Snow, Ice and Extreme Cold

Key Points

- Most of the time Seattle's winter weather is controlled by the Pacific Ocean which remains relatively even in temperature throughout the year. Occasionally, however, cold air from the interior of the continent pushes into the Puget Sound region and causes dramatic cold spells, ice and snow.
- While Seattle does not receive as much snow on average as many parts of the country, snowfall is not uncommon and can be very heavy.
- Accurate weather records began only about 100 years ago, but based on historical accounts, Seattle's winters seem to have been colder and snowier in the 19th and early 20th centuries.
- Meteorologists have made great strides in forecasting snow and ice storms. Roughly 80% of snow storms in the Puget Sound lowlands occur when cold air from the interior of the continent pushes through the Frasier Gap near Bellingham and meets a low pressure system coming off the ocean. If the cold front lingers, snow and ice can be on the ground for weeks[1].
- The main effect of snow is the impairment of transportation. Because nearly all social and economic activity is dependent on transportation, snow can have a serious impact. Most of the effects are cumulative, so the longer transportation is impaired, the greater the impacts.
- Some of the most significant impacts from snow are:
    - Public safety impacts resulting from the inability to get emergency vehicles where they need to go.
    - Utility outages as power demand peaks and pipes freeze. Power losses during extreme cold have resulted in deaths from carbon monoxide poisoning as some people attempt to keep warm by lighting charcoal fires indoors.
    - Economic losses due to business closures and lost wages by workers unable to get to work or required to stay home with children when schools and childcare close.
- Seattle does not have dedicated snow plows, trucks have to outfitted with snow removal equipment when snow threatens.
- Even with all trucks have been outfitted with snow removal equipment, there is not enough of them to plow every street in the city.
- Due to Seattle's steep topography, some streets are too steep to keep open during snow and ice events.
- The Seattle Department of Transportation and King County Metro developed new snow and ice plans following the challenges of the 2008 snow and ice storm. The new plans stress increased use of salt, more pre-staging of snowplows, better gathering of information about conditions of streets and buses and better communication with the public.

- During snow and extreme cold, Public Health – Seattle & King County issues public warnings about the dangers of carbon monoxide poisoning. A regional "Take Winter by Storm" campaign also helps educate on winter preparedness and safety.
- Occasionally, rapidly melting snow can contribute to saturating the ground and becomes a factor in triggering landslides. The last time this happened was in the winter of 1996/97.
- Snow load has collapsed roofs, most recently in 1996/97.

Context

A maritime climate usually keeps Seattle warm in the winter. The prevailing westerly winds that blow in from the Pacific keep cold arctic air from reaching the area most of the time. Occasionally, an arctic front develops in which cold air from the Yukon moves south into British Columbia and through a gap in the Cascades northeast of Bellingham. If this push of cold air is met by moist warm air from the Pacific, snow is often the result. Usually, the snow starts near Bellingham and moves south. Such fronts account for roughly 80% of Puget Sound snow[2].

During major snows storms the transportation system shuts down, trapping people at home or work. Accidents rise among those who try to drive. Access to emergency services is impaired. During exceptional storms, structures can be damaged. This happened in the 1996/97 storm when a number of roofs collapsed. Energy use skyrockets, placing a demand on power generation and distribution systems. Elsewhere in the nation, spikes in energy demand have reached crisis levels. During the 1993/94 winter, some parts of Pennsylvania had to ration power. Some poorer people and those on fixed incomes cannot afford the extra expense and must suffer through the cold.

Snow storms slow the local economy, but there is a debate about whether these slowdowns cause permanent revenue losses. Productivity and sales may decline but often accelerate after a storm. Some permanent effects may occur if some areas are accessible and some are not. For example, holiday shoppers may go to Bellevue to buy Christmas presents if they cannot get to Seattle stores. For workers, snow can be a hardship, especially for those who lack benefits and vacation time. For local government, responding to snowstorms can be a major unbudgeted expense. Some have even had to issue emergency bonds to cover recovery costs.

There is some evidence that widespread and lingering snow can act as a brake on economic activity. The Liscio Report, a private financial newsletter, found that during the cold and snowy winter of 1977/78 economy growth nationally slowed from 6-7% to 1% in the last quart of 1977 and 3% in the first quarter of 1978.

Snow, ice and cold also present health risks. Unfortunately, previous studies tending to downplay their consequences because few fatalities are directly attributable to the weather. As the analysis grew more sophisticated, researchers learned that indirect effects of the storms resulted in many fatalities, e.g., traffic accidents, sledding, exposure to cold, falls and carbon monoxide poisoning. Research by the National Weather Service has found that:

- Ice is more deadly than snow;
- About 70% of deaths occur in automobiles;
- About 25% of deaths are people caught outside;
- 50% of hypothermia cases are over 60 years old, 75% are male and 20% occur at home.

The cold that often lingers after a snow storm can produce its own dangers, especially if the cold is accompanied by power outages. The primary danger is hypothermia. This danger is mainly to the homeless population and those without heat. The elderly and socially isolated are the most vulnerable.

Excessive cold especially when accompanied by wind can cause frostbite and hypothermia. Wind chill is the temperature it "feels like" outside and is based on the rate of heat loss from exposed skin caused by the effects of wind and cold. As the wind increases, the body is cooled at a faster rate, causing the skin temperature to drop. Frostbite is an injury to the body caused by freezing body tissue. The most susceptible parts of the body are the extremities, especially fingers, toes, ear lobes or the tip of the nose. Hypothermia is an abnormally low body temperature, below 95 degrees Fahrenheit. Warning signs include uncontrollable shivering, memory loss, disorientation, incoherence, slurred speech, drowsiness and apparent exhaustion.

