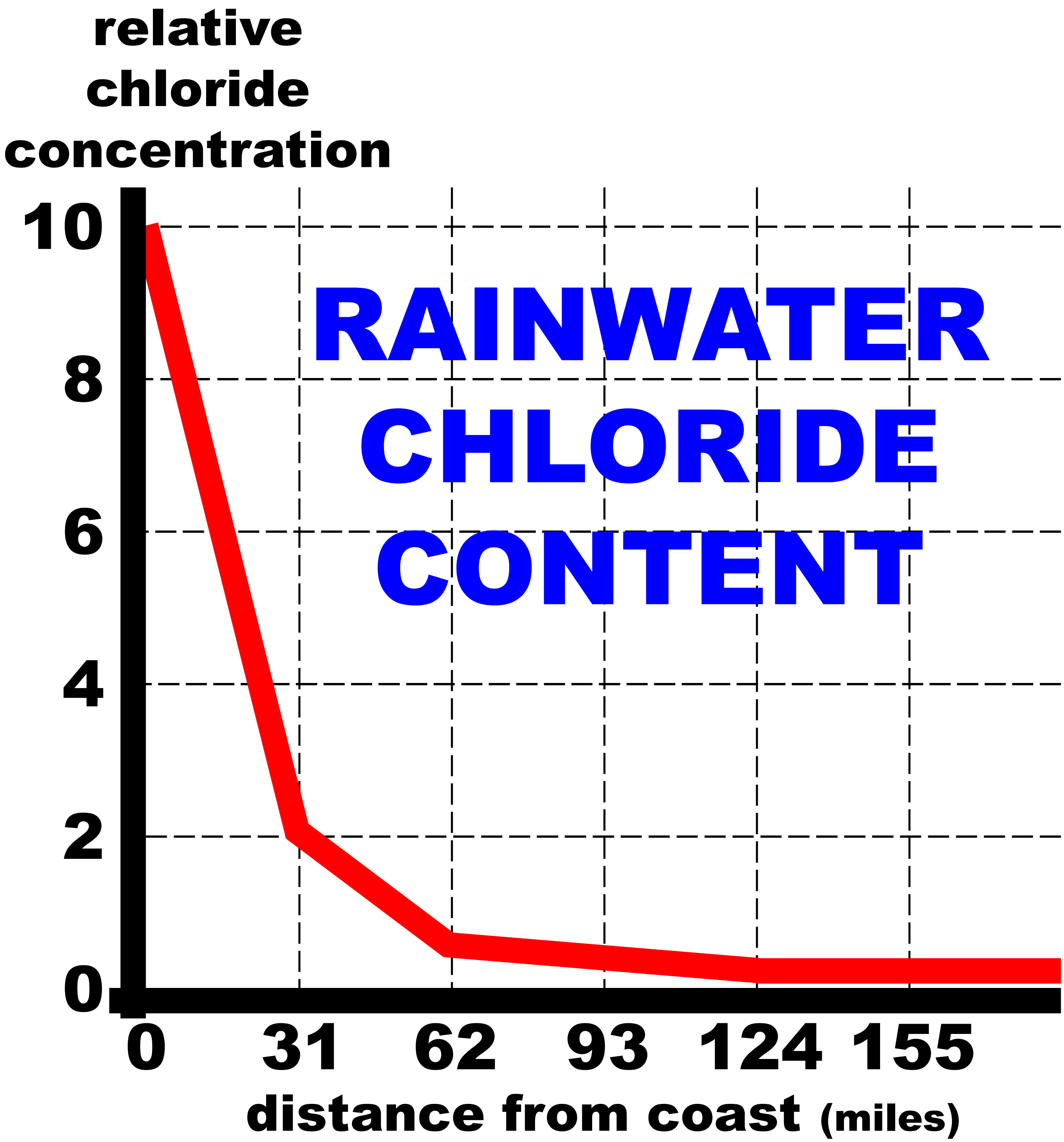


Figure 6: Relative rainwater chloride concentrations from an ocean source, depending upon distance from coast in miles.
(based upon Wright & Colling 1995)

# TOP 20 ELEMENTS -- SEAWATER

| element | concentration | dissolved materials |
|---|---|---|
| chlorine * | 19,500 ppm | $Cl^-$ |
| sodium | 10,770 ppm | $Na^+$ |
| magnesium * | 1,290 ppm | $Mg^{++}$, $MgSO_4$, $MgCO_3$ |
| sulphur * | 905 ppm | $SO_4^{--}$, $NaSO_3$ |
| calcium * | 412 ppm | $Ca^{++}$ |
| potassium * | 380 ppm | $K^+$ |
| bromine | 67 ppm | $Br^-$ |
| carbon * | 28 ppm | $HCO_3^-$, $CO_2^{--}$, $CO_2$ gas |
| nitrogen * | 12 ppm | $N_2$ gas, $NO_3^-$, $NH_4^+$ |
| strontium | 8 ppm | $Sr^{++}$ |
| oxygen * | 6 ppm | $O_2$ gas |
| boron * | 4.4 ppm | $B(OH)_3$, $B(OH)_4^-$, $H_2BO_3^{--}$ |
| silicon * | 2.0 ppm | $Si(OH)_4$ |
| fluorine | 1.3 ppm | $F^-$, $MgF^+$ |
| argon | 0.4 ppm | Ar gas |
| lithium | 0.2 ppm | $Li^+$ |
| rubidium | 0.1 ppm | $Rb^+$ |
| phosphorus * | 0.06 ppm | $HPO_4^{--}$, $PO_4^{---}$, $H_2PO_4^-$ |
| iodine | 0.06 ppm | $IO_3^-$, $I^-$ |
| barium | 0.02 ppm | $Ba^{++}$ |

(* = essential element in trees)

Figure 7: Of 81 elements naturally found in seawater, the average abundance (ppm) of the top 20 elements and their common forms are given. (Rumble 2017; Wright & Colling 1995)

# MAJOR SEAWATER IONS

| | |
|---|---|
| chloride $Cl^-$ | 19 ppt |
| sulphate $SO_4^{--}$ | 2.7 ppt |
| bicarbonate / carbonate $HCO_3^-$ | 0.14 ppt |
| bromide $Br^-$ | 0.07 ppt |
| borate $H_2BO_3^-$ | 0.03 ppt |
| fluride $F^-$ | 0.001 ppt |
| **total anions** = | 21.9 ppt |
| sodium $Na^+$ | 10.6 ppt |
| magnesium $Mg^{++}$ | 1.3 ppt |
| calcium $Ca^{++}$ | 0.4 ppt |
| potassium $K^+$ | 0.4 ppt |
| strontium $Sr^{++}$ | 0.01 ppt |
| **total cations** = | 12.7 ppt |

**total salinity listed = 34.6 ppt**

Figure 8: Average concentration of major cations and anions in seawater (parts per thousand = ppt). (Wright & Colling 1995)

# SALT WATER MEASURES

| S in ppt | EC mS/cm | mass % | TDI g/l |
|---|---|---|---|
| 5ppt | 8mS/cm | 0.5% | 5.3g/l |
| 10 | 15 | 1.0% | 10.0 |
| 15 | 22 | 1.5% | 14.7 |
| 20 | 29 | 2.0% | 19.3 |
| 25 | 35 | 2.5% | 23.4 |
| 30 | 42 | 3.0% | 28.0 |
| 35 | 48 | 3.5% | 32.0 |
| 40 | 54 | 4.0% | 36.0 |

**1 dS/m = 1 mS/cm = 100 mS/m = 667 TDI mg/l.**

Figure 9: Salinity (S) in parts per thousand (ppt), Electrical Conductivity (EC = 68°F / 20°C in mS/cm), salt concentration mass percent, and total dissolved ions (TDI in g/l).
(Rumble 2017; Hardie & Dolye 2012)

