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Incorporating Climate Variability into Water Balance Modelling to Help Inform Water Management Design: The Pebble Mine Project

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Abstract

Water plays a key role in the operation of mining projects, and it is essential that water management facilities be designed to manage the inflows and outflows required for proper operations, as well as accommodate any unpredictable runoff resulting from storms events. The amount of water available varies by year, season, and day, so how do you design for this? Establishing a predictive water balance model during the mine design stage is one of the most important considerations for minimizing water management problems during the operation and closure stages for a project. The water balance model needs to simulate mine operations under normal climate conditions and also under unusually wet and dry periods of varying durations. Key water management planning may be driven by the spring melt of a winter snowpack in cold regions, the variation in snowpack accumulation, and the timing of the freshet season.

The current industry standard for introducing climate variability into water balance modelling is to model monthly precipitation values as distributions, which are typically based on the mean and standard deviation values of historical monthly precipitation. The water balance model is then run for thousands of iterations using Monte Carlo simulation techniques to produce a large range of potential precipitation conditions and corresponding results. This procedure is effective, but it has a major shortcoming in that it simulates precipitation in every month as being completely independent of precipitation in any proceeding or following month. Areas that experience strong climate cycles resulting in extended dry or wet periods may not be correctly represented by this type of modelling.

This paper presents a case study for the proposed Pebble Mine project (Pebble) in Alaska and highlights the importance of a climate variable water balance model for informing the water management plan and design. The Pebble water balance model utilizes a 68-year monthly time-series of temperature and precipitation that was developed using a long-term regional dataset in combination with the extensive hydrometeorological dataset collected for Pebble. The time-series data were stepped through the model

incrementally by year for the planned life of the project, thereby preserving the inherently cyclical nature of the climate record including wet and dry cycles, while creating 68 unique sets of water balance results for each month of each year of the project. The results were used to develop a robust water management strategy that supplies sufficient water to maintain full mine operations, even during prolonged dry periods, and maintains downstream flow requirements for aquatic habitat and resources.

Introduction

The annual runoff pattern in south-central Alaska is dependent on both the annual precipitation pattern and seasonal temperature variations. It is typically represented as a bimodal hydrograph, with high flows during the spring and fall, and low flows during the winter and summer. The high flows in the spring are largely due to snowmelt, while those during the fall are largely due to rainstorms. The magnitude and timing of the spring freshet flows are driven by the accumulation of winter snowpack and the temperature variation of the spring season. Low flows are largely supplied by groundwater discharge, since surface water is largely trapped in snow and ice during the winter, and is scarce due to evaporation and low rainfall during the summer.

Long-term climate records have shown variability in temperatures, not only from year to year but also on multi-year and multi-decadal scales. The patterns of temperature variability are strongly correlated to oceanic temperatures and atmospheric settings in the Pacific Ocean, which most notably are the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) systems (Shulski and Mogil, 2009). Warm and cold phases of the ENSO cycle typically last for several months every two to four years (Papineau, 2001) while the PDO phases tend to shift on a multi-decadal scale (Wendler and Moore, 2012). In 1976 the PDO underwent a dramatic shift from a predominately negative phase to a predominantly positive phase. The climate post-PDO-shift resulted in warmer temperatures and increased precipitation compared to the climate before the PDO-shift (Hartmann and Wendler, 2005).

The air circulation over Alaska is driven by the ENSO and PDO systems, therefore, the climatic conditions at Pebble tend to be relatively wet and warm, or cold and dry, depending on the phases of these systems. The large variation in seasonal, yearly, multi-year, and multi-decadal climate and runoff patterns presents a challenge for water management planning. Accurately predicting climate trends and cycles is not possible (Wendler et al., 2017), but the large range of potential conditions can be modelled using historical data. A water balance model that captures the inherently cyclical nature of the historic climate record is a useful design tool for minimizing the potential for water management problem to occur during the operation and closure stages of a project.

Background: The Pebble Project

The proposed Pebble project is the world's largest known undeveloped copper and gold resource. It is located in southwest Alaska, approximately 200 miles (322 km) southwest of Anchorage and approximately 20 miles (30 km) west of the communities of Iliamna, Newhalen, and Nondalton (Figure 1). Pebble is proposed to be a conventional drill, blast, truck, and shovel operation with a mining rate of up to 90 million tons per year (82 million tonnes per year). The project has a proposed 20-year operating mine life with a total of 1.2 billion tons (1.1 billion tonnes) of material mined (PLP, 2017). The developed mine site will include an open pit, a tailings storage facility (TSF), a power plant, water treatment plants, milling/processing facilities, and supporting infrastructure (Figure 2). Plans for the design and operation of Pebble have focused on the avoidance and minimization of environmental impacts to waterbodies, wetlands, wildlife and aquatic habitat, and areas of cultural significances. The mine layout has been minimized by locating the majority of the site infrastructure in one watershed – that of the North Fork Koktuli River (NFK).