History

The unofficial record for the most snow in one winter is 64 inches in 1880. The single-day record is 21.5 inches in 1916[3]. Other historical records that extend back beyond modern record keeping indicate that Seattle was colder and snowier in the past. Several authors mention extended periods of below freezing temperatures.

December 1861. Very cold, with an unofficial -4 degree temperature. Newspapers mentioned ice-skating on Lake Union covered in six inches of ice.

Winter 1880. Usually regarded as the snowiest winter in Seattle. An unofficial 64 inches fell during the season. Snow drifted three to five feet at the waterfront, possibly indicating even bigger drifts at higher elevations. Most significantly, roofs collapsed throughout the city.

January 1893. 45.5 inches fell in less than two weeks.

February 1, 1916. Single-day snow record set at 21.5 inches. The roof of the St. James Cathedral collapsed. Snow drifts were up to five feet.

January 1920. A sledding accident on Queen Anne killed four children and injured five more.

February 1923. 16 inches of snowfall.

January 1943. Total of 18.4 inches in a week closed schools and caused power outages.

January 13, 1950. Near record one-day snowfall of 21.4 inches at SeaTac accompanied by 25-40 mile per hour winds. 57.2 inches fell the entire month at SeaTac. This storm claimed 13 lives in the Puget Sound area. The winter of 1949-50 was the coldest since official records began.

Winter 1956. 23 days of measurable snowfall. There is no indication if this was a record, but it does point out that Seattle snows can persist for weeks.

December 1964. Eight inches of snow fall.

December 1968 Ten inches fell on New Year's Eve. Despite the chances for increases in alcohol-related accidents, there was not a reported increase.

January 1969. 19 inches accumulated at SeaTac on the 28th. Nearly 46 inches fell during the month.

January 1972. Intense cold. Nine inches of snow fell at SeaTac. Schools closed. This storm was connected to landslides later that year.

December 1974. Nearly ten inches of snow fell as the power went out in many parts of the city.

November 1985. Eight inches fell on Thanksgiving Day.

December 1991. Snow closed SeaTac and brought traffic to a halt.

December 1996 Near record snow falls the day after Christmas. Metro halts service completely for the first time in its history. Freeze and snowmelt contribute to flooding and landslides during the following week.

December 2008. Seattle experiences a rare extended period of lingering snow.

The city's Snow and Ice Response Plan gives more detailed information for recent years. Data from the National Oceanic and Atmospheric Administration for the Seattle-Tacoma area shows that from 1990 to 2003 there were 146 days of snowfall. This includes 70 days when there was only a trace amount of snow. Of these 146 days, 131 had light snowfall of less than 1 inch and 22 had heavy snowfall of more than 1 inch[4]. **Error! Reference source not found.** indicates the snowfall from October through March between 1948 and 2009.

Likelihood of Future Occurrences

Seattle will continue to get snow storms, but the trend is uncertain. Detailed records in the Puget Sound region date back only 120 years. While climate change will increase the average annual temperature, the effects on snow events is less predictable. Mountain snowpack is predicted to drop dramatically as more precipitation falls as rain rather than snow.

Other global weather patterns will continue to overlay global climate change to complicate matters even more. These include the El Niño Southern Oscillation (ENSO) that alternately brings El Niño and La Niña to the Pacific Northwest. El Niño is characterized by warmer, somewhat dryer winters; La Niña is

characterized by wetter, cooler and snowier winters. The Pacific Decadal Oscillation which works in a similar way to ENSO, but on a decade long scale[5].

It is possible that Seattle could get generally warmer winters but still have periodic large storms. It is also possible that Seattle could see a period of extended cold as occurred in the latter half of the 19th century and early 20th century.

