Risk Analysis of Probable Maximum Flood and Climate Change at the PolyMet Flotation Tailings Basin

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1.0 Executive Summary

The proposed PolyMet mine is in northeastern Minnesota near the towns of Babbitt and Embarrass, near the topographic divide between the Partridge and Embarrass River in an area that has experienced significant climate change. Temperatures and annual precipitation has increased substantially, as has the intensity of storms.

Probable maximum precipitation (PMP) is the greatest accumulation or depth of precipitation for a given time duration that is meteorologically possible for an area or a point. The largest potential flood for an area is often considered the probable maximum flood (PMF), which is not simply the runoff resulting from a PMP on a watershed, but depends on the antecedent conditions within the watershed, including soil wetness, snowpack, and temperature during the storm (for melting snow), although precipitation tends to be higher when the atmosphere is warmer.

A PMP may be determined by estimating the precipitation that would occur if atmospheric moisture, transport of moisture into storms, persistent upward motion, and strong winds where orographic uplift is important are optimized for a particular place and situation. Simple scaling allows the precipitation from a heavy storm to be scaled upward by multiplying the observed precipitation by the ratio of probable maximum precipitable water (PW) to PW observed for the storm.

Global warming caused by an increase in greenhouse gases increases the ocean heat content which also increases atmospheric water vapor. Because changes in wind are unlikely to counter the effects of increasing the atmospheric water vapor, PMP estimates are likely to increase proportional to the water vapor increase. The current PMP estimate can be scaled upward according to projected increase in PW due to global warming to estimate the PMP likely in the future.

The PolyMet tailings basin is effectively a closed basin with no inflow other than possibly during its first few years. It would be constructed on top of an existing taconite tailings impoundment rather than on a firm foundation. Freeboard will vary depending on the initial conditions, but if there is a 100-year snowpack or a substantial storm occurring six days prior to the PMP, as described above, it is likely to be minimal.

The relevant PMP is effectively that for a single point without considering runoff. Precipitation will either pond or seep into the surface of the impoundment, therefore the relevant storm is the longest significant one over a small area, meaning the 72-hour event. Considering the northern location, snowpack could also be relevant for a late spring PMP on snowmelt event.

Using the standard methods, PolyMet estimated the PMP to be 38 inches in 72 hours. Climate change will add up to 30% to that, bringing the PMP to 49.4 inches in 72 hours. A reasonable snowpack estimate would add a snow water equivalent of about 18.8 inches. The total PMF that would end up in the tailings basin is the sum of 49.4 and 18.8, or 68.2 inches, within 72 hours. This is almost twice the value analyzed by PolyMet for the PMP/PMF.

The global warming enhanced PMF runoff would increase the hydrostatic pressure by at least an additional 30 inches on top of the already rapid increase caused by the PMP. This substantially increases the potential for a piping failure of the impoundment. Depending on the amount of tailings beach and other runoff area, the additional rainfall could be sufficient to exceed the freeboard and cause a dam overtopping or at least the use of the spillway.

Regardless of the specific mechanism, the PMP with global warming significantly increases the chance of dam failure, either by overtopping, piping or foundation failure. PolyMet has not analyzed these potential risks.

2.0 Introduction

On August 4, 2014, the tailings impoundment at the Mt Polley Mine in British Columbia failed, releasing 10 million cubic metres of water and 4.5 million cubic metres of slurry into Polley Lake, from which the waste continued to flow through Hazeltine and Cariboo Creek into Quesnel Lake. A four-kilometer tailings impoundment emptied into and contaminated water bodies for miles downstream. Even though the failure was not due to flooding, the failure increased awareness of the potential for large tailings impoundments to fail and destroy downstream water bodies.

The PolyMet Copper/Nickel mine proposes to construct a copper/nickel mine in sulfide ore near the headwaters of the Embarrass River. A flotation tailings basin (FTB) ultimately holding 225,000,000 tons of tailings would be constructed on top of an existing taconite tailings impoundment (Figure 1). Flood analyses for the FTB considered the probable maximum flood (PMF), it did not consider how the probable maximum precipitation (PMP) that drives the PMF would change in the future due to global warming.

The purpose of this report is to consider how climate change increases the risks of flood failure for the PolyMet FTB. This report describes the design of the FTB at PolyMet and how the climate is changing both globally and in Minnesota near the project. The report considers how a PMP is estimated and how it is used to estimate the PMF for tailings dam construction. The report also discusses the factors of PMPs and PMFs that will change as the climate warms. The report estimates the increases in PMP and PMF that will occur at PolyMet over the next 100 years.

Modern dams, both tailings and water storage, are designed with the assumption of climatic stationarity by using a static design value of PMP. Currently accepted PMP values are significantly increased when future changes in dew points from observational trends or numerical models are taken into account (Stratz 2014).

3.0 Background

3.1 Tailings Pond Failures

Over 400 tailings dams have failed worldwide over the past several decades (Rico et al 2008). Tailings dams fail like water storage dams, but they are not constructed and operated like water storage dams, and the differences lead to them being more vulnerable to failure than water storage dams. The differences include their embankments being formed by locally derived fill, the dam being raised in multiple stages which create contact points between construction layers, less regulation than water storage dams, dam stability requires constant monitoring, and because remediation after mining ceases is very costly (Rico et al 2008).

Many factors cause tailings impoundments to fail, including flooding, piping, overtopping, liquefaction, or a combination (Rico et al 2008). Mt Polley failed due to a failure in the foundation (IEEIRP 2015). Tailings dam failures discharge polluted water and tailings with a variety of textural and physical-chemical properties. The amount of water in the impoundment is as important as the volume of tails and the dam height, in most instances (Rourke and Luppnow 2015).

The damage caused by a tailings dam failure depends on the amount of the dam that is released and how far it flows downstream. The water content of tailings helps control the length of run-out during a failure, with more water leading to longer run-out (Rico et al 2008). Floods into the tailings impoundment can increase the water content and make for a highly variable consistency, with some mostly water and some being primarily a tailings paste. Run out also increases with the height of the dam.

A larger pond area, meaning ponded water on the surface of the tails, as a proportion of the tailings impoundment surface area, leads to large amount of tailings released upon failure (Rourke and Luppnow 2015), in addition to increasing the hydrostatic pressure on the dam. As the moisture in the tailings increases beyond a certain point, dependent on the type of tailings, decreases the cohesion in tailings making them more likely to slide. These factors indicate that flood events can lead to failures even if they do not cause overtopping.

3.2 Probable Maximum Precipitation and Floods

Probable maximum precipitation (PMP) is the greatest accumulation or depth of precipitation for a given time duration that is meteorologically possible for an area or a point (Kunkel et al 2013). It may also be considered to be the maximum precipitation that is potentially possible for an area. The largest potential flood for an area is often considered the probable maximum flood (PMF). The PMF is not simply the runoff resulting from a PMP on a watershed, but rather depends also on the antecedent conditions within the watershed, including soil wetness, snowpack, and temperature during the storm (for melting snow), although precipitation tends to be higher when the atmosphere is warmer. Clavet-Gaumont et al (2017) define a PMF as the flood resulting from either a PMP on top of a 100-year snowpack or a 100-year rainfall on top of a "mature probable maximum snow accumulation." They also found seasonal differences that relate to northern watersheds, with the highest precipitable water in a storm event occurring in late spring when snowpack is close to maximum and to being ripe. (In a tailings basin with no inflow, the PMF may simply be the depth of the added rainfall, or equal to the entire PMP over the contributing area.)

PMPs can be estimated in two ways, using either statistical or physically-based methods. A statistical method involves fitting observed data, usually precipitation for a relevant storm duration, to a probability distribution. Then, storms are stochastically generated using the probability distribution (Beauchamp et al 2013). This means that using a probability distribution that describes the storm amounts occurring in an area and a random number generator, a series of storms are created for analysis.

A physically-based method is one in which an observed severe weather event is analyzed and upgraded using a series of "what if" considerations. Specifically, how much more water could have been advected into the storms? That may be considered with precipitable water (PW) measurements and estimates. PW is the total depth of water in a column of the atmosphere. Wind speeds and directions could also be adjusted to maximize orographic effects. A physically-based model may be better than a statistical model estimate because it must adhere to physical limits. The laws of physics do not present an upper limit to a time series based on a probability distribution. A bounded probability distribution could possibly be used, but a problem with that is a generated long time series could include several PMPs as the bound could be reached more than once. Another problem with using a probability distribution to simulate extreme events with climate change is it assumes the underlying probability distribution will not change due to climate. That means that the factors controlling precipitation remain stationary, which is demonstrably not true (Kunkel et al 2013).

The first three links found on a google search for PMP were to reports from the late 1970s and early 1980s - Hydrometeorological Report (HMR) 51 (Schreiner and Riedel 1978), HMR52 (Hansen et al 1982), and HMR53 (Ho and Riedel 1980). These original physically-based methodologies are still in common practice. This demonstrates, however, how out-of-date the methodology is.

PMP estimation using the HMR methods involves moisture maximization, transposition and envelopment (Schreiner and Riedel 1978). Moisture maximization involves increasing the maximum moisture in the atmosphere for an observed storm to a value consistent with the location. This means determining the maximum PW in a storm. During a storm it depends on air temperature, which controls the amount of water the air can hold, and the rate that moisture can move into the storm to replace the falling rain. The highest PW occurs for the highest temperature air masses. PW is generally higher during summer when the air is warmer.

Transposition means moving that maximum precipitation so that it lines up over the watershed of interest. Topography and distance from a water source is a primary control. HMR51 applies in all areas of the US east of the 105th meridian, but it is not appropriate for example to transpose an observed storm on the coast to Minnesota because both distance and the Appalachian Mountains prevent movement of the moisture. It is reasonable to consider the Great Lakes as a source in Minnesota.

Envelopment means that there is a smooth transition of storm amounts to duration of storm over the area. In other words, a storm of a given length will be broken into smaller time periods with storm depths that are consistent with the principles of moisture maximization and transposition. This is done by creating contour maps of equal maximum precipitation or moisture maximized precipitation of different durations.

Kunkel et al describe estimating it best: “The general approach, using data and physical judgment, is to estimate the precipitation that would occur if all the relevant factors in a particular place and situation achieved their optimum values simultaneously and remained in place for the specified duration over the basin area” (Kunkel et al 2013, p 1402). The factors as described above are “atmospheric moisture, transport of moisture into storms, persistent upward motion, and strong winds where orographic uplift is important” (Id.).