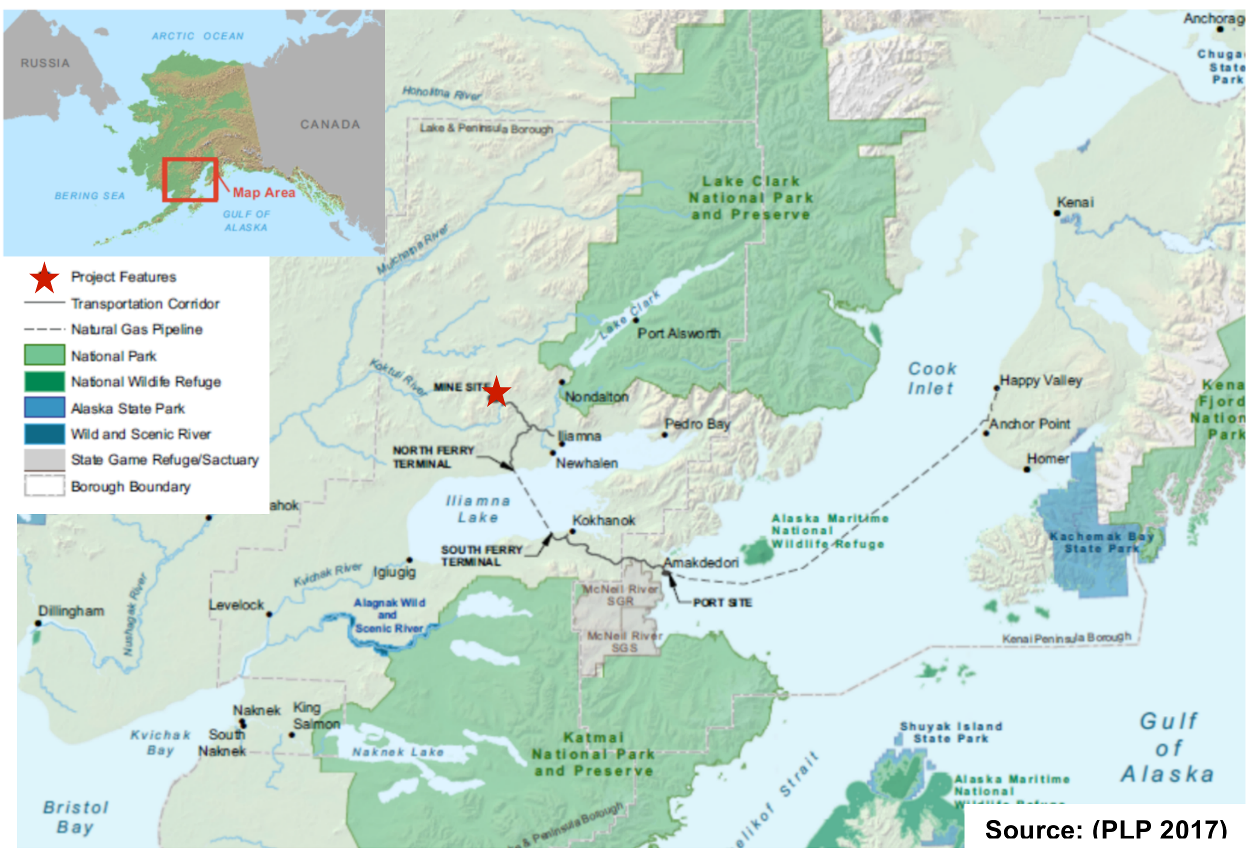

Figure 1: Pebble project location

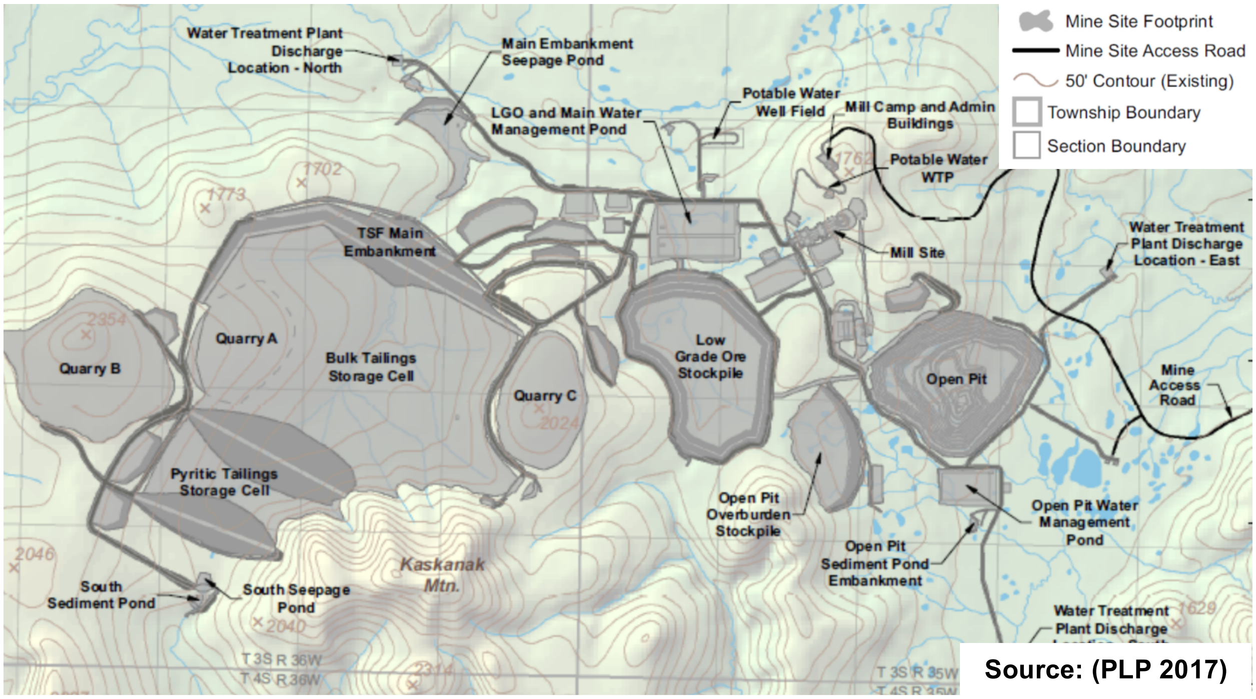

Figure 2: Mine site layout

Hydrometeorology at Pebble

The climate of Pebble is classified as maritime continental, with summer temperatures moderated by the open waters of the Bering Sea and Cook Inlet, and winter temperatures influenced by the presence of sea ice in Bristol Bay during the coldest months of the year (KP, 2012). Mean monthly temperatures range from about 55°F (13°C) in the summer to about 2°F (–17°C) in the winter (PLP, 2017). The Mean Annual Precipitation (MAP) in the NFK drainage is approximately 57 inches (1,450 mm) and in the South Fork Koktuli River (SFK) drainage is approximately 51 inches (1,300 mm). About one-third of this precipitation falls as snow (KP, 2012).

Climate Variability

Long-term temperature and precipitation estimates were developed for Pebble on the basis of 5 years of data collected in the mine area and 68 years of data collected by the US Weather Service at the nearby (~20 miles away) airport at Iliamna. Streamflows were collected at 26 stream gauging stations in the NFK, SFK and Upper Talarik (UT) watersheds, of which 3 are operated by the USGS; these watersheds are shown on Figure 3 (KP, 2012).