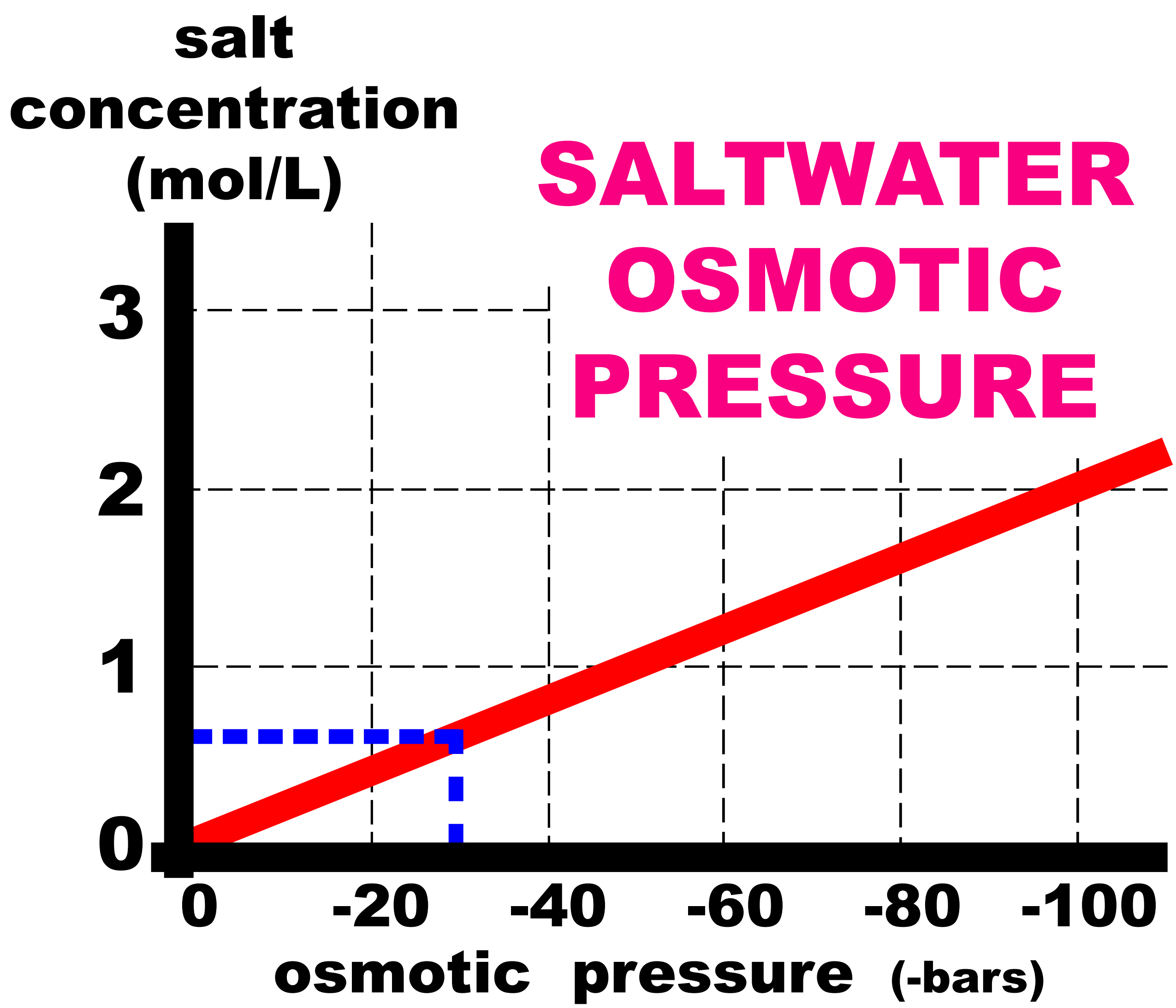


Figure 10: Osmotic (water) pressure in negative bars for high concentrations of salts (mol/L). Dotted lines represent average surface seawater values. (Rumble 2017)

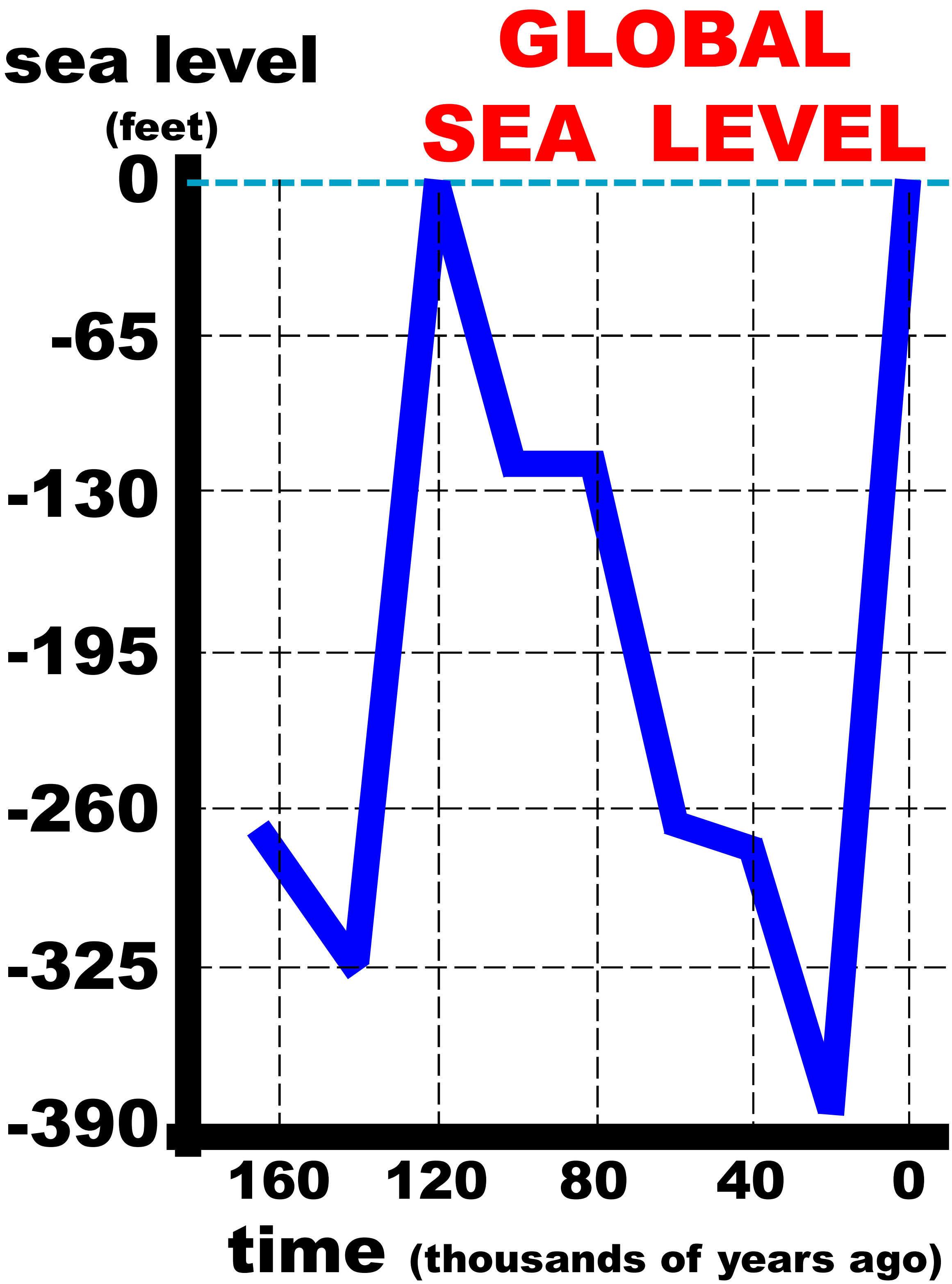


Figure 11: Historic sea level changes in feet estimated over the last 160,000 years. (after Hine et.al. 2016)