PMF estimation is the estimated runoff resulting from the PMP being applied to the watershed of interest. Translating low-frequency precipitation events to flooding depends highly on the nature of the watershed, including antecedent conditions and anthropogenic impacts such as the amount of watershed that has been developed or the amount of watershed that has been affected by recent fire (Kundzewicz et al 2014).

PMF also depends on temporally distributing the PMP to maximize the flood hydrograph, both in delivery of precipitation during the event and in the timing of the PMP in the meteorology of the area (Beauchamp et al 2005). A common method for estimating soil moisture conditions for the PMF is to assume a storm equal to half the PMS (probable maximum storm) occurs six days prior to the PMS (Beauchamp et al 2005). The intervening six days are dry and the soil is modeled to be drying (Id.). A more realistic method may be to insert the PMS into an observed or stochastically generated climate regime so that soil water conditions are truly randomly estimated.

Rainfall/runoff models are usually calibrated to conditions that have been seen previously in the watershed, so storms that are larger than those used to calibrate the model will stress the model beyond its calibration point. PMP rainfalls amounts are far outside the range of calibration for the models. Therefore, the PMF prediction is likely very inaccurate. Infiltration may not occur at the rates simulated and overland flow routing may consider the flow to occur too slowly. These, and other factors, would cause the predicted runoff peak to be larger than simulated. Stressing a model beyond its range of calibration may cause a very high uncertainty band on the predictions.

4.0 PolyMet Tailings Impoundment

The proposed PolyMet tailings impoundment would be developed on top of an existing taconite tailings impoundment (FEIS, p 3-89). It had been developed in three stages beginning in the 1950s, with perimeter starter dams and iron-ore tailings placed directly on native soil (Id.). The tailings basin has been closed except for ongoing closure operations since January 2001 (Id.).

The taconite tailings basin had been constructed using the upstream-type dam construction method, the least safe of three traditional methods (Chambers 2015, p 2). Because the existing basin will form the base of the proposed basin, the safety of the future operations would depend on the existing structure. The proposed tailings basin would also be wet tailings. Because of the low permeability of the tailings, the impoundment would likely remain saturated throughout the operating period and long into the closure period. PolyMet expects the seepage catchment system to capture seepage for centuries, indicating that wet conditions would occur for a long time.

4.1 Flood Estimate and Design at the PolyMet Tailings Impoundment

The PolyMet tailings basin would lie within the Embarrass River watershed at the topographic divide with the Partridge River watershed. In fact, some of the impoundment embankments are or would be on the topographic divide. The groundwater divide may not coincide with the topographic divide due to the seepage of tailings water as the existing impoundment was built

up (Radue and Pin 2009, p 3). Figure 1 shows a map of the tailings basins and currently contributing tributary areas and land use. Figure 2 provides a different view of the area, showing the offsite area draining to the tailings basin as Spring Mine Creek, with a stormwater flow arrow showing the inflow between Cell 1E and Cell 2E. If the boundary in Figure 2 accurately depicts the watershed for Spring Mine Creek, the ponds that lie east of the creek are not part of the tailings watershed[1]. Figure 3 shows that at full buildout, there will be dam embankments that prevent most offsite runoff from reaching the tailings basin.

Construction would occur in increments over the 20-year operating plan (PolyMet 2017, p 7). Dams would be constructed using existing coarse tailings (PolyMet 2017, p 8). The increments would include freeboard, but also include increments that create failure surfaces at each point where a new layer is added. The minimum specified freeboard would be 5.25 feet for a full PMP (Id.). Tails would be placed into the impoundment as a wet slurry, ranging from 28 to 32% solids by weight (PolyMet 2017, p 10).

[1] Figures 2 and 3 and other figures in PolyMet (2017) show a stream entering the pond east of the tailings that flows across the divide between the Embarrass River and Partridge River watershed. This indicates there is uncertainty around what would currently flow onto the tailings impoundment.

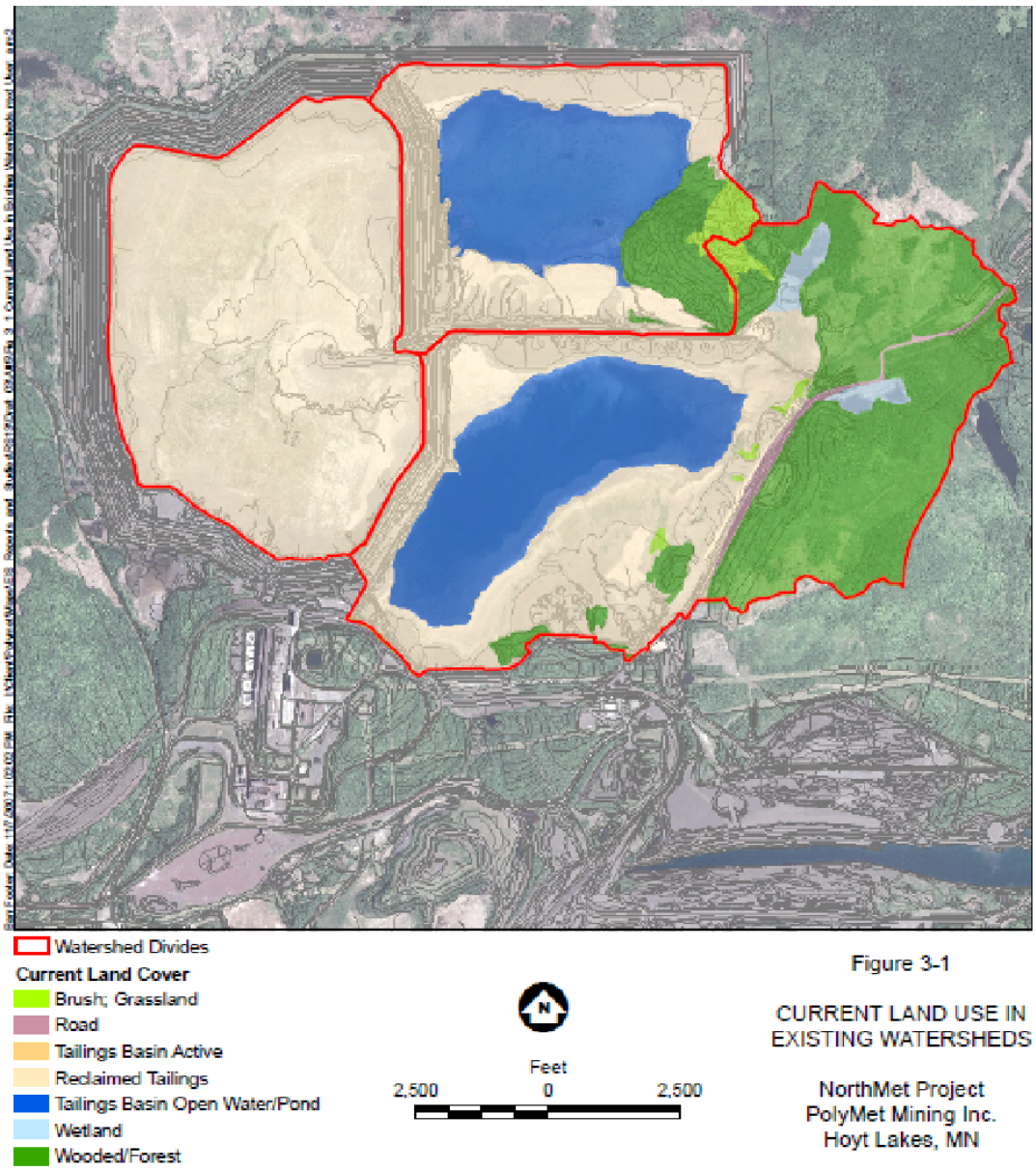


Figure 1: Portion of Figure 3-1, Barr (2008) Attachment A-5, showing the current drainage areas and land use to the tailings impoundment.