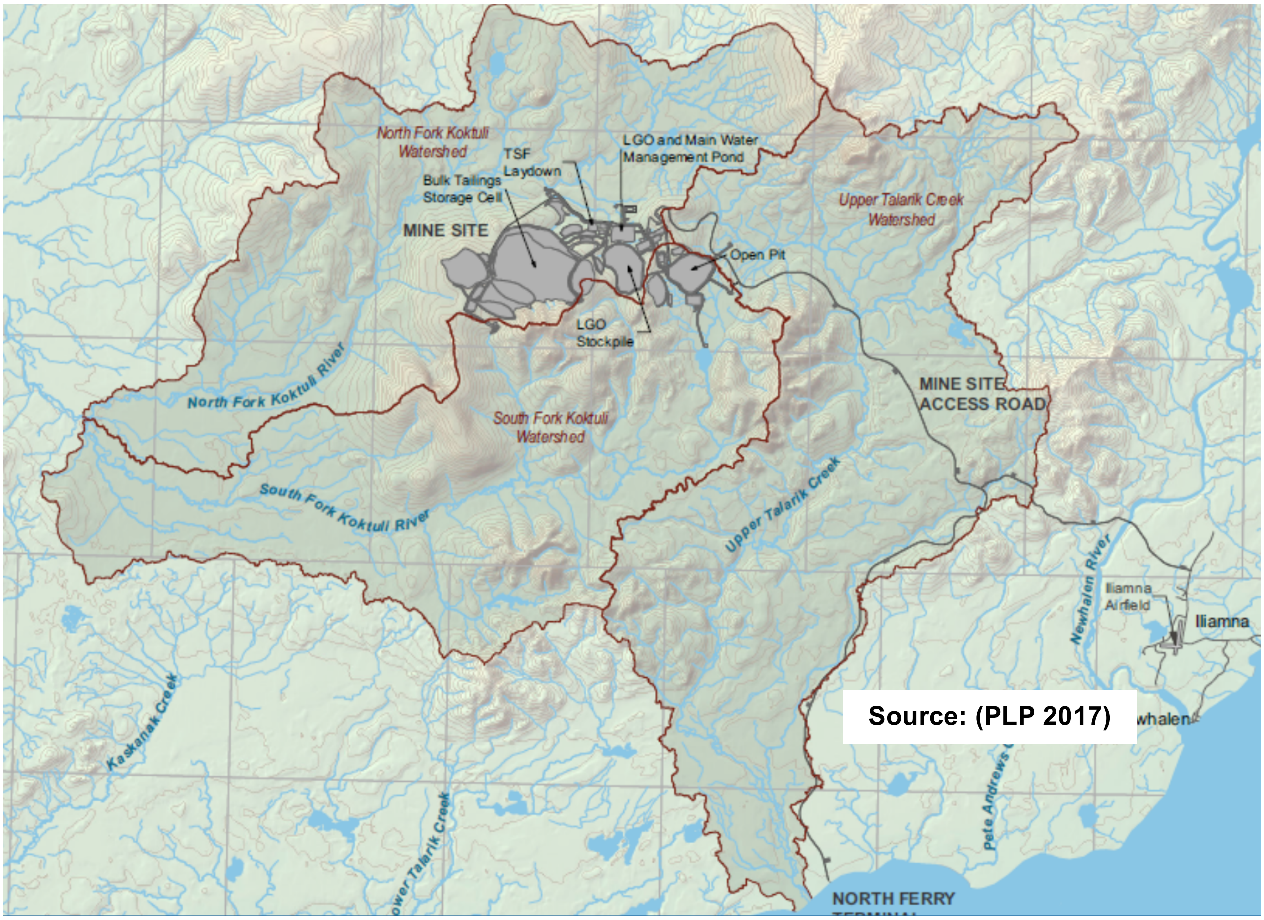

Figure 3: Pebble watersheds

Precipitation at Pebble is very difficult to accurately measure because of consistently strong wind conditions and the associated precipitation gauge under-catch. A watershed model, which was calibrated to the extensive stream flow and groundwater level dataset, was used as the primary basis for developing the precipitation estimates at Pebble (Cathcart and Smith, 2013).

The long-term annual average temperatures and annual total precipitation estimates for Pebble are shown in Figures 4 and 5, respectively. The average annual temperature is estimated to be 30°F (–1°C); however, the warmest annual average temperature is 35°F (2°C) in 1978, while the coldest annual average temperature is 24°F (–4°C) in 1956.

The average annual precipitation is estimated to be approximately 57 in. (1,300 mm), while the driest year on record, 1968, had a total precipitation of 33 in. (833 mm), and the wettest year, 1971, had a total precipitation of 98 in. (2,490 mm). Figures 6 and 7 demonstrate the year-to-year and multi-decadal climate variability that has been historically observed at Pebble.