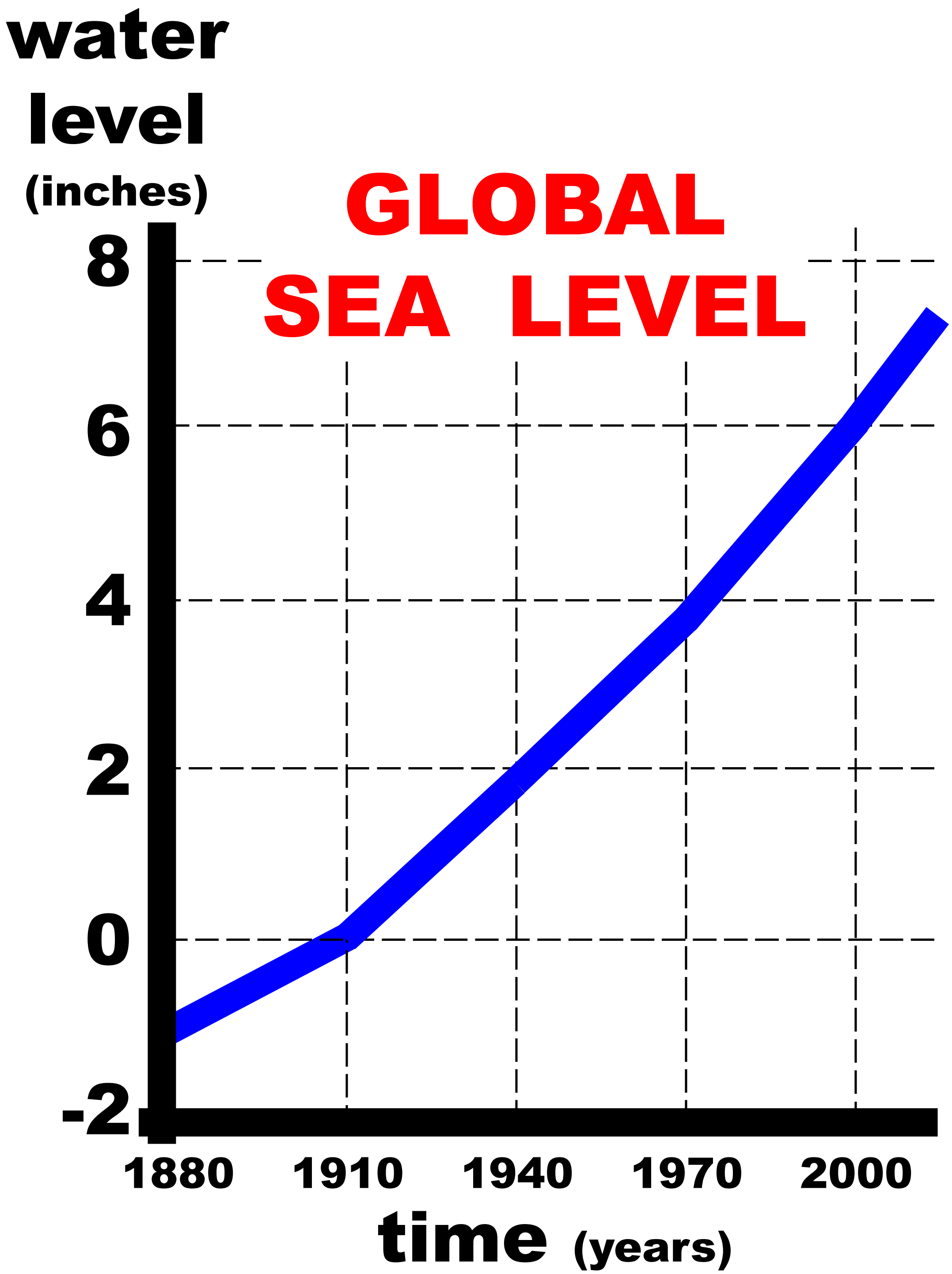


Figure 12: Average annual sea level change in inches over last 130 years. (after Hine et.al. 2016)

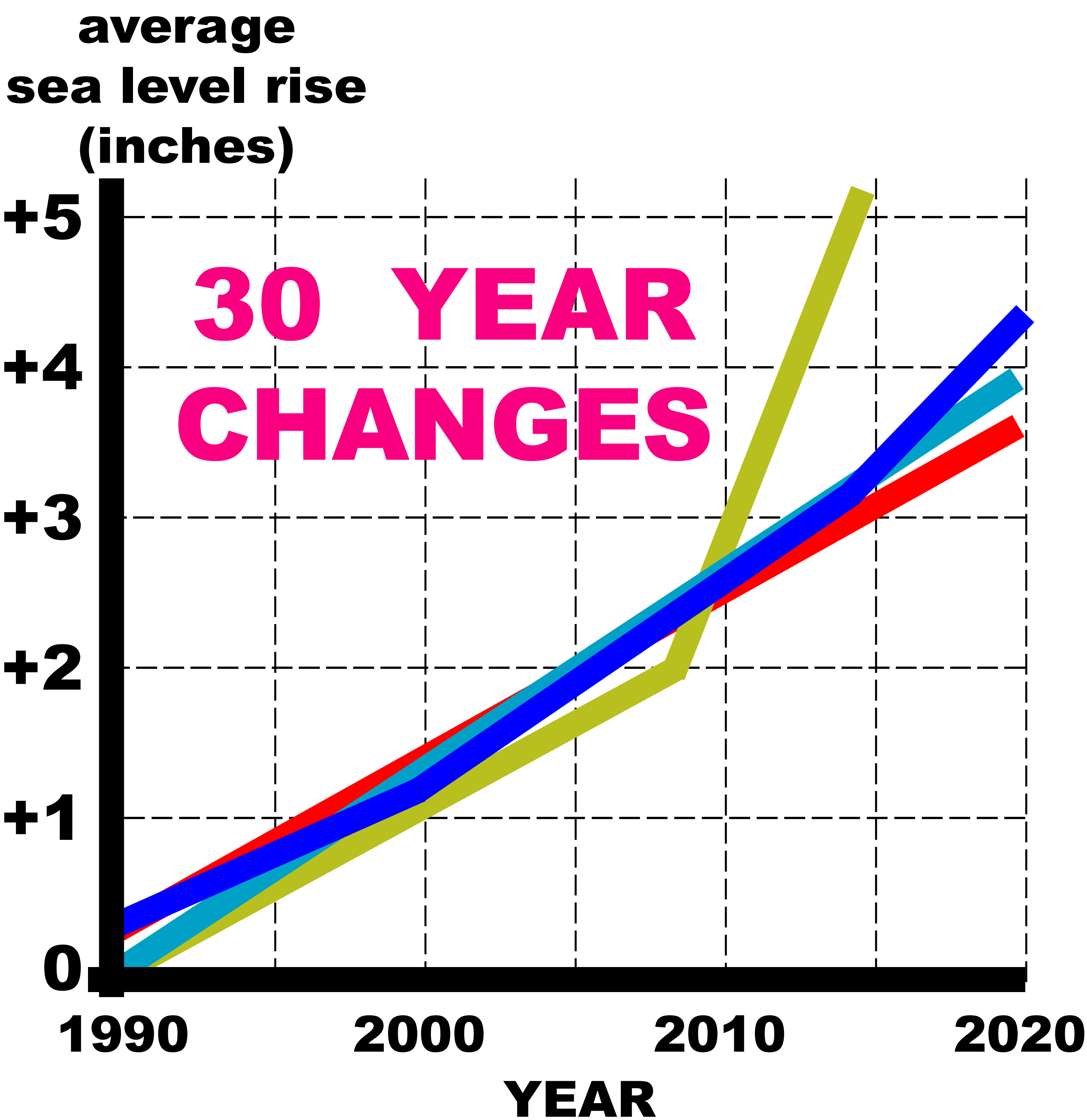


Figure 13: Historic satellite and tide gauge sea level measures by year for various locations.
(J. Englander & NOAA data sources)