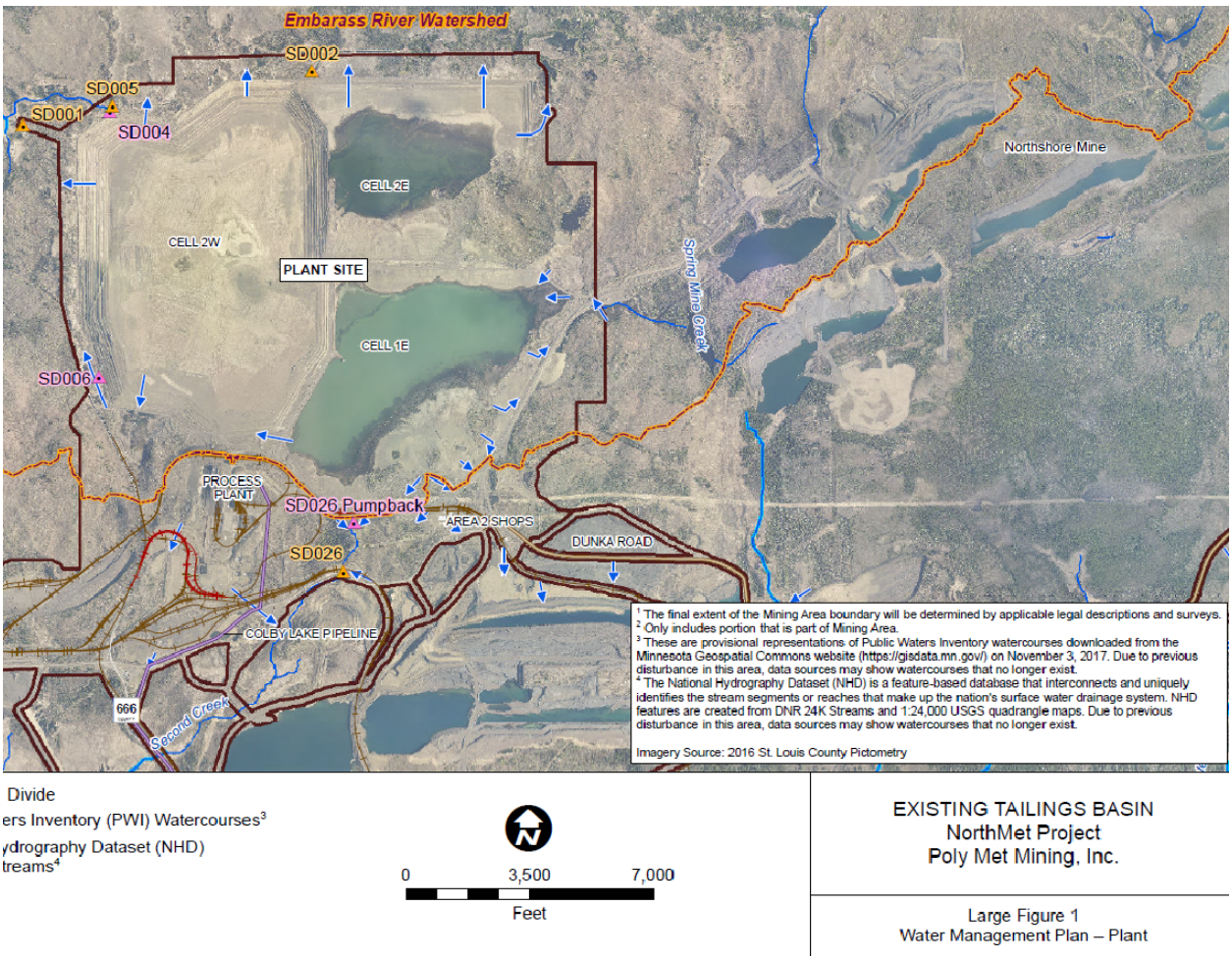


Figure 2: Portion of Large Figure 1 (PolyMet 2017) showing the Plant Site and area to the east that drains to the plant site.

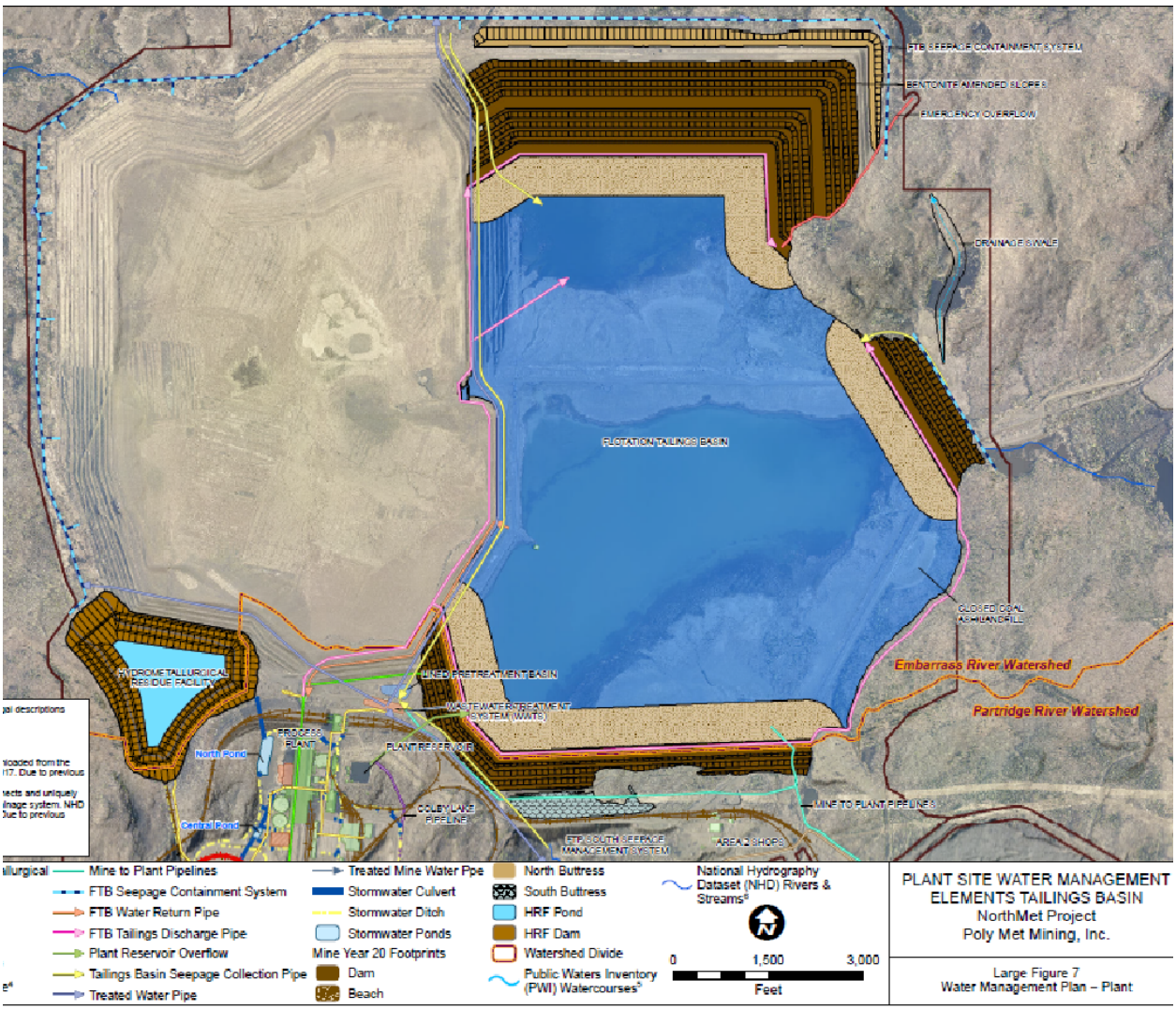


Figure 3: Portion of PolyMet (2017) Large Figure 7 showing the Water Management Plan for the Plant, at full buildout after 20 years.

For water balance for the tailings basin, Barr (2008) estimated only the watershed yield, which did not consider severe storm runoff. Although they considered actual climate data from 1977-1996, they used monthly time steps which would have masked the high flows from a heavy storm. Large, short-term changes in water contained in the impoundment would not have been considered. Drainage area to the Tailings Basin includes the upland area east of Cells 1E and 2E (Barr 2008). The actual area draining to the tailings basin will vary with time and some tributary area may be diverted from the tailings into the future (Barr 2008, Attachment A-5). Total existing area, including the tailings cell and offsite area, currently draining to Cell 1E, Cell 2E, and Cell 2W is 1590.5, 747, and 957.7 acres, respectively. The land cover area will vary with time as more of it becomes covered with tailings basin pond.

The FEIS for the proposed PolyMet mine does not present an analysis or discussion of the PMF, other than to say there would be a spillway in case a flood event exceeded freeboard (FEIS, p 3-120, p 5-103). Minimum freeboard would apparently be 5.25 feet (PolyMet 2017). PolyMet completed a dam break analysis for the 72-hour PMP event, with and without a dam break in tailings cell 2E (PolyMet 2017, p 20). A dam break would inundate 34 houses (Id.). They also did a seepage stability analysis based on the ponding that would result from the PMP (PolyMet 2017).

The tailings design at PolyMet relied on PMP estimates based on HMR51 (Weaver 2011). The total PMP depth depends on storm duration and the area the precipitation falls over. The largest storm depth occurs when the smallest areas are considered (Figure 4). For the small watershed relevant at the proposed PolyMet tailings impoundment, the smallest areas are most relevant. Weaver (2011) chose to use the 38-inch, 72-hour storm for a one square-mile watershed upstream from the FTB. Values for a two and three square-mile watershed were estimated to be 36 and 35 inches, respectively. Values for a 10 square-mile watershed were 32.2 inches (Weaver 2012).

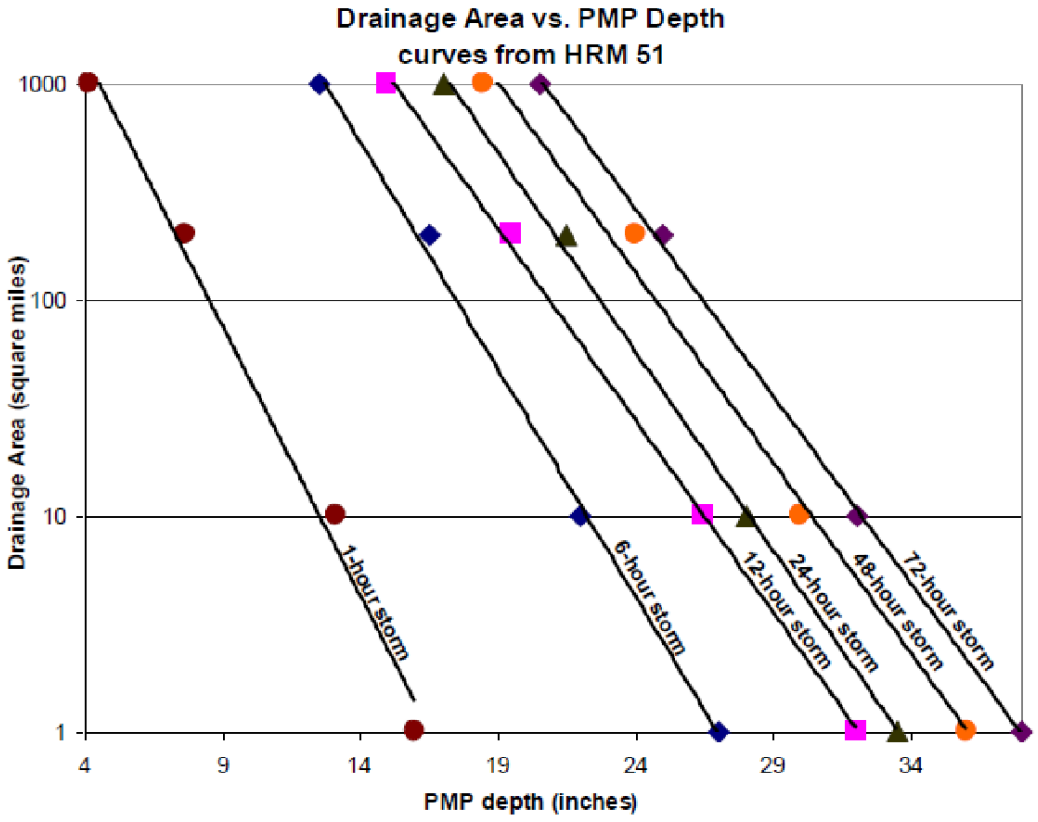


Figure 4: Relation of drainage area, storm duration and probable maximum precipitation depth (Weaver 2011).