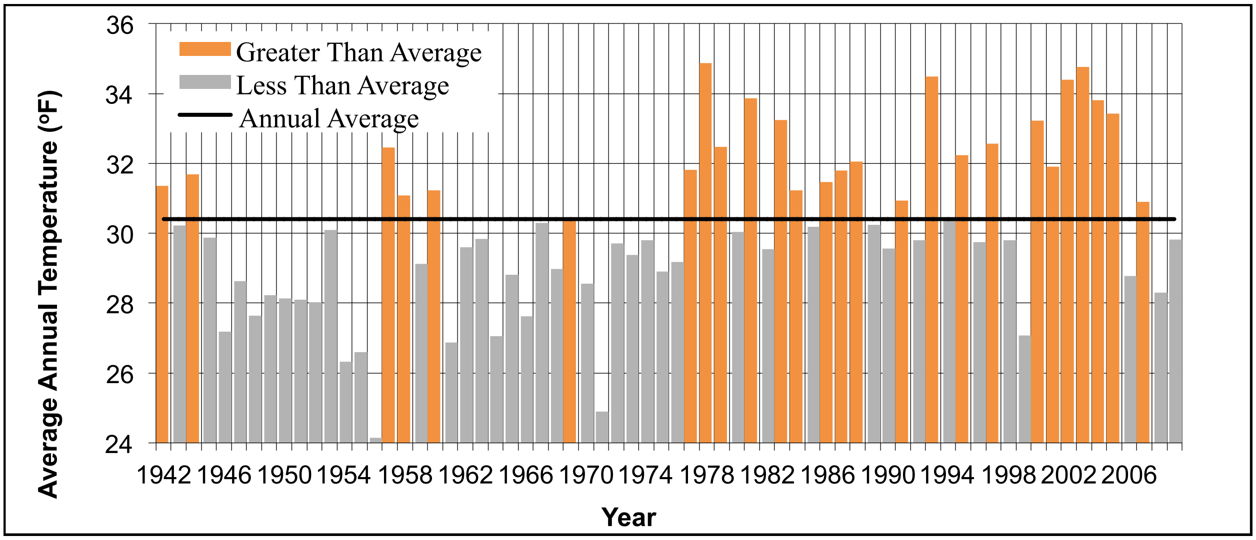

Figure 4: Long-term mean annual air temperature at Pebble

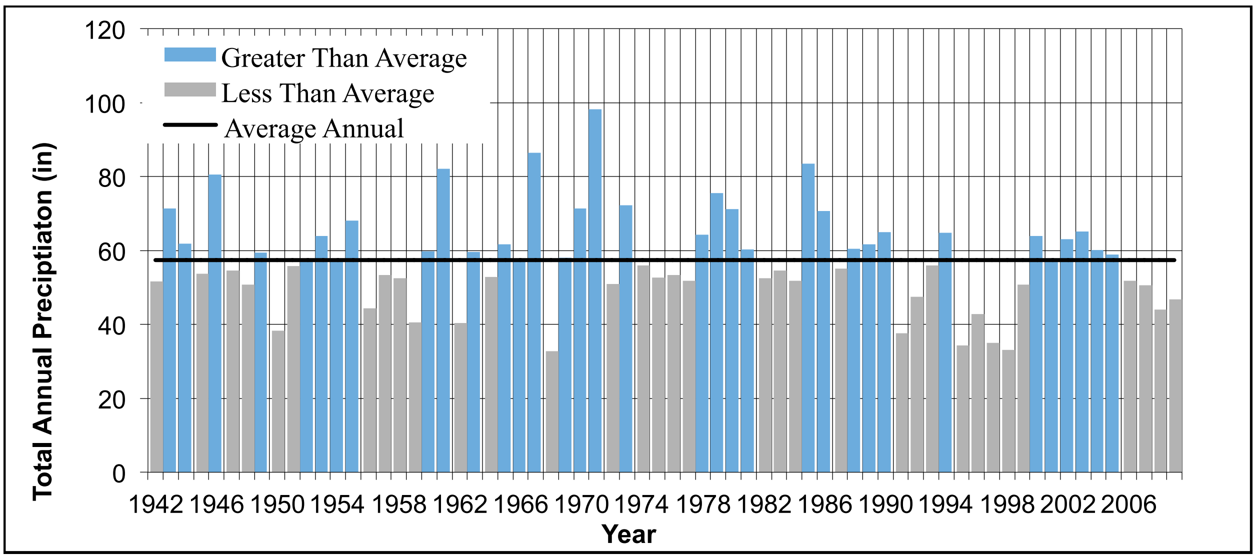

Figure 5: Long-term annual precipitation at Pebble

The long-term records also indicate the strong seasonal and month-to-month climate variability at Pebble. Figure 6 shows the patterns of monthly average air temperature and monthly total precipitation for the full data record, and Figure 7 shows the monthly runoff for each year of record in grey (as determined by the water balance model) and the long-term average runoff in blue. The annual hydrograph