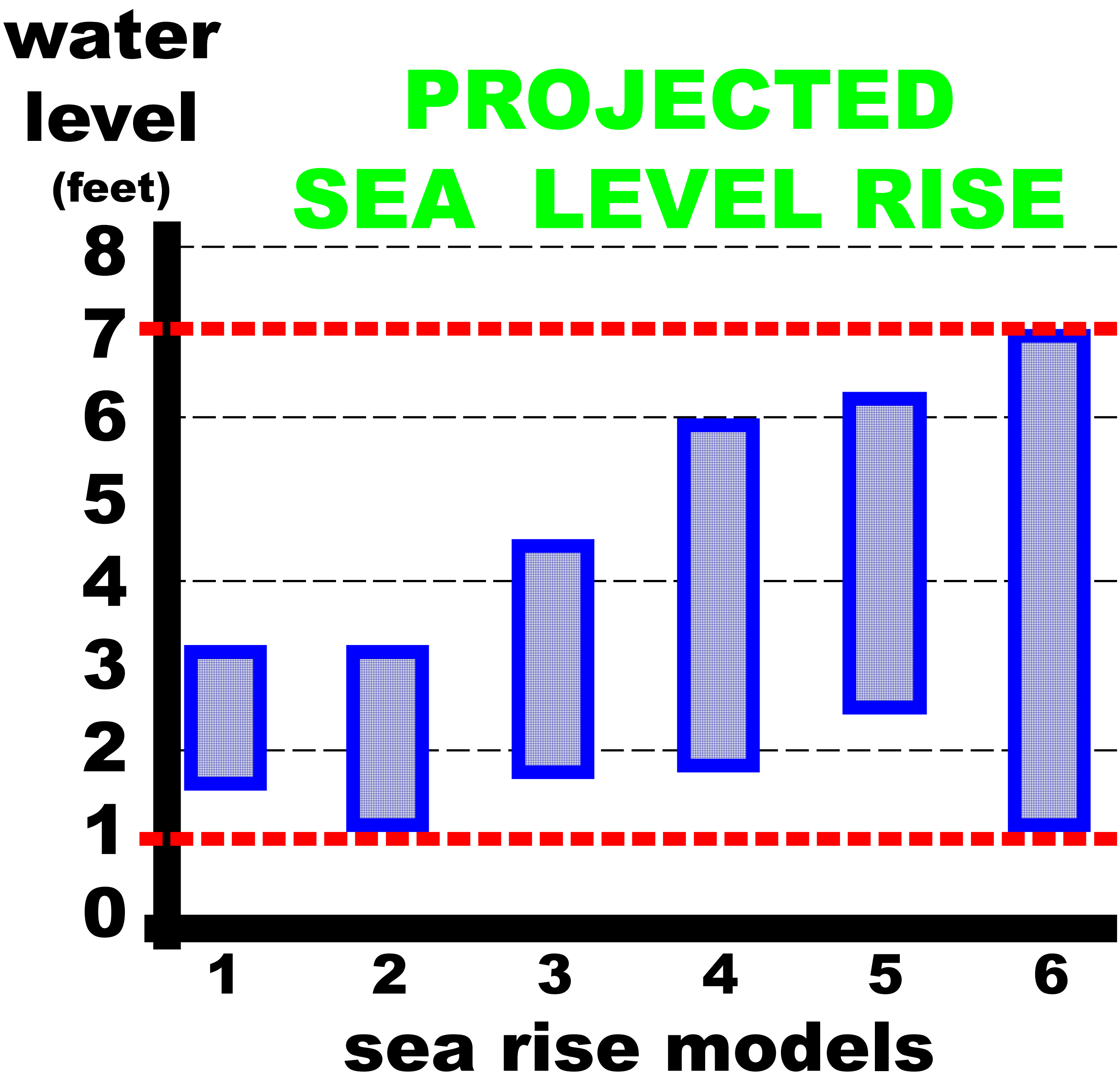


Figure 14: Projected sea level rise in feet by year 2100 based upon six different models. (after Englander 2014)

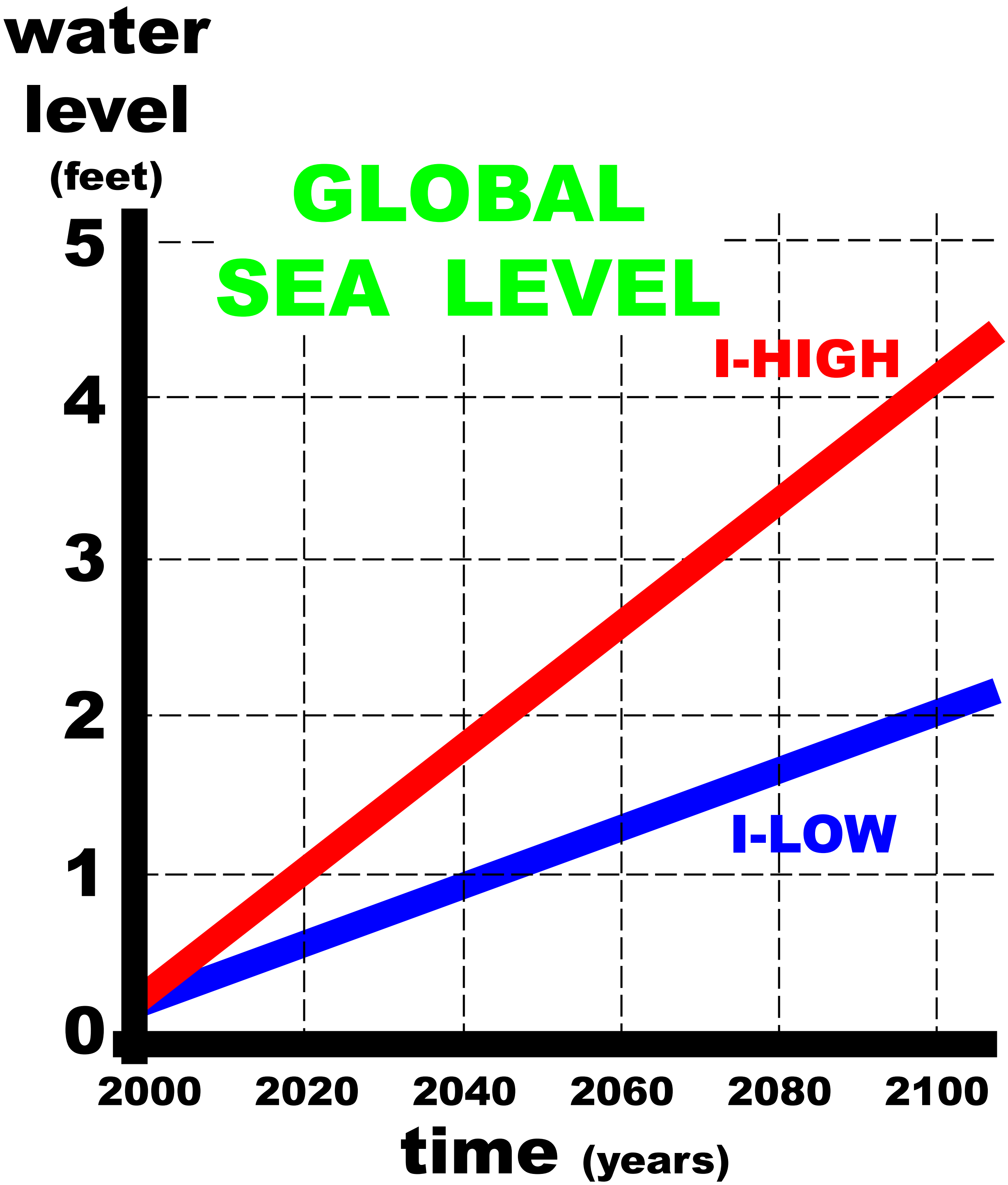


Figure 15: NOAA projected sea level increase in feet developed for regional planning purposes using an intermediate high risk and an intermediate low risk sea level change calculation. (after Hine et.al. 2016)

# SEA LEVEL RISE CHANGES

1. ocean level rises.
2. coastal freshwater table rises.
3. saltwater / freshwater interface moves inland, upward & upstream.
4. water-way flow increases.
5. well water more salty.
6. tree ecological viable volume declines.

Figure 16: Saltwater / freshwater interface changes as sea levels rise. (after Hine et.al. 2016)