The most likely and most impactful dam break would be one that occurs on the north side of the tailings (Weaver 2012, p 4). During closure, the FTB would cover 1400 acres and have an average of about 10 feet of freeboard over 160 feet of tailings (Id.). The dam break analysis assumed that all precipitation is contained within the FTB in the freeboard (Weaver 2012, p 5). Weaver analyzed failure as if it would be due to piping, which is seepage through the dam eroding soils from the dam, so the dam does not have to be overtopped (Id.). One error is that they completed the analysis using a water surface profile analysis program called HEC-RAS; this program is not designed to simulate the unsteady flow that results from a dam break. The inundation map based on these assumptions and simulated in HEC-RAS, Figure 3 in Weaver (2012), shows that much of the area between the tailings impoundment and Embarrass River, east of Trimble Creek, would be covered in tails. If the PMP value is higher than analyzed, the area of inundation would be higher. Also, if the PMP is higher, the factors of safety used to design the dam (PolyMet 2012) would be less than designed.

The Mt Polley failure noted above suggests a different failure mode for the PolyMet FTB. The foundation at Mt Polley failed and a failure to analyze properly the geotechnical strength may have been the cause. The FTP at PolyMet would be constructed on top of existing tailings, therefore the foundation will be an impoundment with foundation design and construction methods from the 1950s. The PolyMet design would add substantial pressure to that foundation and large flood flows would increase that pressure.

5.0 Climate Change in the Project Area

Global temperatures have been increasing for most of the 20th century and first part of the 21st century (Figure 5). There is no longer any legitimate debate about that trend. Minnesota's temperatures have significantly increased in the recent past, with global warming manifesting in higher temperatures and many concomitant climate changes (Interagency Climate Adaptation Team 2017, EPA 2016) (Figures 6 and 7). Temperatures have increased a quarter degree Fahrenheit per decade since 1895 (Id.). A decrease in severe cold weather has caused the increase in temperature. The largest changes have occurred in northern Minnesota (Figure 6). This observation holds even at the national scale (Figure 7).

The Minnesota Interagency Climate Adaptation Team (2017) lists the highest confidence in a rapid decline in severity and frequency of extreme cold and that extreme rainfall is becoming larger and more frequent. The second highest confidence is in heavy snowfall events becoming more frequent. Annual precipitation has also been increasing, but with various unique vagaries, as discussed in the following section.

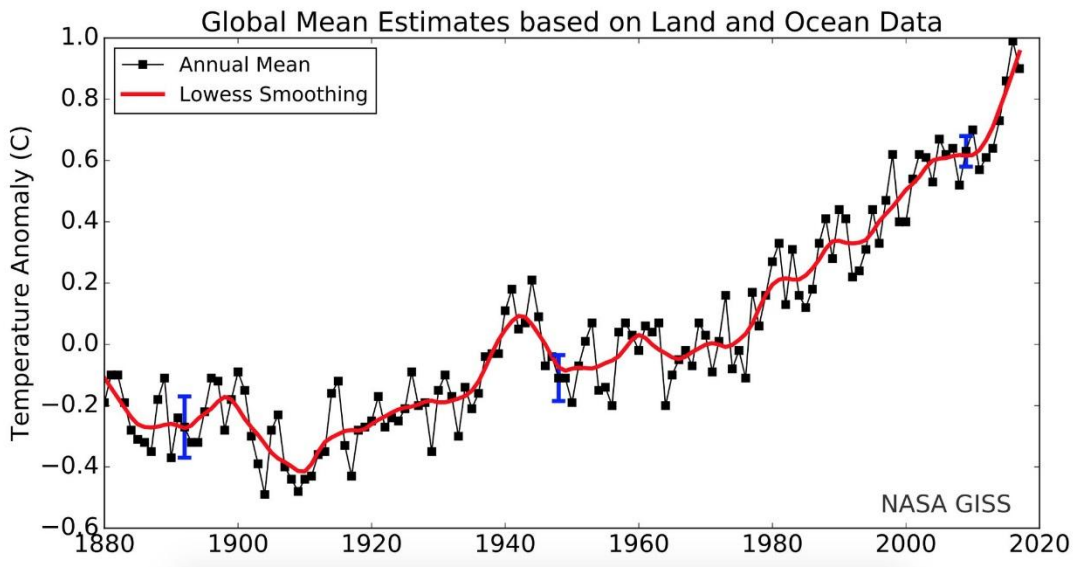
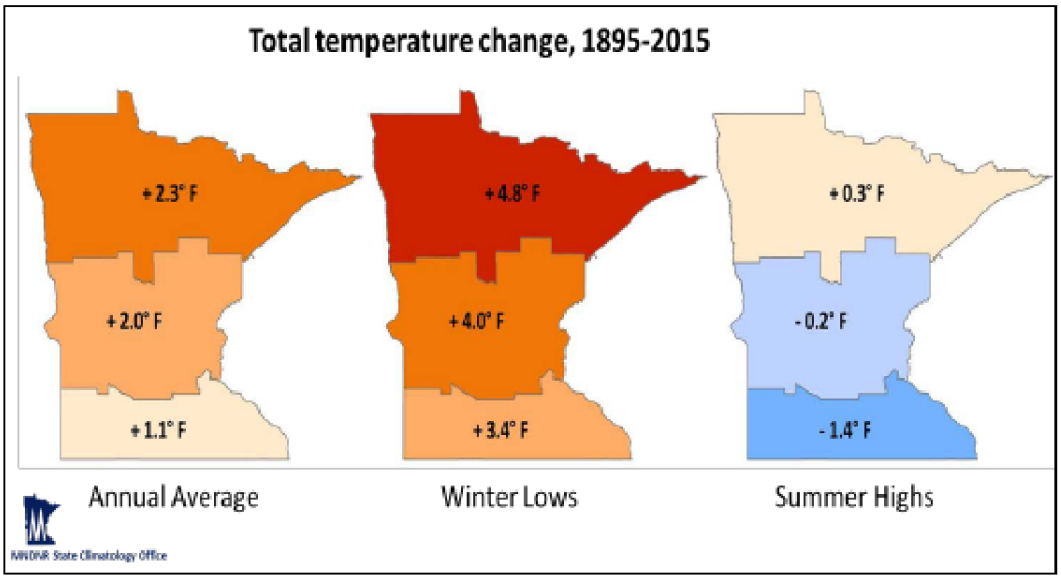


Figure 5: Global mean temperature estimates based on land and ocean data (AGU Blogosphere, January 18, 2018, https://blogs.agu.org/wildwildscience/2018/01/18/2017-another-year-amazing-heat-not-natural-greenhouse-gases/



Comparisons of total change between 1895 and 2015 using 30-year averaging periods, for annual average temperature, winter low temperature, and summer high temperatures over the northern, central, and southern portions of the state. Values were obtained by subtracting the average of the first 30 years of record (1895-1924) from the average of the last 30 years of record (1986-2015). Each region is a blend of three climatic divisions, as defined by the National Centers for Environmental Information (https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php), which is also the source for the divisional climate data used (http://www.ncdc.noaa.gov/cag/time-series). Maps prepared by Minnesota State Climatology Office.

Figure 6: Figure 3 from Interagency Committee on Climate Change (2017) showing total temperature change by region and season.

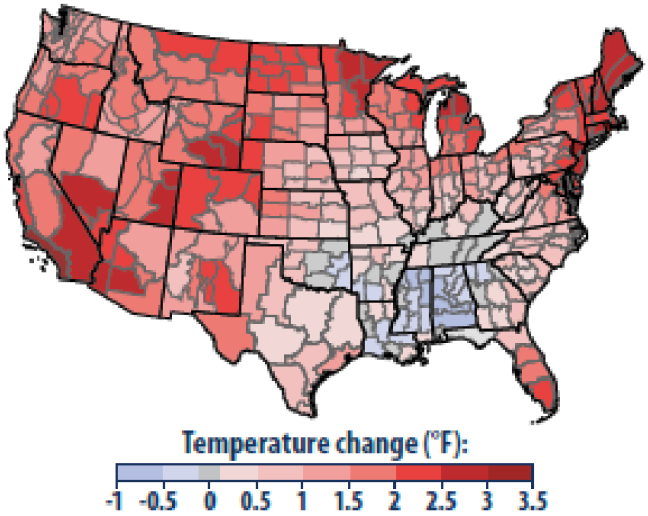


Figure 7: Observed temperature change over the past century (EPA 2016)

5.1 Precipitation

A general rule of thumb regarding climate change is that wet areas will become wetter and dry areas will become drier. Most global climate models predict that precipitation intensity will increase with global warming (Groisman et al 2005). For the US, annual precipitation has increased the most in the Northeast, Midwest and southern Great Plains than in the rest of the country, especially the Southwest and Southeast, which have experienced decreases in annual precipitation (Figure 8). Average annual precipitation in Minnesota has increased about 0.25 in/decade since 1895 (Figure 9).

Additionally, the amount of precipitation which falls during heavy rainfall events has increased, with the largest increase occurring the upper Midwest and Northeast (Walsh et al 2014) (Figures 10 and 11). EPA has noted:

> Changing the climate is likely to increase the frequency of floods in Minnesota. Over the last half century, average annual precipitation in most of the Midwest has increased by 5 to 10 percent. But rainfall during the four wettest days of the year has increased about 35 percent. During the next century, spring rainfall and annual precipitation are

like to increase, and severe rainstorms are likely to intensity. Each of the factors will tend to further increase the risk of flooding. (EPA 2016)

The amount of rainfall occurring during heavy events will increase even in areas that overall experience less precipitation because warmer temperatures hold more moisture which can lead to higher rainfall amounts. The observed change in very heavy precipitation has increased 37% in the Midwest (Figure 10). Projections are that by 2081-2100, the frequency of precipitation that will occur in very large events will increase by more than 3 times in the eastern portion of Minnesota (Figure 12).