typically has peak runoff during the spring and fall and low runoff during the winter and summer. The first peak generally occurs in May, as a result of snowmelt, while the second peak occurs between August and October, as a result of rainfall events. Variations in temperatures, however, can sometimes produce peak freshet runoff in June as a result of colder and longer winters producing large snowpacks and/or the late onset of the spring melt period.

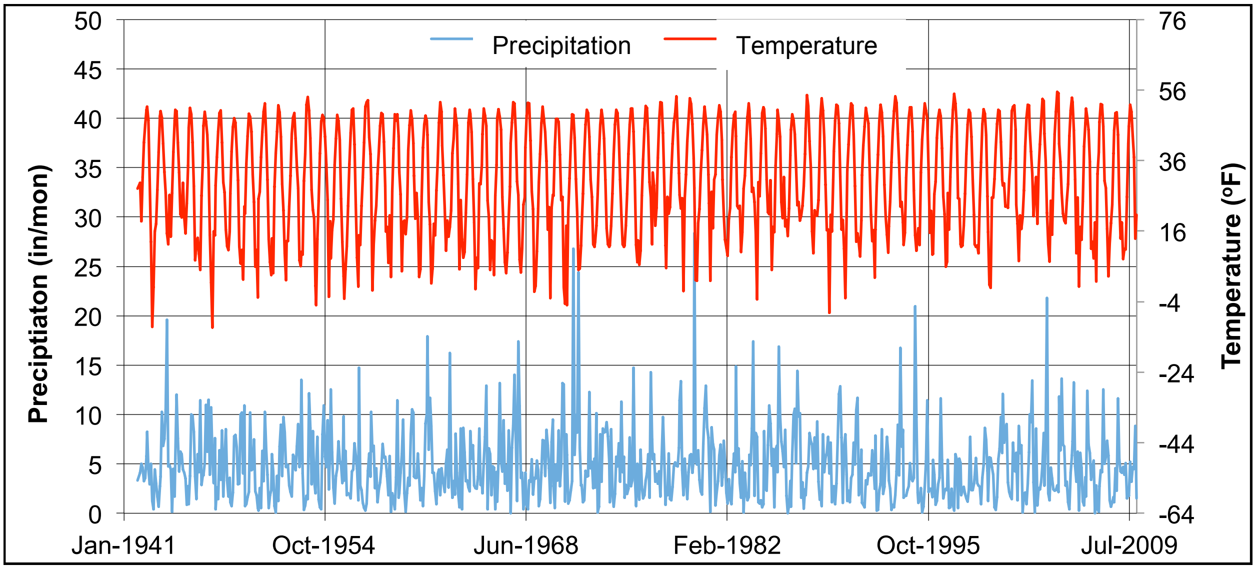

Figure 6: Long-term monthly average temperature and monthly total precipitation at Pebble