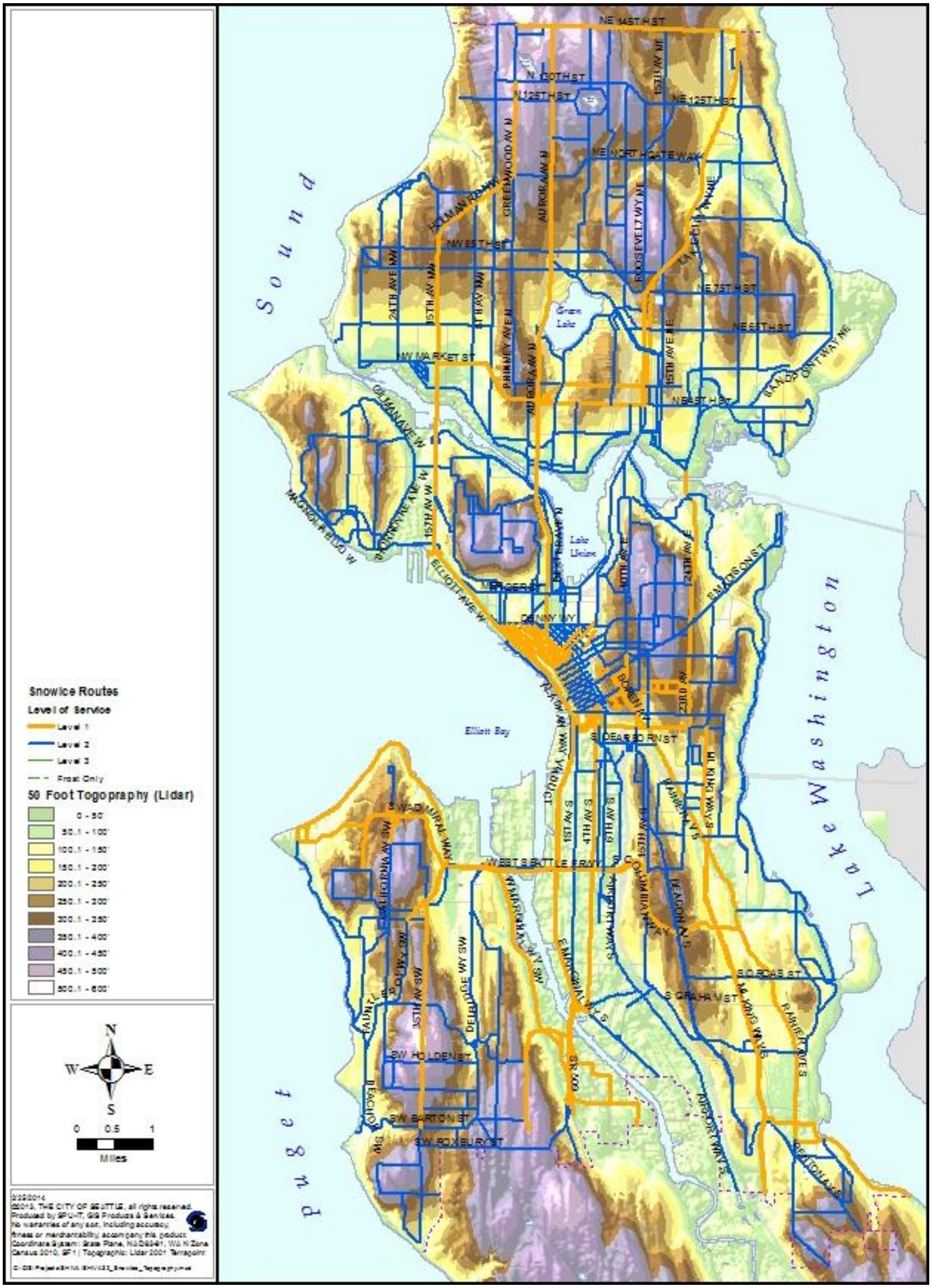
Vulnerability

Seattle's geology and climate work against it during snowstorms. First, the hilly topography makes many areas of the city impassable even after a light snowfall. Queen Anne Hill, Beacon Hill, parts of West Seattle and areas facing Lake Washington and Puget Sound seem especially prone to isolation during storms because of the many steeply graded streets that serve them. Second, the relative infrequency of heavy snowstorms makes it challenging to plan a response. Finally, the lack of dedicated equipment adds to the city's vulnerability.

The city's poorer and older residents are the hardest hit. The homeless are the most vulnerable. Although attempts are made to find extra space for them in shelters, many are still on the streets even in harsh weather. People without back-up sources of heat will also suffer from the cold during outages. In 2006, several incidents of carbon monoxide poisoning occurred when people attempted to burn charcoal indoors to maintain heat.

Anyone needing medical care is vulnerable when the transportation system is impaired. Older people are indirectly affected since they require medical care most frequently and snow can make it more difficult for them to receive it. When critical outpatient services cannot be accessed, medical needs may escalate. Patients may deteriorate and require ambulance transport, emergency department care and

Figure 1. Snow and Ice Routes by Service Level[6].


Puget Sound
Lake Washington
Elliott Bay
Lake Union
Green Lake
NE 145TH ST
N 130TH ST
N 125TH ST
NE 125TH ST
NE NORTHGATE WAY
NW 85TH ST
NE 75TH ST
NE 65TH ST
NW MARKET ST
NE 45TH ST
SAND POINT WAY NE
ELLIOTT AVE W
DENNY WY
E MADISON ST
S DEARBORN ST
WEST SEATTLE FRWY
S GRAHAM ST
SW HOLDEN ST
SW BARTON ST
SW ROXBURY ST
SnowIce Routes
Level of Service
Level 1
Level 2
Level 3
Frost Only
50 Foot Togopraphy (Lidar)
0 - 50'
50.1 - 100'
100.1 - 150'
150.1 - 200'
200.1 - 250'
250.1 - 300'
300.1 - 350'
350.1 - 400'
400.1 - 450'
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admission. This places an additional burden on the healthcare system in King County. Children are another risk group because they play along dangerous streets. Several have been killed in sledding accidents.

Several socio-economic groups have high exposure to winter storms. Seattle retailers are vulnerable because a major part of the snow season overlaps the holiday season. The loss of sales at this time can be critical. Seasonal, temporary, contract and other workers who lack paid time off lose income during snow storms.

Consequences

Snowstorms are a recurring hazard in Seattle. Their indirect, secondary effects outweigh their direct effects. The two biggest direct impacts are cold and immobility. These drive the main secondary impacts, which get worse the longer the snow and ice remain on the ground. As the 2008 experience demonstrated, snow and ice can linger for weeks in Seattle and the city government, residents, workers and business must be prepared for this situation.

Seattle will face transportation impairments while snow is falling and up to eight hours after it has stopped along most snow routes. Non-designated streets will face longer impairments. The city does not have enough snow removal equipment to plow every street in the city.