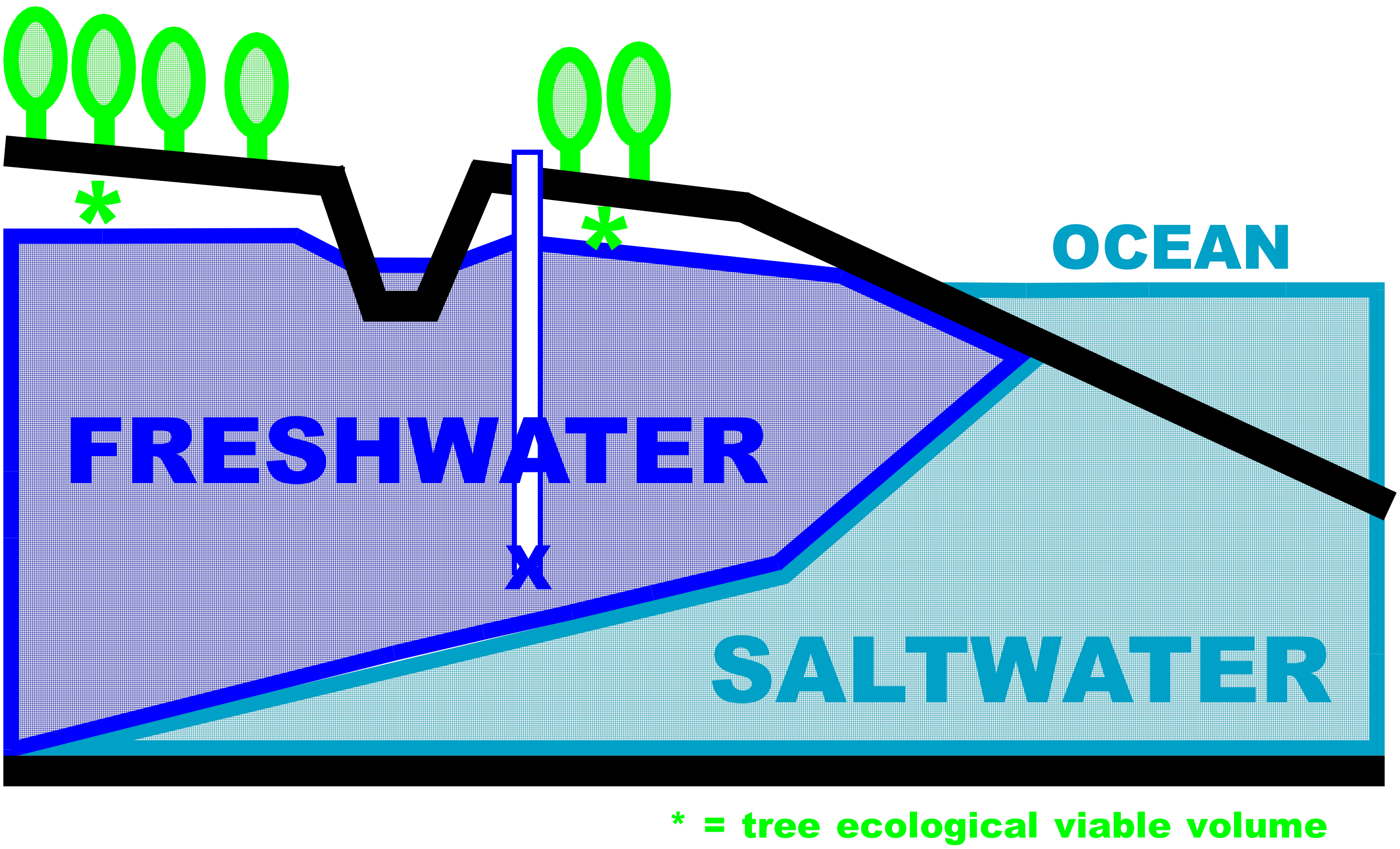


Figure 17: Saltwater and freshwater interface along coast.
(after Hine et.al. 2016)

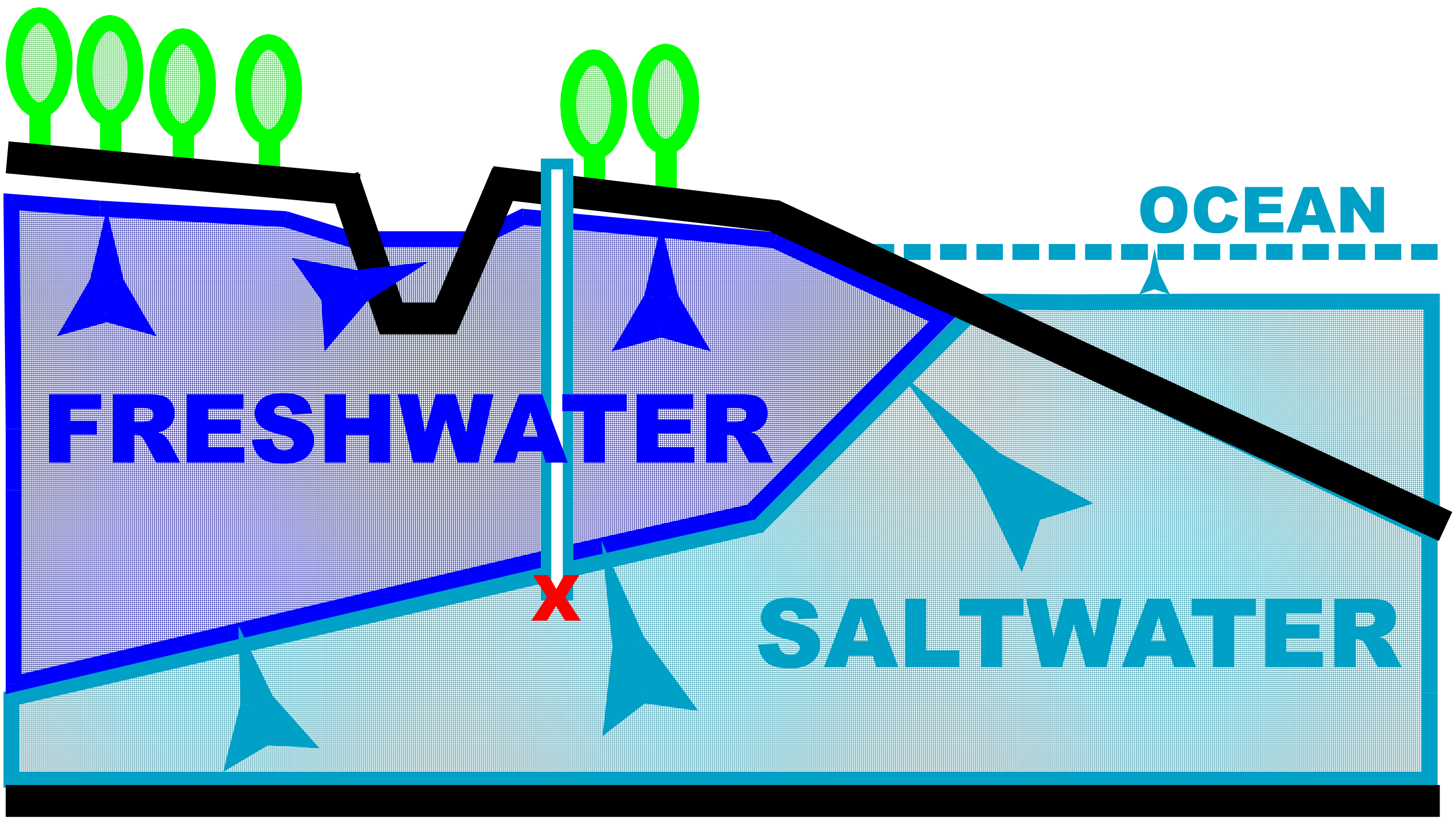


Figure 18: Saltwater and freshwater interface along coast changes with increased sea level. (after Hine et.al. 2016)

# TREE SITE & LANDSCAPE DRAINAGE

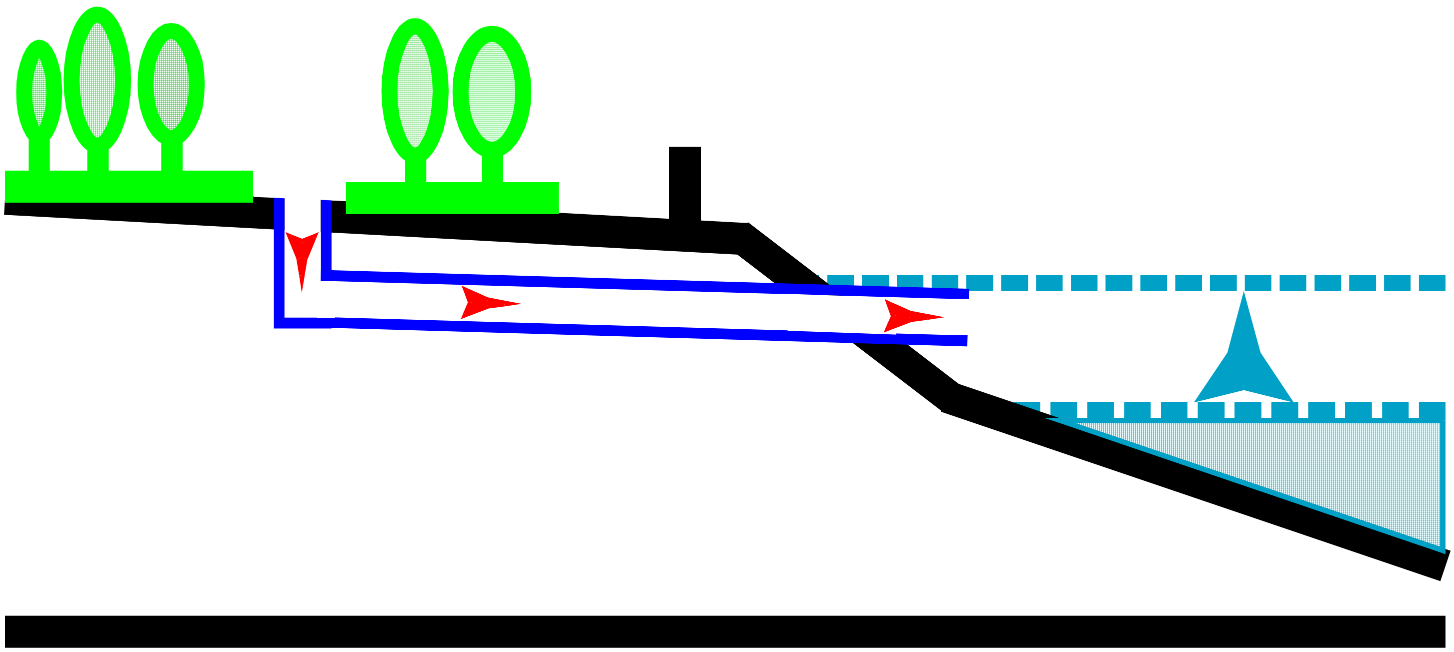

Figure 19: Rising ocean levels impact tree site and landscape drainage capacity (reduced flow & reverse flow).
(after Hine et.al. 2016)