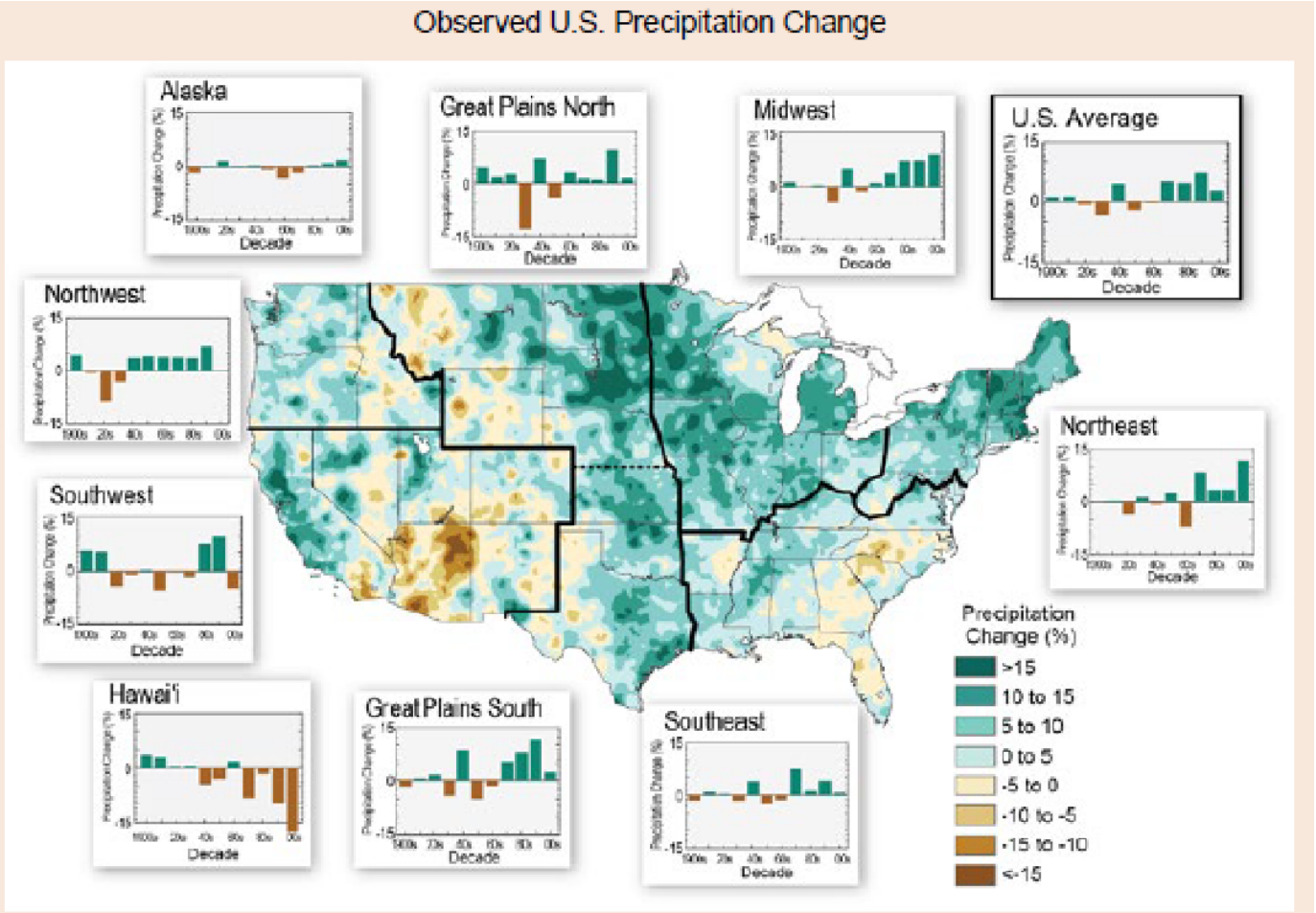
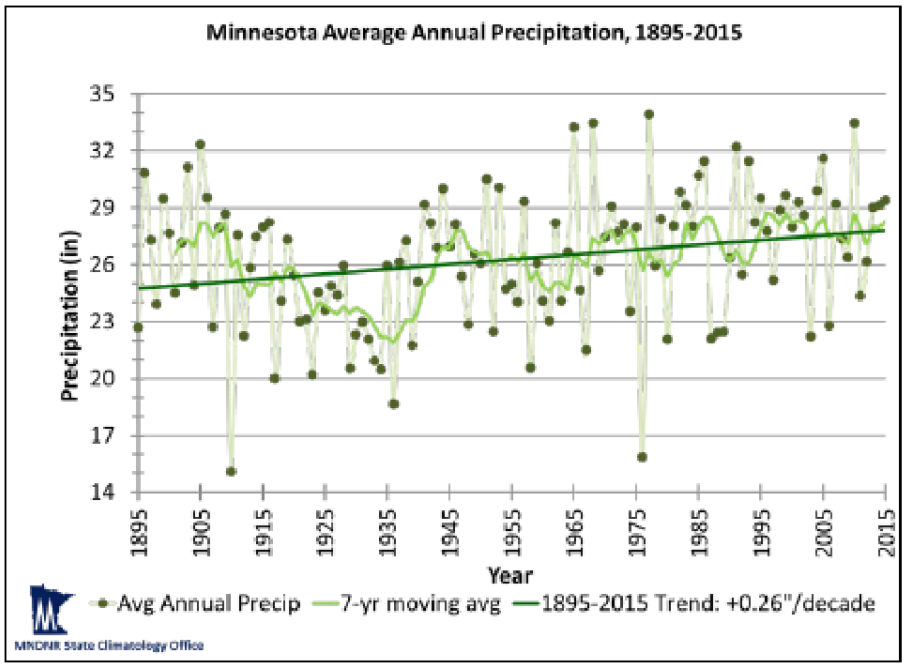


Figure 2.12. The colors on the map show annual total precipitation changes for 1991-2012 compared to the 1901-1960 average, and show wetter conditions in most areas. The bars on the graphs show average precipitation differences by decade for 1901-2012 (relative to the 1901-1960 average) for each region. The far right bar in each graph is for 2001-2012. (Figure source: adapted from Peterson et al. 2013[48]).

Figure 8: Figure 2.12 from Walsh et al (2014) showing the annual precipitation changes for 1991-2012 compared to the 1901-1960 average.



Statewide average annual precipitation, 1895-2015. The 1895-2015 trend (solid dark green line) is based on linear statistical techniques and does not imply an exact decade-by-decade precipitation increase. Source: National Oceanic and Atmospheric Administration (NOAA) Climate at a Glance (http://www.ncdc.noaa.gov/cag/)

Figure 9: Figure 4 from Interagency Climate Adaptation Team (2017) showing average annual Minnesota precipitation.

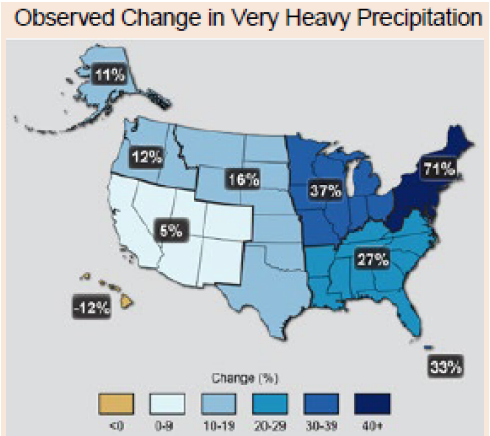


Figure 2.18. The map shows percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region of the continental United States. These trends are larger than natural variations for the Northeast, Midwest, Puerto Rico, Southeast, Great Plains, and Alaska. The trends are not larger than natural variations for the Southwest, Hawai'i, and the Northwest. The changes shown in this figure are calculated from the beginning and end points of the trends for 1958 to 2012. (Figure source: updated from Karl et al. 2009[1]).

Figure 10: Figure 2.18 from Walsh et al (2014) showing percent increases in very heavy events from 1958 through 2012.

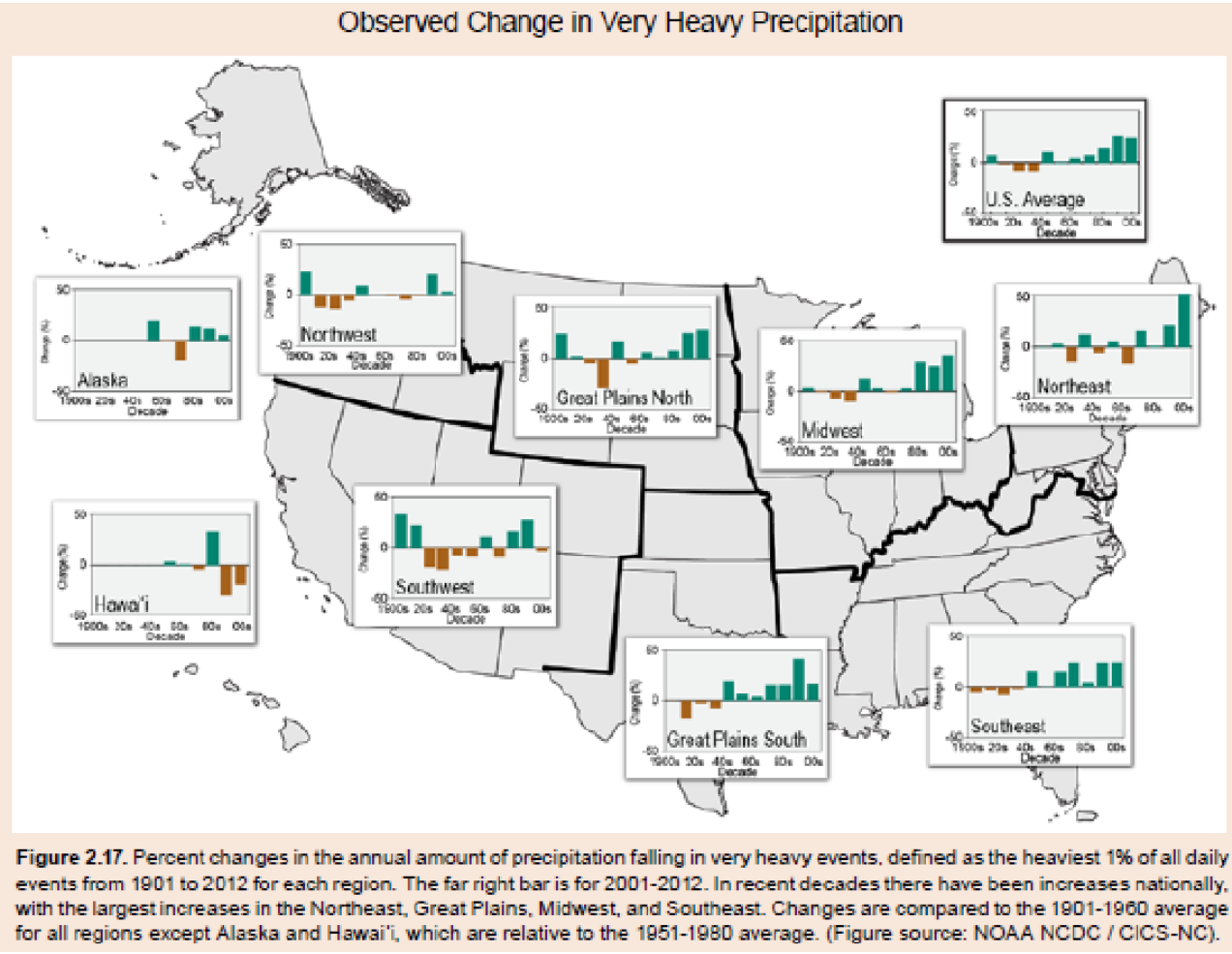


Figure 2.17. Percent changes in the annual amount of precipitation falling in very heavy events, defined as the heaviest 1% of all daily events from 1901 to 2012 for each region. The far right bar is for 2001-2012. In recent decades there have been increases nationally, with the largest increases in the Northeast, Great Plains, Midwest, and Southeast. Changes are compared to the 1901-1960 average for all regions except Alaska and Hawai'i, which are relative to the 1951-1980 average. (Figure source: NOAA NCDC / CICS-NC).