Residents must be prepared for several days of restricted access to many services and shutdowns of schools and other institutions. Workers and business need to develop contingency plans to get people into work and open businesses.

Power outages during snow storms and the cold weather that often accompanies them remains a serious threat. Hypothermia and carbon monoxide poisoning will continue to be risks.

Climate change may introduce new challenges. The frigid weather places increased demands on the power system as people try to heat their homes. In the past, demand peaks have not reached the point of crisis and there have been no cases of power rationing as in other parts of the country. However, if projections are correct and snowpack is reduced, City Light may have to purchase additional power from external sources to meet demand.

Secondary effects of snow can be flooding and landslides as the snow melts. In heavy snowstorms, structural damage is likely. During the 1996 snowstorm, over 80 roofs suffered damage. These failures are always a danger since the Seattle area is prone to wet, heavy and sticky snow

Because Seattle once had a colder, snowier period during the late 19th and early 20th century, Seattle must remain open to the possibility that such a period could return again. The more extreme winter storms of this period would present challenges to our more complex and time-dependent society. The types of impacts would be the same as the more likely scenarios, just worse.

Most Likely Scenario

A major snow storm strikes Seattle during a weekday. The snow had been predicted reducing the commute load. Snow alternates with cold temperatures. Combined 12" of snow accumulates. It remains on the ground for a week. As the snow is melting another storm dumps freezing rain on it. The freezing rain snaps branches causing scattered power outages.

Category	Impacts 1 = low 5 = high	Narrative
Frequency	5	Heavy snowstorms do not occur every year in Seattle but are not rare events either. The most likely future severe snow storm would be similar to those that have occurred recently (e.g., 2008, 1996).
Geographic Scope	5	This snowstorm affects the entire Central Puget Sound region. The snow moves up from the south to the north. South Seattle receives more snow than north Seattle.
Duration	3	Snow falls for three consecutive days. It remains frozen on the ground for four days then a warm front moves in and rapidly melts the accumulation.
Health Effects, Deaths and Injuries	1	There are no deaths that are directly attributed to the storms. Investments in public warning about using charcoal indoors and sledding on dangerous hills save lives.
Displaced Households and Suffering	2	No households are displaced but many people cannot make it out to go shopping and some stores are not receiving supplies. As a result some vulnerable people are going hungry and not receiving needed medical attention.
Economy	2	The storm hits in mid-December hurting Christmas retail sales. Shoppers forgo purchases or shift to buying online.
Environment	1	Salt is used to melt ice, but the quantities used are not enough to do permanent damage to marine ecosystems when they wash into the waste water system.
Structures	2	The snow collapses the roofs of 5 buildings causing them to be red tagged.
Transportation	2	The storm is forecast. Seattle is able to start pre-treatment of roads and Metro is able to chain buses. These actions mitigate the effects of the storm beginning mid-day. The commute is very bad but could have been much worse. During the next three days roads have snow accumulations because the snow is falling faster than roads can be plowed. Once the snow stops the arterials are cleared to specifications in the Seattle Snow and Ice Plan but residential streets remain snowbound.
Critical Services and Utilities	2	The storm does not cause any large scale infrastructure outages, but numerous small water lines freeze. Public safety vehicles have a harder time reaching some parts of the city.
Confidence in Government	1	Due to improvements in the City's Snow and Ice Plan, it meets its targets. The public experiences some hardships near the end of the storm but does not blame the government for them.
Cascading Effects	2	During the storm a tour bus slides down a hill crashing into a building injuring 15 people. 140 buildings have their pipes freeze.

Maximum Credible Scenario

Seattle has a winter similar to those it had in the 19th century. Multiple snow storms hit the region straining snow removal budgets. In the biggest storm 24" falls in 36 hours on top of 12" existing base.

The storm begins as freezing rain and transitions to snow. The intensity of the storm was missed in most forecasts. It begins mid-day. Roofs collapse. After the storm, extreme cold sets in freezing Lake Union.

Category	Impacts 1 = low 5 = high	Narrative
Frequency	3	Seattle seems to have had snowier weather in the 19th century. This scenario envisions a set of storms marginally worse than these incidents.
Geographic Scope	5	The whole Central Puget Sound region is affected by this storm.
Duration	4	The entire incident lasts two and a half weeks from the first snowfall to the melt.
Health Effects, Deaths and Injuries	2	9 people are killed falling off roofs, sledding and burning charcoal indoors.
Displaced Households and Suffering	3	2 apartment buildings have roof collapses. The collapses do not injure anyone, but residents must seek shelters. Others are driven from their homes when they lose power. All told 235 people need shelter. Many in the general public begin to run short of food and medicine.
Economy	3	The storm hits during the December shopping season. Businesses cannot remain open. Major employers have to close.
Environment	2	Major amounts of salt and sand are used to keep roads open. It washes into the drainage system and ultimately into Puget Sound.
Structures	2	6 buildings suffer collapsed roofs.
Transportation	4	Surface transportation experiences major degradation. While snow is falling Seattle crews are unable to keep up with intensity of the storm. After the snow stops falling they are able to catch up within 48 hours but residential streets remain nearly impassible. Airports must halt flights until the snow stops.
Critical Services and Utilities	3	Public safety personnel have difficulties reaching many parts of the city. The ice accompanying the storm brings down power lines in many areas of the city. The snow impedes power restoration. Many water pipes freeze causing businesses and residences to lose water service.
Confidence in Government	3	The public becomes frustrated at their lack of mobility. They need help getting basic supplies and think the government should be doing more to help them.
Cascading Effects	3	The snow storm causes many traffic accidents including a gas tanker that crashes and burns. Ice and extreme cold have caused power and water outages.