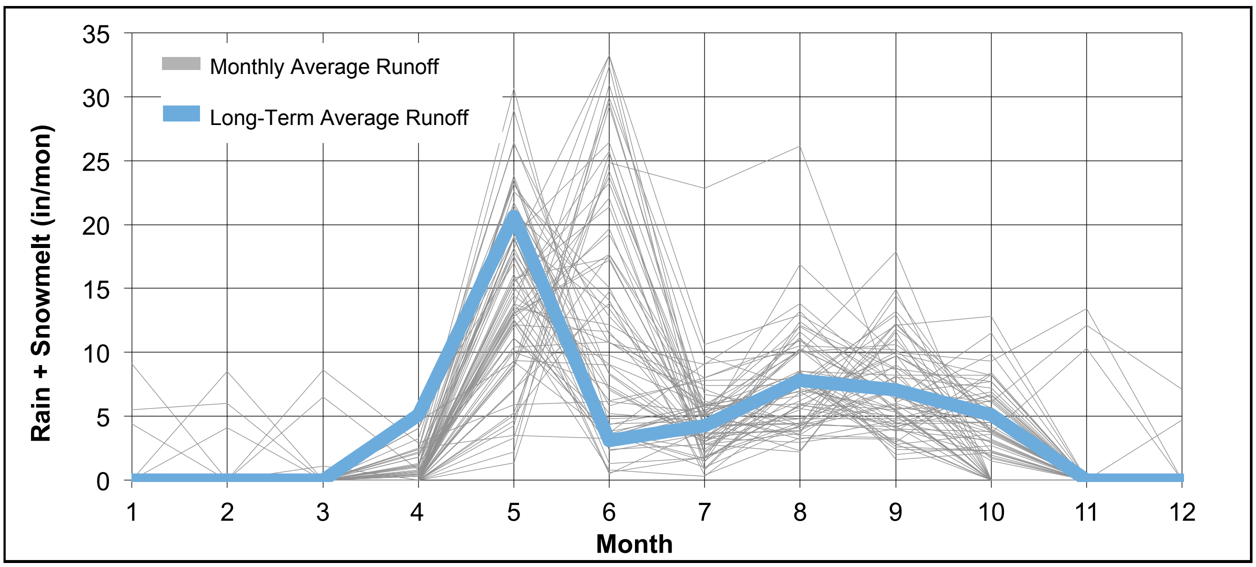

Figure 7: Long-term and average monthly rainfall and snowmelt at Pebble

Water Management Strategy and Water Balance Model

The main objective of the water management plan for Pebble is to manage water that originates within the project area in an environmentally responsible manner while providing an adequate water supply for mining operations. Primary design considerations are the need to capture and treat all contact water prior to its release to the environment, to operate the mine without requiring additional water from off-site sources, and to release water to sustain or enhance downstream aquatic resources. Development of the water management plan involved the consideration of these factors with the constraints of the project facility layout, process requirements, area topography, hydrometeorology, aquatic habitat/resources, and regulatory discharge requirements, which ultimately led to the need for six water management ponds (WMP). The primary purposes for each are summarized in Table 1, and the locations of the ponds are shown on Figure 2.

Table 1: Description of water management ponds

Water management feature	Purpose
Open pit WMP (OP WMP)	Manage surface and groundwater from open pit dewatering prior to treatment at the water treatment plant (WTP)
Low Grade Ore WMP (LGO WMP)	Collect and manage runoff and seepage from the Low Grade Ore (LGO) stockpile. Surplus water from this pond will be directed to the Main WMP.
Main Embankment seepage collection pond	Collect and manage runoff and seepage from the Main TSF embankment. Surplus water from this pond will be directed to the Main WMP.
TSF (bulk tailings cells)	Storage of non-potential acid generating (NPAG) tailings solids and management of runoff from tailings beaches and quarries. Surplus water from this pond will be directed to the Main WMP.
TSF (pyritic tailings cell)	Storage of potential acid generating (PAG) tailings solids and to provide chemical stability of the solids (wet cover). Surplus water from this pond will be directed to the bulk tailings cell.
Main WMP	Storage and management of surface water runoff from the Mill site and surplus water from other water management facilities. Surplus water from this pond will be used as make-up water in the process and treated at the WTP.

All of these water management facilities will be designed to meet dam safety requirements and will have appropriate storm storage and freeboard allowances. The storm storage and freeboard requirements are based on estimates of extreme precipitation and/or runoff events, such as the 100-year, 24-hour precipitation event, or the Probable Maximum Flood (PMF) event. The runoff volumes associated with these events are considered over and above the maximum operating pond levels.