Figure 11: Figure 2.17 from Walsh et al (2014) showing the observed changes in the annual amount of precipitation that falls in very heavy events.

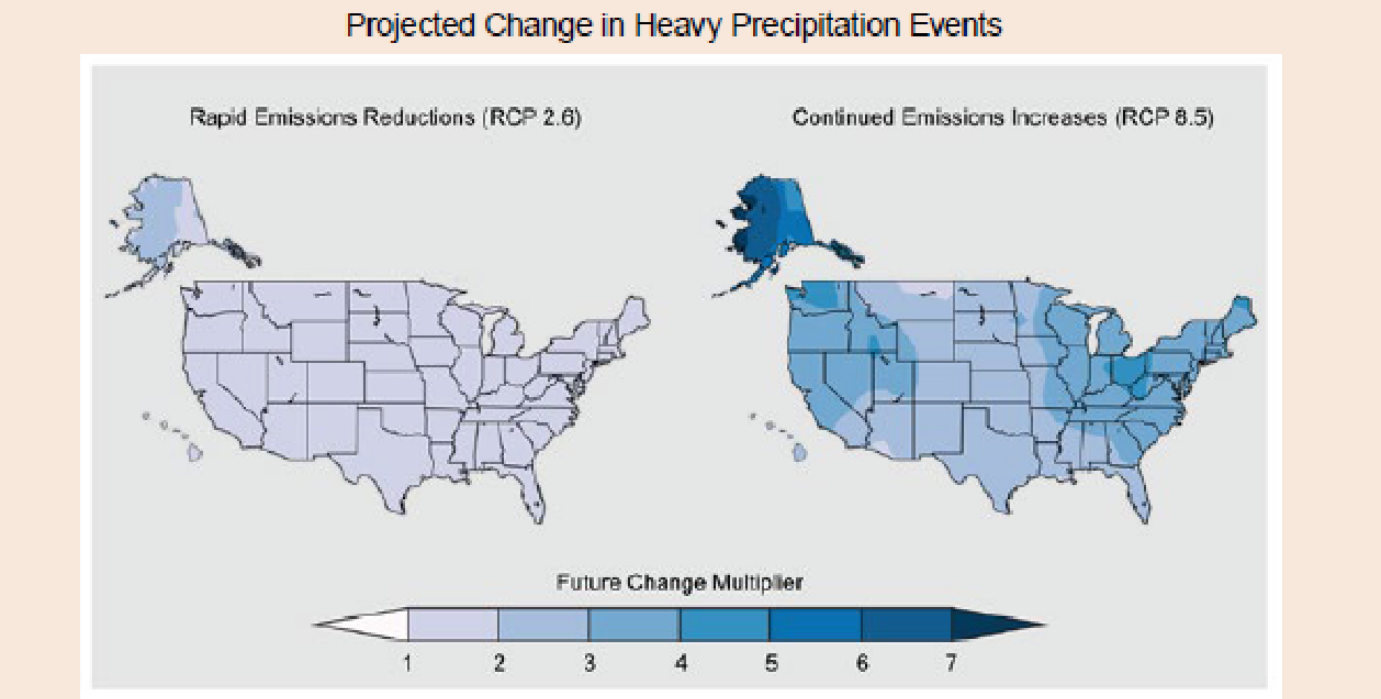


Figure 2.19. Maps show the increase in frequency of extreme daily precipitation events (a daily amount that now occurs once in 20 years) by the later part of this century (2081-2100) compared to the later part of last century (1981-2000). Such extreme events are projected to occur more frequently everywhere in the United States. Under the rapid emissions reduction scenario (RCP 2.6), these events would occur nearly twice as often. For the scenario assuming continued increases in emissions (RCP 8.5), these events would occur up to five times as often. (Figure source: NOAA NCDC / CICS-NC).

Figure 12: Figure 2.19 from Walsh et al (2014) showing the projected change in heavy precipitation events for the period 2018-2100 for two potential emissions scenarios. The scale is a muliplier, meaning that frequency will be multiplied by the value in the legend

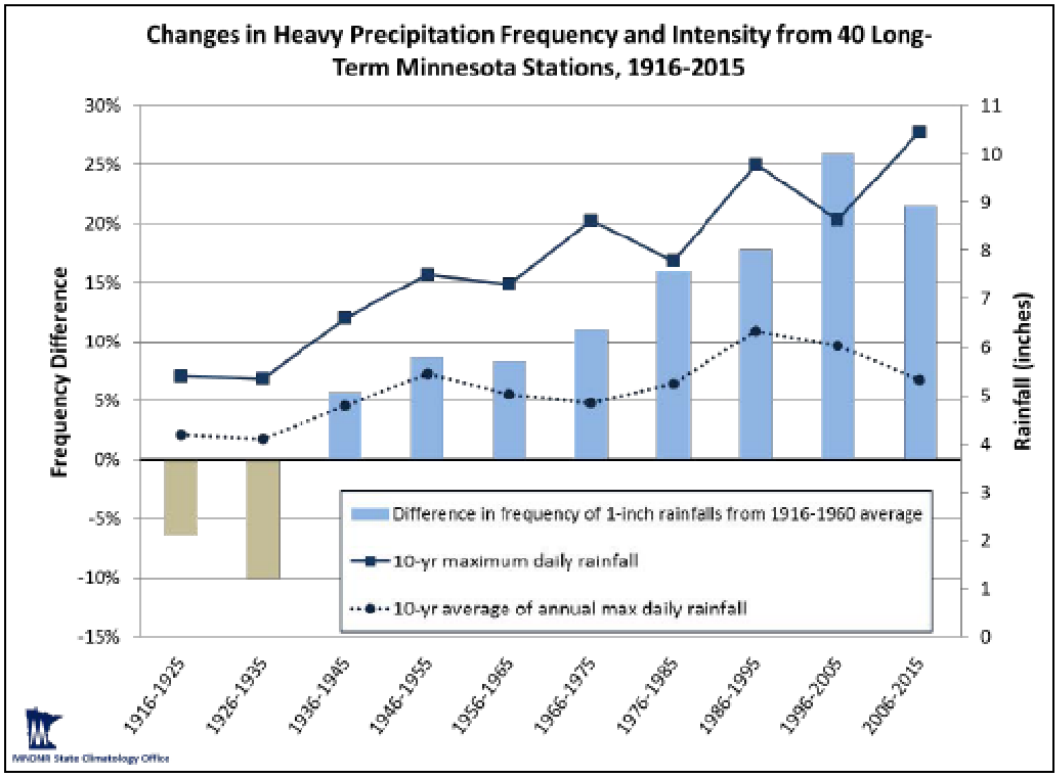
Groisman et al (2015) found there has been a widespread, around the globe, increase in the frequency of very heavy precipitation during the past 50 to 100 years. They describe the trend in the wettest day per year and the wettest five consecutive days per year as a "consensus change" over North America (Groisman et al 2015, p 1340). This finding holds for wet and dry regions and in areas where annual precipitation has increased or decreased. The trend toward more precipitation occurring in low frequency events holds regardless of changes in annual precipitation. These observations have been confirmed with GCM models.

Groisman et al (2005) provides the following physical explanation for an increase in heavy precipitation with global warming:

> Global warming, which has been especially pronounced during the recent decades in extratropical land areas and in minimum temperatures, is related to a reduction in spring snow cover extent, and thus to an earlier onset of spring- and summerlike weather conditions. Warming also relates to a higher water vapor content in the atmosphere, which has been documented in many regions of the world. This in turn results in an increase in the frequency of

Cumulonimbus clouds, which is related to the general increase in thunderstorm activity. This development can explain an observed widespread increase in very heavy precipitation in the extratropics. Furthermore, in humid regions an increase in summer minimum temperatures is related to an increase in the probability of severe convective weather and is likely related to changes in the frequency of heavy and very heavy rain events. It is difficult to directly relate estimates of changes in very heavy precipitation with flooding. However, great floods have been found to be increasing in the twentieth century. Groisman et al 2005, p 1343-1344)

By the 2081 to 2100 period, heavy precipitation events will increase across the US (Figure 12). Projections are that the increase will be from three to four times in eastern Minnesota, meaning that a storm that now occurs once in 20 years will now occur up to four times as often (Figure 13).



Changes in the frequency of one-inch rainfalls relative to the 1916-1960 average (vertical bars), from 40 long-term stations in Minnesota. Also shown are the 10-year average (lower dotted line, right axis) and 10-year maximum values (upper solid line, right axis) of the heaviest single rainfall amount recorded each year at any of the 40 stations. Note that the 10-year maximum value has doubled from just over five inches at the beginning of the record, to just over 10 inches at the end of the record. Courtesy of Minnesota State Climatology Office.

Figure 13: Figure 5 from Interagency Climate Adaptation Team (2017) showing changes in heavy precipitation frequency and intensity for Minnesota.