Conclusions

Seattle does not sit in the Snowbelt and Seattleites do not have the experience of many Midwesterners and New Englanders. Seattle is a northern city, though, and it can and does receive heavy snowstorms. This creates a dilemma for the government and the population. Extensive preparations become very

costly if the snow fails to materialize; if snow does come and the city has not prepared, significant transportation problems arise.

Water Shortages

Key Points

- A water shortage occurs when the demand for water exceeds supply. It can be caused by the onset of a drought or sudden infrastructure failure, such as a major pipeline failure or treatment plant shutdown.
- It is extremely unlikely that Seattle would run out of water. To avoid failure of the water supply, a series of increasingly severe usage curtailments would be enacted to ensure that Seattle would have enough water for essential functions. While the curtailments would mitigate a greater disaster, they would have increasingly severe impacts on residents and businesses.
- The City of Seattle supplies water to people and businesses within the city limits and to many customers in King County and southwest Snohomish County through wholesale water deliveries. It depends on its two Cascade watersheds, the South Fork Tolt and Cedar Rivers, for its water supply. Both of these reservoirs are managed for instream flows for fish.
- Wells in the Highline area provide limited supplemental back-up for peak loads and emergencies.
- Peak demand for water for people and businesses occurs in the summer. Replenishment of the city's reservoirs does not occur until the spring, however, when snow accumulated during the winter melts and runoff from rains is stored. Low winter precipitation followed by hot summer weather or later-than-normal return of fall rains can cause a shortage.
- A drop in demand has mitigated the pressure on the water supply. Total water consumption has gone down despite increases in population in the area served by SPU. Since the early 1990s, conservation programs, plumbing code changes and pricing have all contributed to reduced water use in the region.
- During shortages, the City of Seattle undertakes "Phased Curtailments" in four stages: Advisory, Voluntary, Mandatory and Emergency. Restrictions may begin to impose hardships on the community during the Mandatory and Emergency Phases.
- Maintaining public health is the highest priority in managing a water shortage. In extreme conditions, shortages can result in a degradation of water quality, reduction in the flow of water available for firefighting or sufficiently low pressure that water cannot reach certain areas.
- In an Emergency Curtailment, both stringent restrictions and surcharges will be imposed. Such restrictions would be an economic burden on businesses that are heavy water users and customers without the means to pay for surcharges.

Context

Water shortages develop when the supply of water is too low to meet demand. The cause can be either a drop in supply or a rise in demand or both. They are not the same as droughts, which are prolonged periods without precipitation. Shortages often develop as a result of drought but can also be caused by overconsumption or structural failures such as pipeline breaks.

Seattle uses water for direct consumption, e.g., drinking, washing and watering lawns, and to generate electricity. Both types of consumption are cyclic. Water use peaks in the summer with demand determined by the heat and dryness of the weather. Power consumption peaks during the winter. The extent of its demand also depends on the weather. The colder the winter, the more power required.

The city manages its reservoirs in the Cascades to provide water supply for consumption and fisheries, as well as to provide flood management and hydropower generation. During the spring, the city captures runoff from melting water from the winter snowpack and rainfall and stores the runoff in city-owned reservoirs. Water is stored there until the demand increases and releases from storage are required. During times of peak demand, water is drawn from the reservoirs at a greater rate than it is being replaced. This yearly cycle of recharge and draw-downs is the city's "water-budget." For Seattle's drinking water supplies, the end of the yearly drawdown cycle is dependent on the timing of fall rains, which is uncertain and is not forecasted well in advance.

The city draws most of its water for direct consumption from two watersheds in the Cascades—the South Fork of the Tolt River and the Cedar River—and from well fields in the Highline area. The Cedar supplies two-thirds of the city's water, while the South Fork of the Tolt supplies one-third. The Highline wells provide water in emergencies and peak water use periods[vii]. This water is delivered to Seattle's retail customers and SPU's wholesale customers through large diameter pipes.

As for power, City Light gets most of the power it generates from dams on the Skagit and Pend Oreille River. When the amount of water in the reservoirs drops, City Light cannot generate as much power. When peak demand exceeds supply, City Light buys power from other sources, mostly the Bonneville Power Administration. Most of these demand peaks are anticipated so the utility can buy power ahead of time or swap power with another utility. The real costs occur when water shortages are unforeseen and the city must make emergency purchases.

Droughts are slow-onset or "creeping" disasters because their effects accumulate slowly over time. There is always doubt about when to adopt water restriction measures. Water resource managers are never sure if they are overreacting whenever usage restrictions are requested preemptively. This doubt can cause managers to delay action until the drought is well underway. SPU and City Light, with real-time information about snowpack known, can forecast supply for the summer. They cannot, however, predict the end of the drawdown cycle and timing of fall rains.

To respond to a water shortage, SPU uses four levels of water use curtailments: advisories, voluntary restrictions, mandatory restrictions, and emergency curtailments. As a shortage worsens, SPU enacts progressively more stringent restrictions.