A water balance model was developed using the long-term monthly temperature and precipitation dataset established for Pebble. Modelling climate variability played a key role in dictating the range of operating pond volumes, pumping rates, and water treatment rates that will be required in order to facilitate normal operations of the project even under unusually wet and dry conditions of varying duration.

Water Balance Model

The water balance model is site-wide and considers all mine facilities including the TSF, open pit, process plant, LGO stockpile, and water management ponds. The model tracks the movement of water through the Pebble footprint area including runoff from the mine facilities, groundwater inflows, evaporation, water stored in facilities, and water lost to the tailings voids. The water balance is used to predict the full range of possible flows in the mine site area and to estimate the water storage capacity requirements for the mine under normal, wet, and dry climatic conditions.

Climate variability was introduced into the Pebble water balance by utilizing the 68-year monthly time-series of temperature and precipitation, as discussed in previous sections. The time-series data were incrementally stepped by year within the model, for the planned life of the project, therefore persevering the inherent cyclical nature of the climate record. A schematic of how the shifting time-series is used in the model is shown on Figure 8. The model generated 68 unique sets of results of water flow and storage over the full life of the mine, and distributions were then fit to each set of 68 output values so that probabilities of occurrence could be determined. These results facilitated the development of a robust water management strategy that accounts for a full range of possible climate and runoff conditions. Adequate storage in each of the WMPs was determined so that excess water during extended wet periods can be captured and stored to maintain full mine operations during periods of extended dry periods, while maintaining adequate flow releases for aquatic resources both during wet and dry periods.

	Realization 1	Realization 2	Realization 3	Realization 4
Mine Life: Years 1 to 20	Year 1	Year 2	Year 3	Year 4
	Year 2	Year 3	Year 4	Year 5
	Year 3	Year 4	Year 5	Year 6
	. . .	. . .	. . .	. . .
	Year 19	Year 20	Year 21	Year 22
	Year 20	Year 21	Year 22	Year 23
	Year 21	Year 22	Year 23	Year 24
	. . . .	. . .	. . .	. . .
	Year 66	Year 67	Year 68	Year 1
	Year 67	Year 68	Year 1	Year 2
	Year 68	Year 1	Year 2	Year 3

Figure 4: Schematic of shifting time-series

Climate Variability Water Balance Model Results

The climate variability water balance model was used as a tool to help define the water management plan so that it can meet its main objectives as defined above. The Main WMP operation is used as an example to illustrate the results of the water balance model.

The priority for the Main WMP is to supply water to the process plant at all times. The logic in the model was set up such that enough water always remained in the pond to supply the process, even during prolonged dry periods. (Note that the longest period of below-average precipitation in the historic record is five years.) A secondary priority of the Main WMP is to regulate inflows so that surplus water can be discharged at reasonably constant rates to the WTP for treatment and ultimate release to the downstream environments. This water is intended to maintain aquatic habitat and resources. The challenge was to determine the balance between storage in the WMP and the water treatment rates that would maintain a water supply to the process while providing adequate flows to the downstream aquatic habitat and resources. This was an iterative process, with pond volumes and treatment rates varied to meet the goals. Ultimately, variable treatment rates were required to meet the objectives. Flow rates to the WTP were reduced when pond volumes were approaching low levels and increased when pond volumes were approaching high levels. The low-level trigger was determined by evaluating the amount of water required in the pond to maintain water to the process under prolonged dry periods, while the upper trigger was determined to maintain enough free storage in the ponds to allow for the large inflow volumes during high runoff years, and particularly high snowmelt volumes.

The results from the water balance model for the Main WMP are provided on Figure 9. The pond volume results from all 68 model realizations are shown on Figure 9A. Two unique realizations were selected to demonstrate the flexibility of the water management plan to address the high variability climate at Pebble. Realization 1, shown on Figure 9B, represents the wettest 20-year sequence within the time-series data with an annual average precipitation of 64 in. (1,635 mm), an annual maximum of 98 in. (2,490 mm), and an annual minimum of 51 in. (1,295 mm). Realization 2, shown on Figure 9C, represents the driest 20-year sequence with an annual average precipitation of 51 in. (1,288 mm), an annual maximum of 65 in. (1,562 mm), and an annual minimum of 33 in. (838 mm).

The first year of precipitation under Realization 1 is very high, and consequently, there is a drastic increase in pond volume in Year 1 of operations. The maximum operating pond volume was determined assuming these conditions; therefore, the risk of miss-operation is minimalized. Spikes in the pond volume are seen on an annual basis for each year of operations under this realization, representing the effects of snowmelt in the spring and rainfall in the fall. The magnitudes of the spikes vary depending on the phases of the ENSO and PDO. The water management strategy effectively manages these events by drawing down the pond volume each year to provide sufficient capacity to captured the runoff from the spring snowmelt, and then again for the fall storms.