# JURISDICTION & OWNERSHIP ISSUES

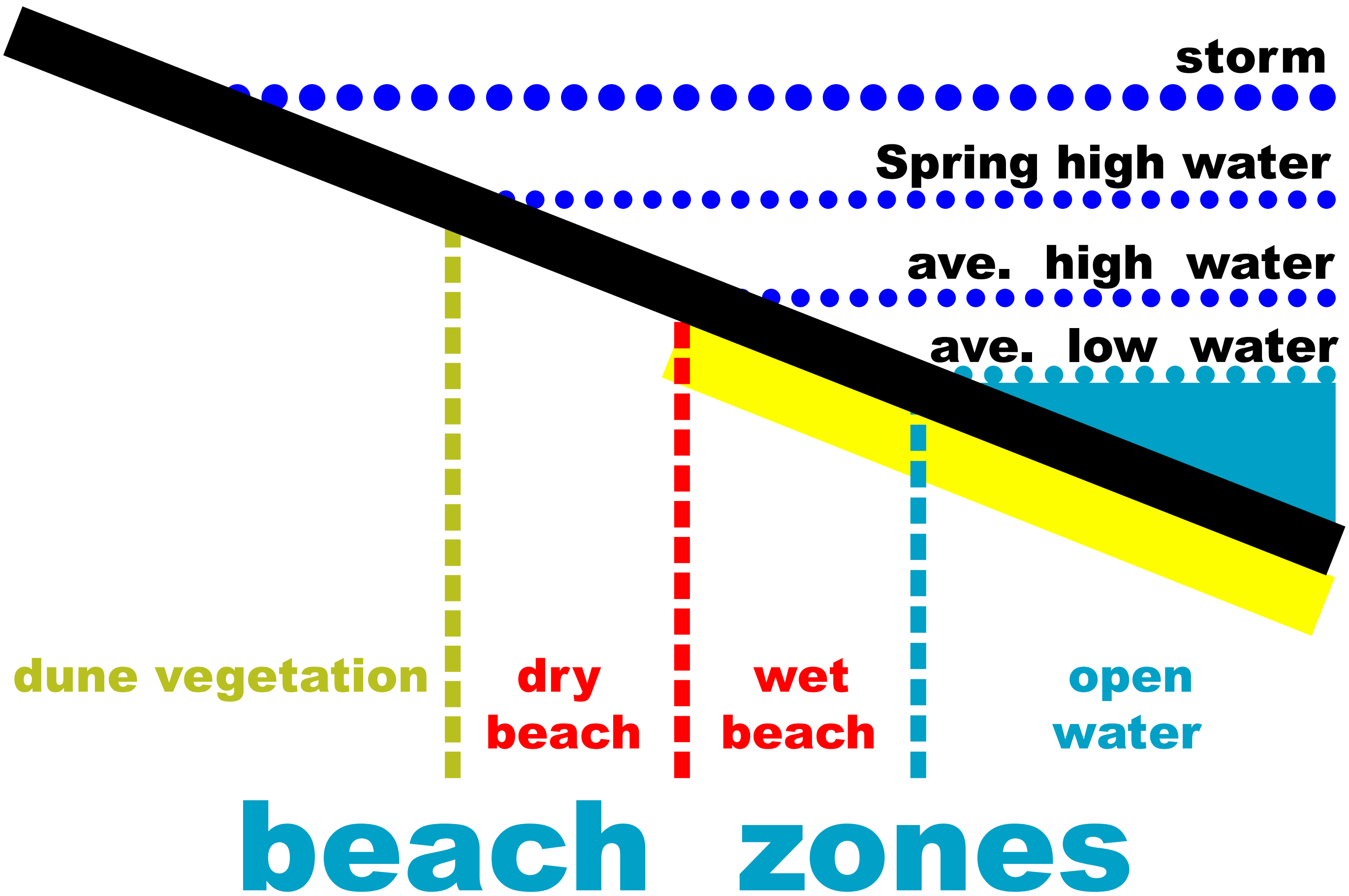


Figure 20: Beach zones normally associated with sea level, and the usual location of public ownership (i.e. yellow line below average high water line). Sea level rise will change these deliniations. (Titus et.al. 2009)

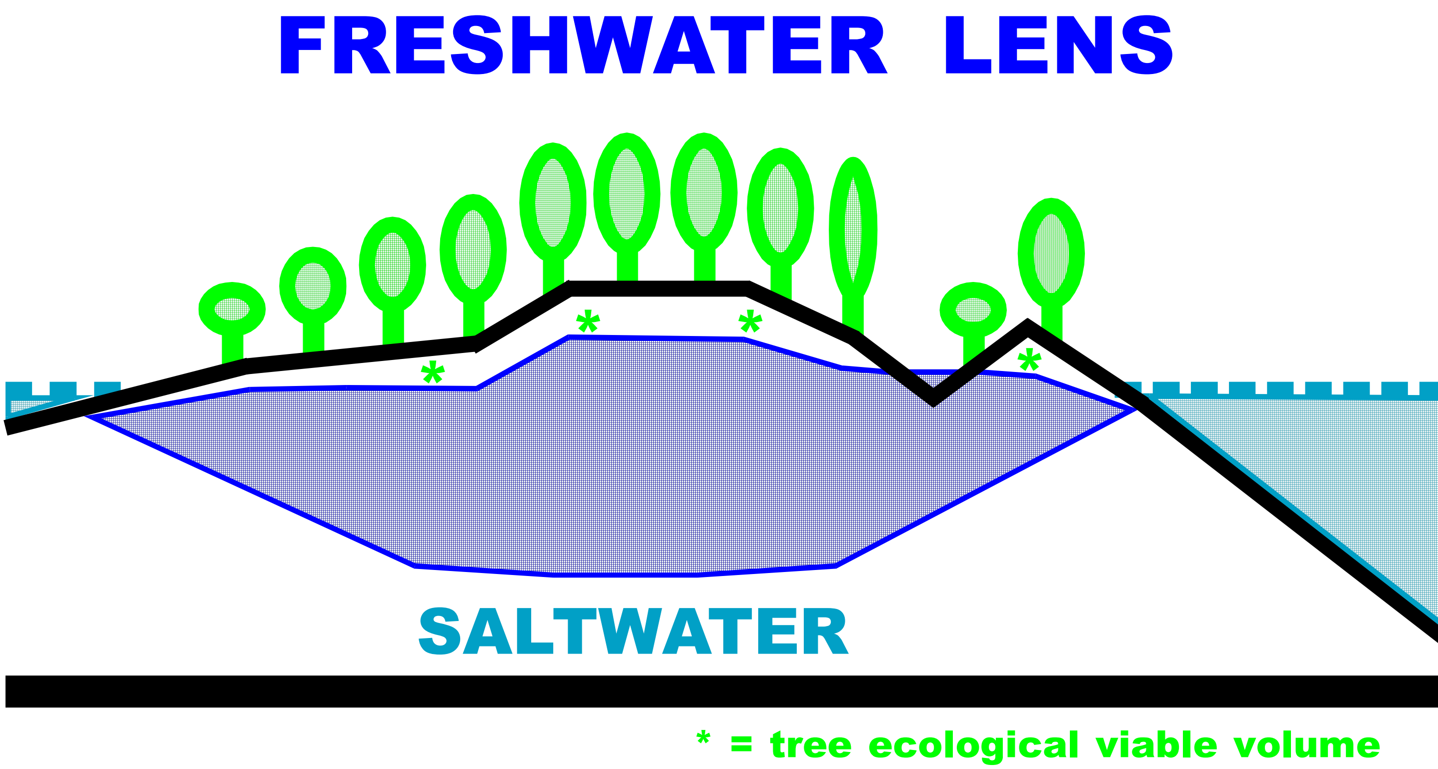


Figure 21: Barrier island's floating freshwater lens and ecologically viable volume for tree growth perched above saltwater. (after Hine et.al. 2016)