Nationally, per capita water use has decreased by nearly 30% since 1975 despite a growing population and economy. While the population that is served by SPU has steadily risen since 1975, water demand leveled off during the 1980s then dropped off sharply in 1992 due to a severe drought and mandatory curtailment measures. Since then, the combined effects of higher water rates, the 1993 state plumbing

code, conservation programs and improved system operations have kept both billed and total consumption significantly below pre-drought levels.

Water consumption further declined between 2000 and 2005 due to additional conservation efforts represented by the regional 1% Conservation Program, significant increases in water and sewer rates and an economic slow-down. Between 1990 and 2005, annual water consumption decreased about 24% (40 million gallons per day), even while population increased by 13%.

Peak water demand has fallen even more than annual average demand since the 1980s. In the 1980s, hot summer weather could produce peak day consumption of over 325 million gallons per day (mgd), compared with only 270 mgd during an extremely hot summer in 1994 when temperatures reached 100 degrees. Ten years later, during the two very hot, dry summers of 2003 and 2004, peak day consumption reduced further, barely reaching 250 mgd.

Droughts do not necessarily cause water shortages, so the existence of one should not be taken as proof of a shortage. Droughts do often contribute to shortages, though. The most common measure of drought intensity is the Palmer Drought Index that describes dryness. The values usually range from -4 (extremely dry) to +4 (extremely wet), although numbers beyond these bounds can occur. The values are a function of precipitation and temperature that are obtained by comparing current local scores with average scores for the area. One significant drawback is that it underestimates the role of water stored in snowpack, which is important for Seattle's water supplies[viii].

Breaks in the pipeline distribution system or events that force SPU to shut down the water system preemptively, such as a failure at one of the water treatment facilities, can also cause shortages. Pipeline breaks or other infrastructure failure often result from other disasters like earthquakes, floods and explosions, but they can occur as a result of mechanical failure or human error. More information on water pipe breaks can be found in the section on infrastructure failures.

Public inconvenience is the most visible and widespread effect of a shortage. If the public is not aware of the severity of the shortage, it will not be inclined to support restrictions. Most residents define a shortage differently than city officials. While the city defines shortages by the amount of supply, the public defines them in terms of the severity of restrictions.

History

Water shortages are a regular occurrence in the region's history. This section reviews the significant shortages to reveal the duration, severity and cause. Drought conditions are cited as an indirect and imperfect measure of the shortage. Some short-term shortages were caused by pipeline breaks, none of which precipitated an immediate health danger in the city or prompted water rationing. Here are the most important events:

1919-A hot, dry summer.

1928/29: This was a long drought that lasted nearly one year. Rain was 20% of normal. This was the longest recorded drought in Washington at that time. It exacerbated the 1930 drought.

1930/31: Moderately dry weather occurred in Western Washington. The Palmer Drought Index hovered in the -3 range.

1938: At the time, it was a record dry growing season in Western Washington. The state studied the minimum stream flows necessary to preserve fish life. Stream flows are still an issue and complicate the regulation of reservoir levels.

1941-1945: The war years were dry ones. During March and April 1941, the Palmer Drought Index was -4, and then hovered between -3 and -1.5. Temperatures west of the Cascades were usually above normal.

1952/53: Puget Sound was hit with dry weather beginning in January and continuing through April 1953. The worst came during the winter when the Palmer Drought Index reached -4. The lack of winter precipitation was a possible reason that the state ordered power cuts for hydroelectric dams.

1965/66: The entire state was dry. King County recorded Palmer Indices of roughly -1.5 from June 1965 to December 1966.

1967: The summer was dry with no significant rain from the third week in June to the first week in September.

1976/77: Precipitation was 57% of normal in Seattle. For three months, the Palmer Drought Index was in the -4 range. Hydroelectric power generation dropped 47% and City Light had to make emergency power purchases at highly inflated prices. As a result, it had to increase its debt and put a surcharge on electric bills[ix].

1987: Hot, dry summer weather increased water demand, causing a rapid drop in reservoir levels. Mandatory restrictions were adopted. Consumption dropped by 10%.

November 1987: The Tolt pipeline broke, temporarily dropping the supply reaching Seattle Water Department (now SPU) customers by 30%. This impacted 10,000 customers, but only for several hours. Water was rerouted through the Cedar River pipeline, placing additional demands on the Cedar River Reservoir. Voluntary restrictions dropped consumption by 5%. However, November was an off-peak month and the Cedar River pipeline was able to completely supply the city.

1988: The level of Cedar River Reservoir fell below its outlet. The Seattle Water Department responded by installing emergency pumps to extract water. The pumps were left at the site and used again in1992.

August 1988: The Tolt pipeline broke during a period of peak use, threatening 100 suburban customers with loss of service or low water pressure. The public was asked to curtail all unnecessary water use. The goal was a 30% reduction, but only 18% was achieved. The outage lasted several days.

1992: Scarce winter rains prompted emergency measures to avoid severe reservoir depletion. Enforced mandatory restrictions reduced water consumption by 25- 30%. Additional emergency pumps installed in 1988 at Cedar River Reservoir were used. The silver lining to the 1992 shortage is that per capita water consumption remained low even after the shortage ended.

2001: Snowpack appeared to be very similar to that of 1992. Water supply forecasts made through the end of the year looked dire in early March. Snowpack in SPU's watersheds ended up peaking at 75% of normal and reservoirs were full or nearly full by June. Nonetheless, with a state-wide drought emergency in effect, SPU asked customers starting in early April to voluntarily reduce water use by 10%.