5.11 Probable Maximum Precipitation

Observed precipitation depths are increasing and simulations of the future show that these depths will continue to increase. Kunkel et al (2013) is the most comprehensive discussion regarding probable changes in PMP with climate change. As noted above in Section 3.2, PMP values depend on available moisture, moisture transport into the storms, upward motion, and strong winds for orographic forcing.

Regarding atmospheric moisture:

> The radiative energy imbalance caused by increases in greenhouse gas concentrations is highly likely to continue the increases in ocean heat storage and a rise in sea surface temperatures that have already been observed. The warming ocean will in turn lead to a rise in evaporation and atmospheric water vapor content, … A probable consequence is the intensification of the hydrologic cycle and PMP over land and ocean (Kunkel et al 1404, references omitted).

Simulations with GCMs showed there would be increases in maximum PW over all model grid cells, which indicates a general global moistening of the atmosphere (Kunkel et al 2013, p 1404) (Figure 14, middle). The highest absolute moisture value occurs in the tropics up to about 30° latitude, with significant excursions of high moisture further north along the east side of the continents including eastern North America where higher moisture extends north into southern Canada (Figure 14, top). This includes Minnesota. The highest fractional changes, while always positive, occur near the poles and in the driest parts of the globe, like the western US and the Sahara of northern Africa (Figure 14, middle).

Changes in PW therefore indicate a high likelihood that PMP will increase with global warming. Only changes in wind could offset the moisture effect, but GCM simulated changes show that the vertical wind direction changes in the higher latitudes are generally positive, but not high (Figure 14, bottom), and are unlikely a check on an increase in PMP (Kunkel et al 2013). In Minnesota, the wind speed changes appear to be between 0 and 10% positive.

The largest positive changes in vertical wind speed are along the intertropical convergence zone near the equator (Figure 14, bottom). This will increase the transport of moisture into the atmosphere and in addition to increasing the moisture in storms near the equator will increase the transport of moisture at upper atmospheric levels away from the equator.

GCM simulations show that the maximum daily precipitation will increase across most of the globe, with Minnesota being in the 10 to 30% range (Figure 15). This verifies the simulated PW increases and that changes in wind speed will not counter the effect of increasing PW with respect to high rainfall periods.

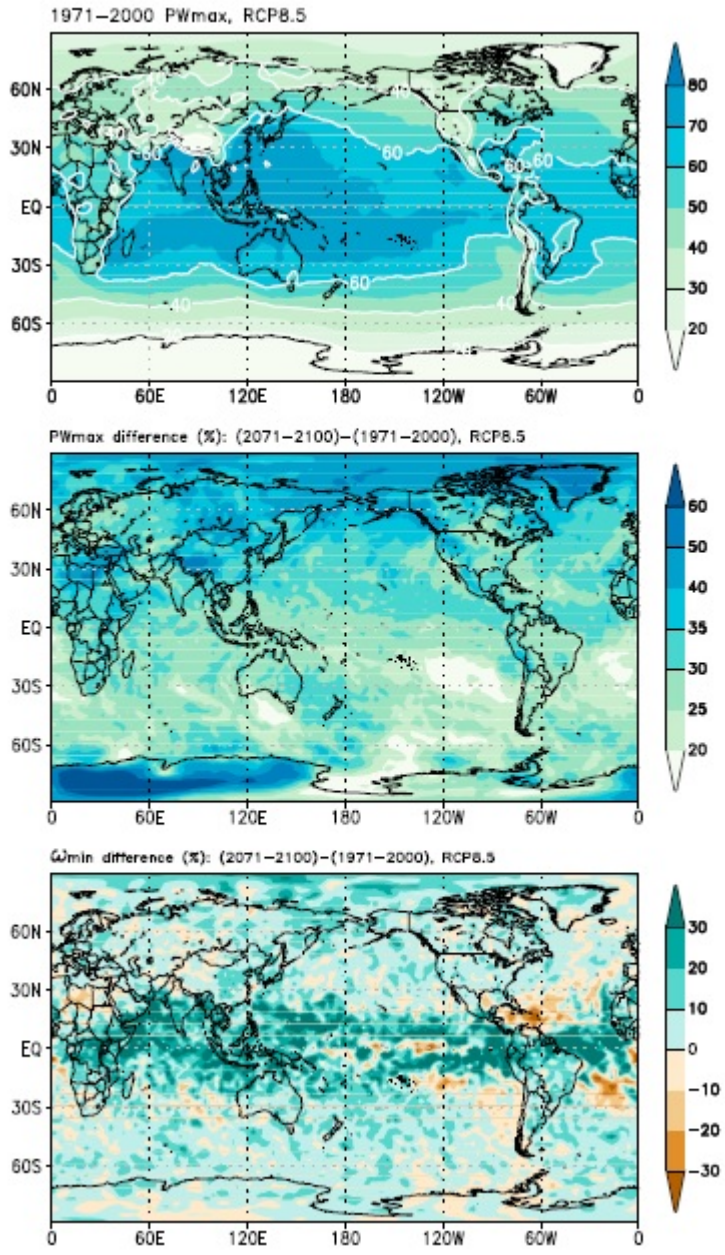


Figure 14: Figure 1 from Kunkel et al (2013). Thirty-year maximum PW for 1971-2000 (mm) averaged over seven climate models (top), fractional change in 12 hour precipitable water (middle) and 6-hour upward motion (bottom) for 2071-2100 relative to 1971-2000, respectively.

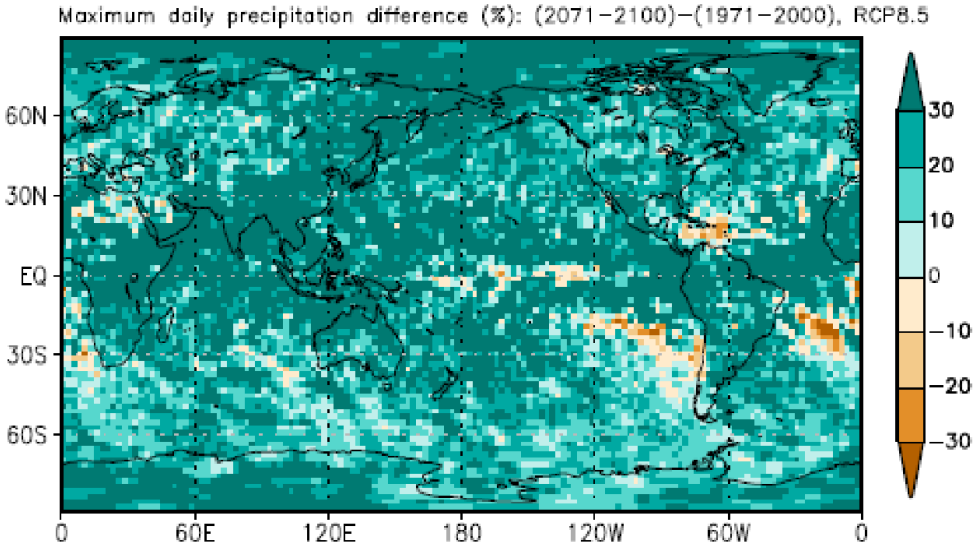


Figure 15: Top of Figure 2 (Kunkel et al 2013). Fractional change of simulated maximum daily precipitation, for 2071-2200 relative to 1971-2000.

Thus, global warming caused by an increase in greenhouse gases will increase the ocean heat content, which will increase atmospheric water vapor. Because changes in wind are unlikely to counter the effects of increasing the atmospheric water vapor, PMP estimates are likely to increase proportional to the water vapor increase. Simple scaling estimates are that the precipitation from a heavy storm can be scaled upward by multiplying the observed precipitation by the ratio of probable maximum PW to PW observed for the storm. The estimate becomes one of estimated probable maximum PW. Design storm intensity estimates can simply be multiplied by a climate change factor. For example, for a case study on a watershed in Malaysia, a CCF ranging from 1.03 to 1.28 was applied to the intensity/duration/frequency relation (Ghazvine et al 2016). On one watershed in Quebec, GCM simulations only increased the PMP up to 6% (Beauchamp et al 2005).

As concluded by Kunkel et al (2013), "the most scientifically sound projection is that PMP values will increase in the future and raise the risk of damaging floods. These conclusions apply not only to the U.S., but also globally to almost all other areas."

5.2 Flooding

The general and obvious point is that heavier rain leads to a larger fraction of the rainfall running off, which could lead to more flooding. The caveat is that higher temperatures could lead to drier antecedent conditions, which could lead to more precipitation evaporating. If this increase in ET exceeds the amount of additional runoff, in some areas the proportion of rainfall becoming runoff may remain similar. Kundzewicz et al (2016) found that extreme precipitation

has trended upward due to climate change, but noted there is little gauge-based evidence for a concomitant increase in floods. However, Walsh et al (2014) noted an observed substantial increase in annual floods, especially in the northeastern third of the US (Figure 16). Some of the more substantial increases occur in western Minnesota, probably along the Red River.