The first year of precipitation under realization 2 is much lower than in realization 1, and results in a much smaller starting pond volume. The minimum pond volumes for this realization are much lower, but the rules applied to the water treatment rates allow for adequate water volumes to be maintained in the pond to provide a constant feed to the process. The treated flows released to the downstream environments are lower in realization 2, but this was deemed acceptable since the flows in all the streams would also be low under natural non-mine conditions for these climatic conditions.

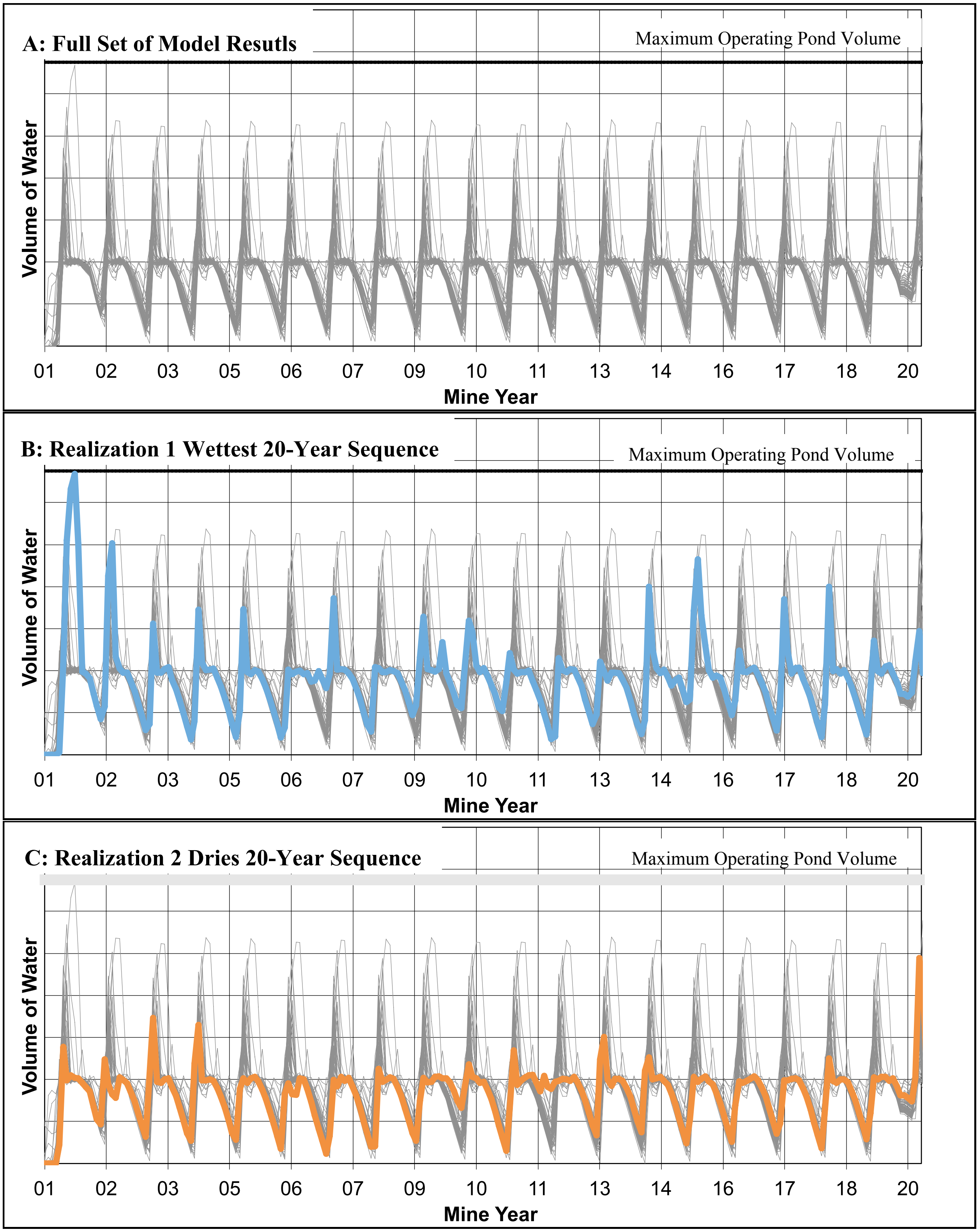

Figure 9: Range of predicted pond volumes for the main water management pond

Conclusion

The climate in south-central Alaska is highly variable with large monthly, seasonal, and annual ranges, and is dependent on the strong climate cycles, resulting in extended dry or wet periods. A water balance model was developed that utilizes 68 years of monthly temperature and precipitation data to address climate variability at Pebble, and its implications for water management strategies. The time-series data were incrementally stepped through in the model by year for the planned life of the project, thereby preserving the inherently cyclical nature of the climate record. Pebble's water management strategy was therefore evaluated under the full range of historic climate variability, regardless of it being a wet or dry phase. The results were a robust water management strategy that includes providing adequate storage in each of the water management ponds to supply sufficient water to maintain full mine operations, while maintaining downstream flow requirements for aquatic resources.

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