2005: The worst snowpack in 60 years of record keeping occurred at SPU's watersheds, causing SPU to enter into the advisory stage. Effective reservoir management and some late spring/early summer rainfall brought reservoirs back to near normal levels. By early July, the advisory was lifted.

Shortages seem to occur once every five to ten years. In most cases, water shortage response actions were implemented during the summer. Unfortunately, the extent of the damages is difficult to determine due to lack of information. The most severe shortages were the result of either low snowpack or dry fall conditions. Often SPU's water utility was the only City-system impacted; in at least two cases, during 1952 and 1977, City Light was also affected. This data suggest some patterns of vulnerability that the next section will explore.

Likelihood of Future Occurrences

The Washington Climate Change Impacts Assessment (WACCIA) conducted an analysis of the effects of climate change on Seattle's water supply. The authors defined system reliability as the percentage of years within their model in which there were no municipal and industrial delivery shortfalls. They found that, given current demand, reliability remains at 99-100% even through 2080. These estimates deal with long-term reliability.

Summer and fall reservoir draw-downs are likely to become more extreme. The same analysis found that Seattle's system currently has a 34% chance of being half full and a 1% of being a quarter full. By 2020, less reserve is likely and these numbers increase to 49% and 4%, respectively[x].

Demand is the critical variable. Total consumption or demand is falling, despite population growth, but consumption can still spike, especially during the summer months during periods of high heat. These periods are predicted to increase with climate change. If a low snow year is followed by a hot summer, Seattle's water supply will face at least a short-term challenge.

If demand rises instead of continuing to fall, Seattle could face long-term challenges in meeting demand. In the worst case, the WACCIA estimates that a 50% increase in demand, a high carbon dioxide emissions scenario and no increase in supply would combine to degrade the reliability of the water supply to 38% by 2080.

The challenges are different for City Light. Historically, its peak demand is in the winter when stream flows are also at their peak. Demand peaks in summer are checked by the limited, 8% - 10% market penetration of air conditioning systems locally. The WACCIA forecast changes to hydropower in the Columbia Basin, where Seattle gets most of its power. It projects that annual production will decline slightly, with increases in the winter offset by declines in the summer. The authors caution that, in the near term, annual production will be more influenced by other factors, like the El Niño/La Niña phenomenon, than climate change.

On the demand side, population increases will lead to an increased demand for heating even as per capita demand goes down due to warming winter temperatures. Energy demand for cooling is projected to increase rapidly as more people acquire air conditioning. Taken together, these projections suggest that adaption to climate change will be easier in the winter than the summer.

Vulnerability

The main direct vulnerability in urban areas in a water shortage are financial, as water restrictions and/or price increases are put in place to lower demand and protect supply. Both drinking water and power could be affected. It is unlikely that restrictions and price increases would become so severe that there would be public health or public safety impacts. The reason is that water is still a cheap commodity in the U.S. and only about 10% is used for direct human consumption.

The history of water shortages shows that the power and water supply systems have different vulnerabilities to drought. Their water demands differ and Seattle's reservoirs are located far enough apart that precipitation can be significantly different at each location[xi]. Often only one system is affected by dry weather.

Overall, the water system seems to have a higher probability of being affected than the power system. The water system cannot supplement supplies from outside the immediate region; City Light's power system can, as it has access to the regional power supply.

The heaviest water users are affected the most by water shortages. Commercial customers have traditionally been the biggest consumers, but many have succeeded in sharply reducing consumption. Some heavy users remain, such as landscapers and greenhouses.

Maintaining stream flows for salmon is the most recent challenge for the utilities. To create these flows, Seattle Public Utilities and City Light must let water bypass their facilities during the spring when the reservoirs are most easily replenished and in the fall when water is being drawn from storage. During dry years, the amount of water they release can cause water reserves to drop significantly.

Water shortages also harm Seattle's utilities and their rate payers. Both Seattle Public Utilities and City Light are publicly owned utilities, so their financial difficulties can be transferred to their customers.

Chance of a water shortage endangering public health and safety is remote. A shortage could indirectly expose Seattleites to harm if it contributes to power failures, if low stream flows suppress power production at a time of peak demand, or to fires due to low water pressure or dry vegetation.

Consequences

Seattle has a water shortage risk that is likely to increase with climate change; however, an even bigger driver will be demand increases. With good planning, it will be possible to boost supply or enact conservation measures to address demand increases. Seattle has two distinct water shortage hazards: water for direct consumption and water for power production.

While Seattle will certainly face water shortages in the future, these will probably be on the same order of magnitude as previous shortages. Seattle's water supplies seem secure. On the power generation side, the situation seems more challenging, but the likelihood that a water shortage will cause rolling blackouts seems remote. More likely is that power rates will increase.

With the effects of climate change on top of regular yearly and decadal fluctuations, a severe multiyear drought could have serious consequences for Seattle and extend beyond economic impacts into the public safety and health spheres. Most of these effects are likely to be indirect increases in fire, power failure and heat exposure risk. Even under the maximum credible scenario, Seattle is better off than some cities that are truly facing a crisis as their entire supply is threatened.

Most Likely Scenario

Low snowpack followed by hot, dry summer and cold fall. Water levels in the Cedar fall below level of outfall. Seattle Public Utilities (SPU) uses pumps to bring water into transmission pipelines. Mandatory water usage restrictions go into effect. Businesses like landscaping operations experience hardships.