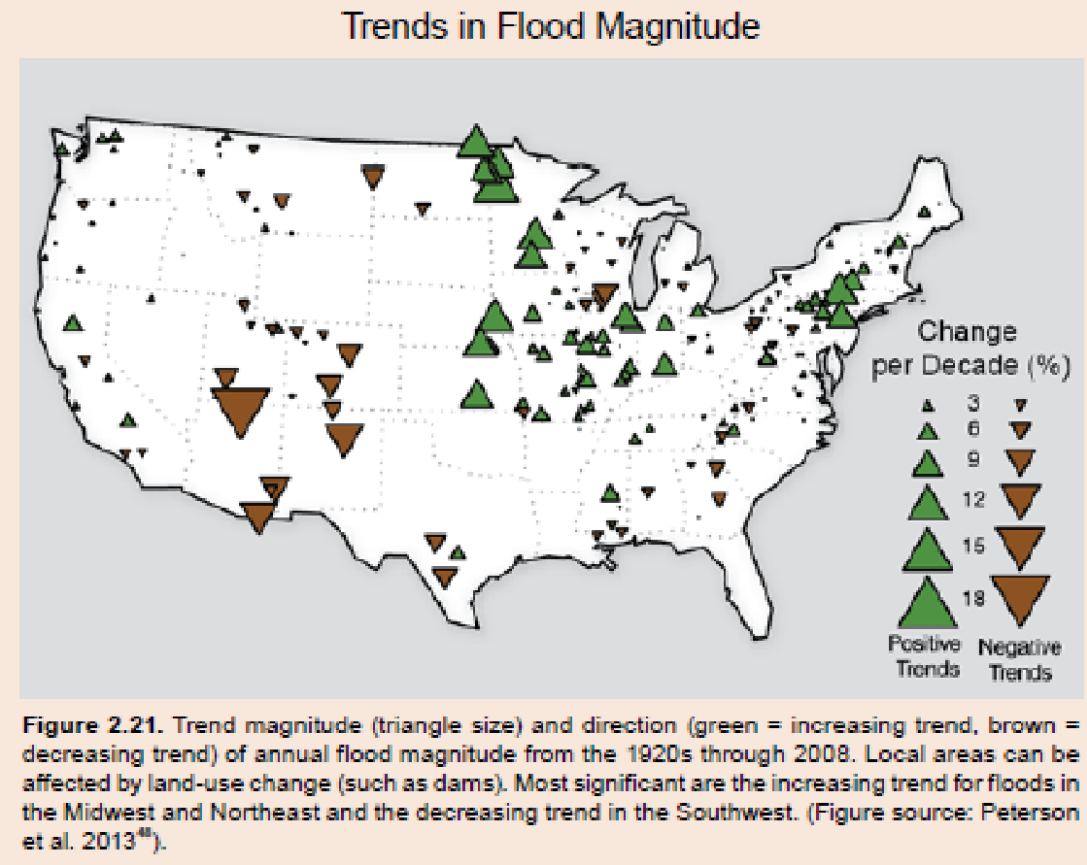


Figure 2.21. Trend magnitude (triangle size) and direction (green = increasing trend, brown = decreasing trend) of annual flood magnitude from the 1920s through 2008. Local areas can be affected by land-use change (such as dams). Most significant are the increasing trend for floods in the Midwest and Northeast and the decreasing trend in the Southwest. (Figure source: Peterson et al. 2013[48]).

Figure 16: Figure 2.21 from Walsh et al (2014) showing trends in flood magnitude.

Many studies point to specific of flooding becoming worse due to climate change. Georgakakos et al (2014, p 70) note that, among many things:

- Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and projected to increase in all regions.
- Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.

Northern Minnesota is projected to have a small increase in annual runoff due to climate change (IPCC 2007). Increased precipitation and temperature can have variable effects depending on the relative and seasonal changes, with increased ET decreasing runoff at some parts of the year while increased precipitation can increase runoff at other times.

Minnesota streamflow has a linear relationship with non-winter precipitation and summer temperatures (Nichols and Verry 2001). Historic stream flow data shows that summertime rainfall runoff peaks have increased as have summertime baseflows (Novotny and Stefan 2007). This is primarily due to increased precipitation, which manifests as heavier individual events rather than more storm events. Increased precipitation in general would increase moisture in the soil, including in an above ground waste or tailings impoundments.

Observed increases in flood losses are mostly due to increased vulnerability, essentially meaning more people are living near flood-prone areas whether or not those areas are growing (Kundzewicz et al 2014). Flood damages can vary greatly for non-climate change related reasons.

6.0 Effects of Climate Change at PolyMet

PolyMet is in northeastern Minnesota, an area that has experienced significant climate change. Temperatures have increased, primarily due to an increase in winter time low temperatures. Annual precipitation and the intensity of storms have also increased. Recent flooding on the Zumbro River and at Duluth exemplify that flooding (Figure 17).

Figure 17: Slide from Powerpoint Presentation, Climate System Research Center and UMass Amherst (undated).

The PolyMet tailings basin is effectively a closed basin with no inflow other than possibly during its first few years. Therefore, the relevant PMP is effectively a point PMP. Also, there is no

issue with simulating rainfall/runoff because precipitation will either pond or seep into the surface of the impoundment. Because the drainage basin is not important and because there is no outlet from the basin until the spillway is reached, the relevant storm is the longest one over a small area, meaning the 72-hour event. PolyMet (2017) recognized this, but did not consider the PMP that will likely result with climate change.

Considering the northern location, snowpack could also be relevant (Clavet-Gaumont et al 2017), for a late spring PMP on snowmelt event. As noted above, the maximum runoff could be the PMP on top of a 100-year snowpack. At the PolyMet tailings basin, all precipitation and melting snow would be retained until it overtops the spillway or seeps into the tails. PolyMet did not consider snowpack as part of its PMP simulation.

Figure 3 shows the final layout of the tailings basin, or flotation tailings pond, constructed on top of the eastern portion of the original impoundment, in stages as described above in Section 4.1. Freeboard will vary depending on the initial conditions, but if there is a 100-year snowpack or a substantial storm occurring six days prior to the PMP, as described above, it is likely to be minimal.

A 30% climate change factor applied to PolyMet's estimated PMP of 38 in/72 hours increases the PMP to 49.4 inches in 72 hours. PolyMet has not estimated the 100-year snowpack, and doing so is beyond the scope of this report. For a rough estimate, I considered the maximum snowfall recorded for a year at Babbitt MN, which was in 2000-01 and equaled 110 inches accumulated by near the end of April (Figure 18). The average snowfall is 42 inches with most recorded by early March. Average precipitation by early March is about 7.2 inches (Figure 19). During an average year, the ratio of snowfall to precipitation is therefore about 5.8. If a similar ratio holds for 110 inches, the snow water equivalent would be about 18.8 inches. This ignores snowmelt that could have occurred, but it should also be recognized that much of that snowmelt would be contained within the tailings. The snowpack considered to be combined with the PMP for this analysis is 18.8 inches, but due to the length of record at Babbitt, this is likely to be less than a 100-year snowpack.

The total PMF that would end up in the tailings basin is the sum of 49.4 and 18.8, or 68.2 inches, within 72 hours. This is almost twice the value analyzed by PolyMet for the PMP/PMF. The additional 30.2 inches of runoff applied to the FTB within 72 hours may not exceed the freeboard, but it would increase the hydrostatic pressure by at least an additional 30 inches on top of the already rapid increase caused by the PMP. This substantially increases the potential for a piping failure of the impoundment. Depending on the amount of tailings beach and other runoff area, the additional rainfall could be sufficient to exceed the freeboard and cause a dam overtopping or at least the use of the spillway. Flows over the spillway are a spill, whether or not the dam fails.

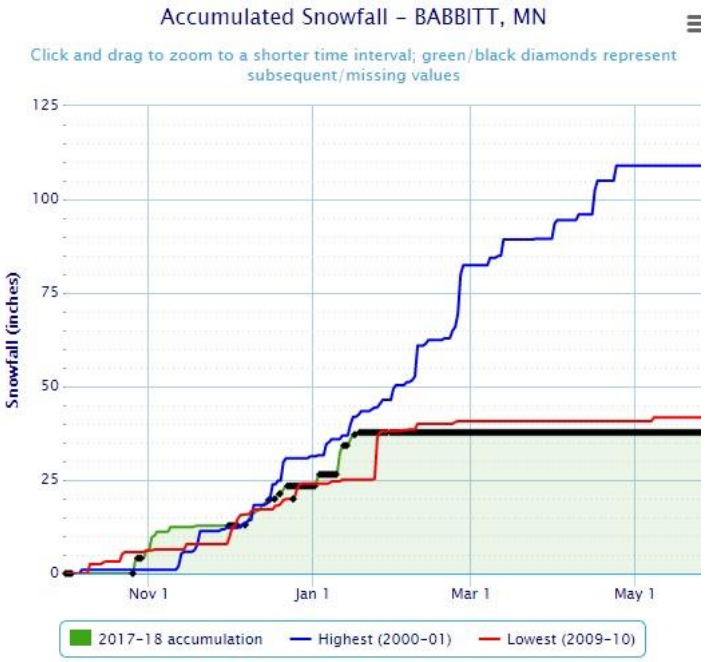


Figure 18: Snowfall accumulations at Babbitt MN, as labeled. From www.weather.gov/dlh/ accessed 1/23/18

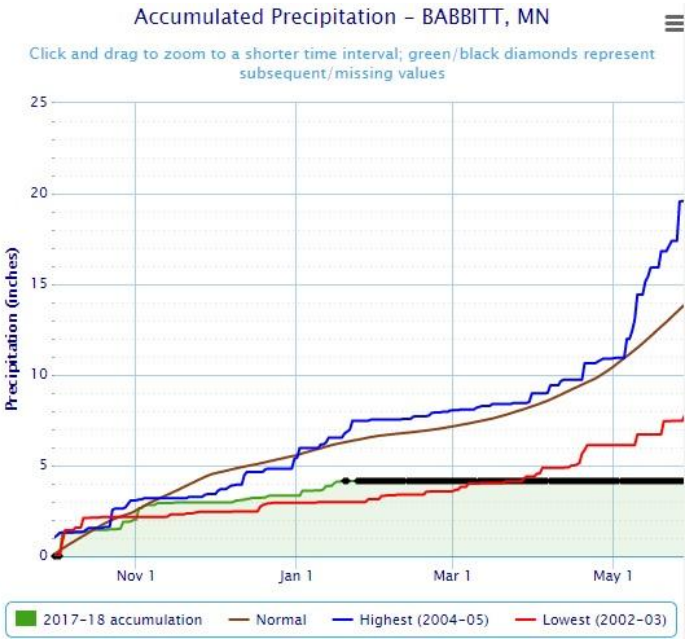


Figure 19: Snowfall accumulations at Babbitt MN, as labeled. From www.weather.gov/dlh/ accessed 1/23/18

7.0 Conclusion – Qualitative Risk Assessment of the Potential Damages of a PMP

PolyMet has not considered the effect that climate change could have on PMP that could affect the PolyMet flotation tailings basin. Instead of 38 inches in 72 hours running into the basin, the total could actually be closer to 68 inches. This extra amount includes snowmelt that would result from a 100-year snowpack on the tailings basin.

The water level in the basin would increase very rapidly. This would lead to rapid changes in hydrostatic pressure and seepage through the impoundment. PolyMet has not analyzed dam stability for such a rapid change. Freeboard could be exceeded as well, depending on initial conditions and the exact configuration of the basin.

The PMP with global warming significantly increases the chance of dam failure, either by overtopping, piping or foundation failure. PolyMet has not analyzed these potential risks.

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