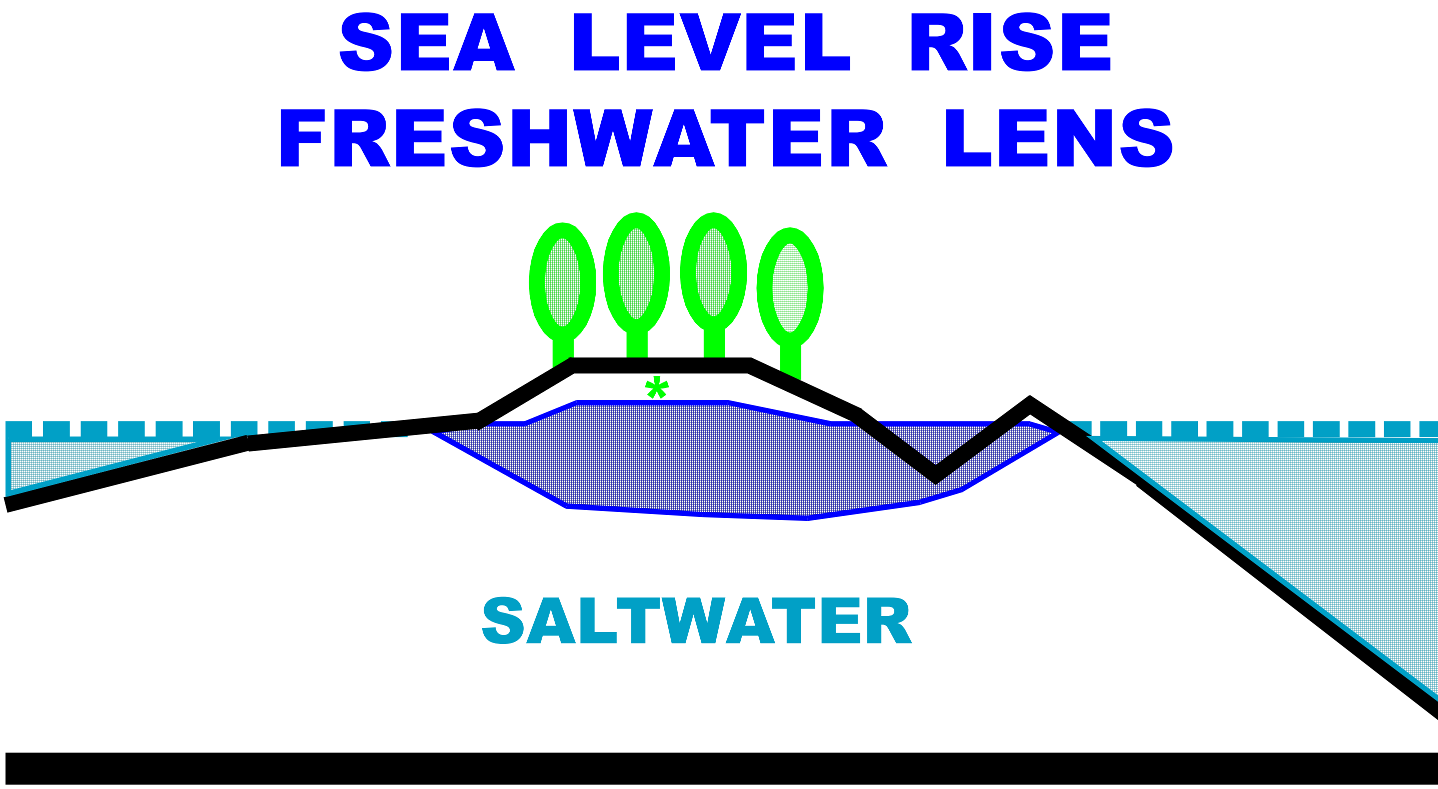


Figure 22: Rising ocean levels deminishing barrier island's floating freshwater lens and ecologically viable volume for tree growth. (after Hine et.al. 2016)

# SEA LEVEL RISE

1. beach & bluff retreat
2. shoreline recession
3. island thinning
4. island wash-over

5. wetland conversion
6. marshland expansion
7. salinity increase on sites
8. tree & forest die-off

Figure 23: Rising ocean level impacts on island trees and forested sites. (after Hine et.al. 2016)

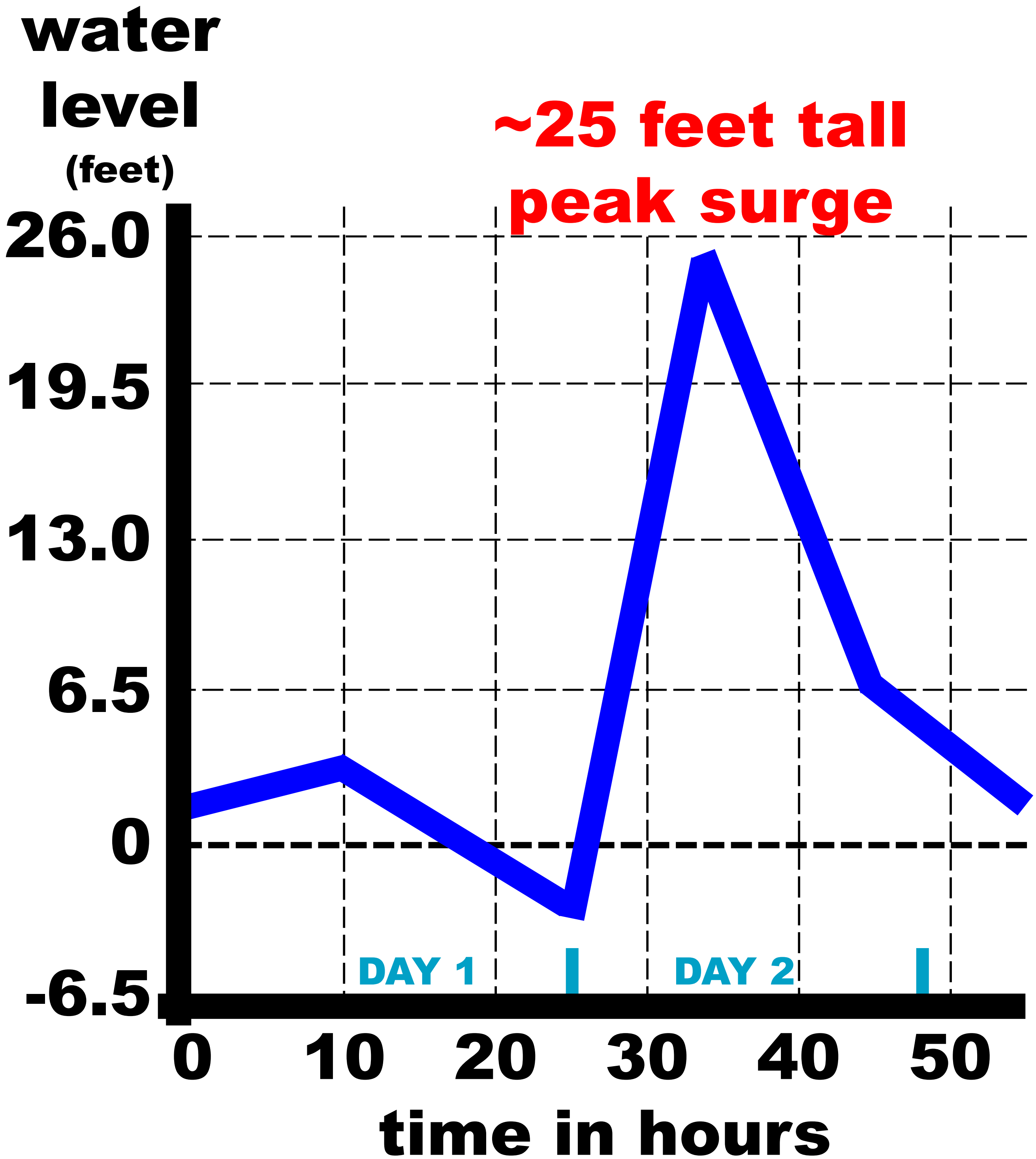


Figure 24: Storm surge associated with hurricane Camille (cat. 5 -- 1969) in Mississippi. (after Hine et.al. 2016)

# Hurricane Surge Levels

| hurricane name | year | surge height |
| --- | --- | --- |
| Sandy | 2012 | 13 ft |
| Katrina | 2005 | 27 ft |
| Dennis | 2005 | 8 ft |
| Isabel | 2003 | 8 ft |
| Opal | 1995 | 24 ft |
| Hugo | 1989 | 20 ft |
| Camille | 1969 | 25 ft |
| Audrey | 1957 | 12 ft |

Figure 25: Selected hurricane surge heights along Atlantic and Gulf coasts of the United States with hurricane name, year of land-fall, and highest recorded surge height in feet.