Category	Impacts 1 = low 5 = high	Narrative
Frequency	5	Regional water shortages occur when the amount of water in the City's watersheds is not enough to meet demand. Often weather related shortages like this one in can be somewhat reliably forecast based on climate models. Seattle has had dry conditions at least 14 times in the past 100 years. This scenario is a about a once every 10 to 50 year event.
Geographic Scope	5	A weather related water shortage would affect all of Seattle and the suburban customers of Seattle Public Utilities. This shortage is a region event.
Duration	5	Weather related water shortages are long duration emergencies. The most serious period of this shortage lasts from June until November.
Health Effects, Deaths and Injuries	1	No one is directly killed or injured as a result of the water shortage.

Category	Impacts 1 = low 5 = high	Narrative
Displaced Households and Suffering	2	No households are displaced due to the shortage and the water supply is sufficient to meet basic human needs. Restrictions on non-essential water usage (e.g., lawn watering) bring inconvenience to the general public.
Economy	2	Businesses that use large amounts of water like landscapers, contractors begin to lose revenue due to curtained operations.
Environment	2	A dry winter and spring stresses plants. Restrictions on watering cause many to die.
Structures	2	No structures are damaged as a result of the water shortage, but the dry conditions create ideal conditions for brushfires. A car fire on I-5 ignites a slope along Beacon hill. The fire spreads rapids and destroys 3 homes and heavily damages 7 others.
Transportation	1	The water shortages doesn't have any significant impacts on the transportation system
Critical Services and Utilities	3	The primary impact is on water service. City Light must curtail power generation to preserve stream flows for endangered salmon. City Light avoids power surcharges and restrictions, but has to forego power sales to other utilities which hurts its bottom-line. Impacts on other critical services are limited. Seattle Public Utilities is able to maintain enough water pressure for firefighting. Hospitals have adequate water for operations.
Confidence in Government	1	The effects of the low snowpack and dry weather are apparent to the public. They see mandatory water regulations as an inconvenient but necessary step to preserve water for critical uses.
Cascading Effects	2	The extreme dry weather contributed to a serious brush fire. The fire was not a disaster by itself.

Maximum Credible Scenario

Several years of low snowpack, hot summers and cold winters begin to place a severe strain on watersheds. SPU must implement emergency curtailments for the first time in its history. City Light has to curtail generation to preserve salmon stream flows at a time when demand is high and the water is low. It must buy power during a summer when high demand in other parts of the country have driven prices up.

Category	Impacts 1 = low 5 = high	Narrative
Frequency	2	This scenario is, like the Most Likely scenario, a weather related drought and water shortage, but it is much more severe. Although Seattle has had other periods of dry weather, Seattle must enact emergency water curtailments for the first time in its history.
Geographic Scope	5	The drought and water shortage are region wide.
Duration	5	The full duration of the drought is years but the worst period is the summer following an exceptionally dry winter.
Health Effects, Deaths and Injuries	1	Due to emergency curtailments and surcharges, water supply is adequate for public health needs. As a result there are no deaths or injuries due to lack of potable water.
Displaced Households and Suffering	3	No households are displaced due to a lack of potable water, but water restrictions and surcharges are hardships for much of the general public.
Economy	3	Many businesses are impacted by curtailments and surcharges. Use of the Ballard Locks impacts commercial maritime traffic. City Light implements surcharges to offset borrowing.
Environment	3	The prolonged dry weather has placed severe stress on Seattle's urban forest. The dry conditions weaken plants making them more susceptible to disease.
Structures	2	The dry conditions contribute to 2 urban wildfires that destroy 10 buildings and damage 25 others.
Transportation	1	The water shortage and drought do not have a significant impact on Seattle's transportation system.
Critical Services and Utilities	3	The water system is severely impacted by the shortage. City Light is able to maintain power without curtailments, but implements surcharges. Due to prioritization water pressure remains adequate for firefighting and public health.
Confidence in Government	3	The public understands the severity of the drought and water shortage, but the increasing bite of curtailments and the implementation of surcharges is not popular. Many are convinced that government could do a better job shielding the public from the costs of the shortage.
Cascading Effects	2	The extreme dry weather contributed to a serious brush fire. The fire was not a disaster by itself.

Conclusions

Experience suggests that Seattle Public Utilities and City Light can manage most shortages effectively. Since droughts require little in the way of emergency equipment, pose little immediate danger to public health and have a crisis period that lasts for weeks or months, there seems to be little reason to activate the Emergency Operations Center. As with other “creeping” hazards, the city does not presently have a system in place for prolonged multi-department emergency management. Nevertheless, the current

system could be used for interdepartmental city involvement to assist the utilities in managing a severe shortage emergency caused by infrastructure failures.

[1] Mass, 2009.
[2] Mass, 2009.
[3] Mass, 2009
[4] Seattle Transportation, 2003
[5] Mass, 2009.
[6] Definition of Service Levels:

1. Bare pavement within eight hours over all land on the most critical arterials as soon as there is a significant lull in the in storm.
2. Bare pavement within eight hours for one lane in each direction on selected major arterials and remaining King County/Metro Transit (Metro) winter storm bus routes, as soon as there is a significant lull in the storm.
3. De-ice hills, curves, bridges, and controlled intersections as soon as there is a significant lull in the storm.

[vii] Seattle Public Utilities Department, 1993
[viii] Wilhite, 1993.
[ix] Forbes and Pond, 1977.
[x] Washington Climate Change Impact Assessment, 2009. P122.
[xi] National Climatic Data Center, 1985.