# Years Between Storm Surge Events

| storm surge severity level | historical impacts | projected sea rise 2' rise | projected sea rise 3' rise |
|---|---|---|---|
| moderate | 7 yrs. | 0.3 yrs. | 0.1 yrs. |
| major | 27 | 1.7 | 0.3 |
| record | 81 | 7.3 | 1.7 |

Figure 26: Average number of years between storm surge flooding events historically (1927-2009), and projections of years between storm surge events for two sea level rise changes. (Stiles 2012)

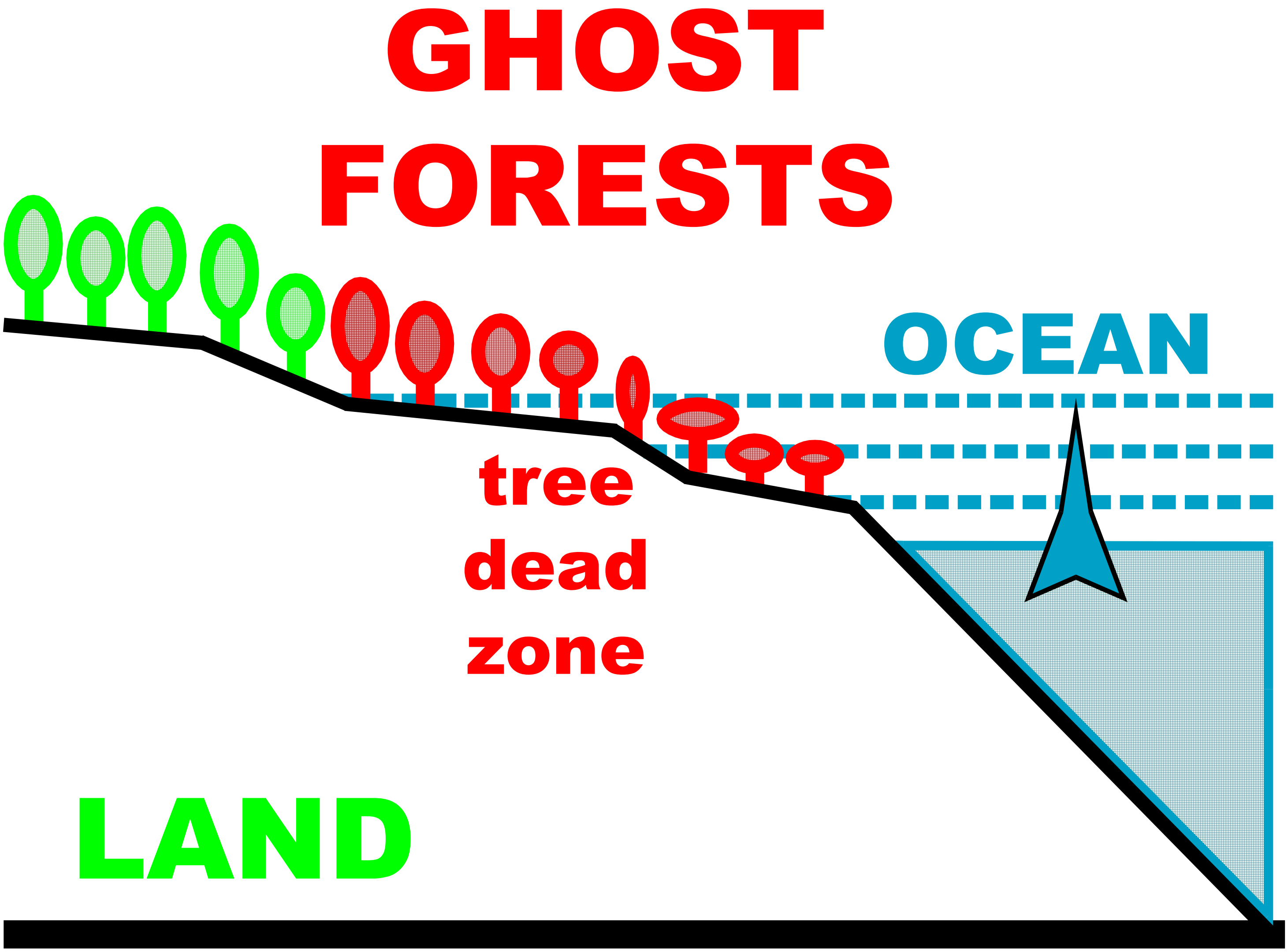


Figure 27: Rising ocean levels impacting coastal community trees and forests, leaving a dead band of trees between marsh and live forest.
(after Hine et.al. 2016)

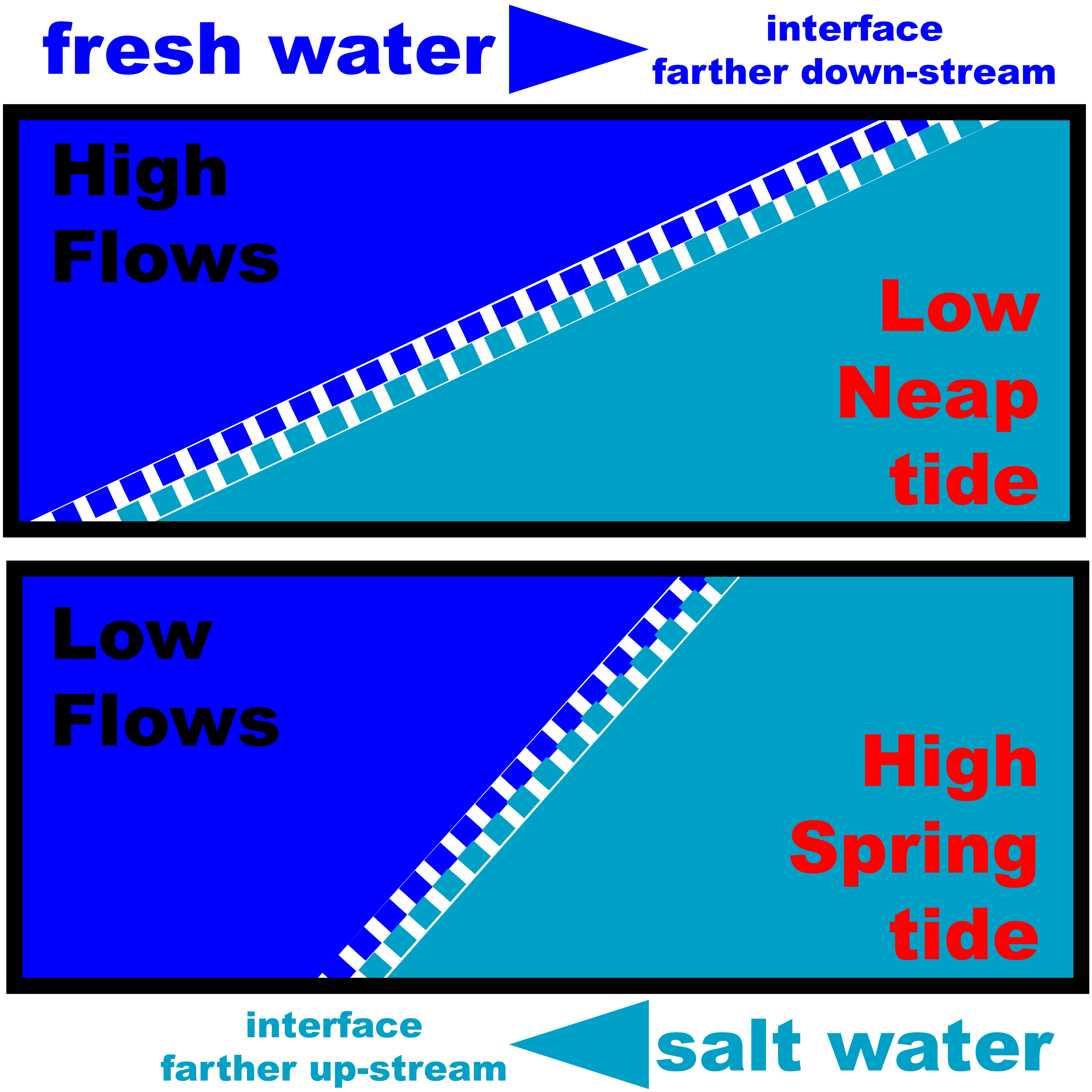


Figure 28: Boundary location of the saltwater / freshwater interface in tidal rivers and how it moves upstream and downstream with changing tide levels. (Conrads et.al. 2013)