2019 tailings dam failure in Brumadinho, Brazil (Photo from Vinícius Mendonça/Ibama, Flickr)

PMP Estimation for Mine Tailings Dams in Data Limited Regions

Bill Kappel

Introduction

Applied Weather Associates (AWA) recently completed Probable Maximum Precipitation (PMP) and detailed meteorological analyses for several mining locations effected by limited data, extreme meteorological patterns, and highly variable topographic settings. These included a large mine in Papua, Indonesia; a high elevation mine in north central Peru; and a large mine in northern Chile.

AWA utilizes a storm-based approach to derive PMP, following the methods descried in Mukhopadhyay and Kappel (2016), the World Meteorological Organization (2009), and Schreiner and Riedel (1978). Additional meteorological parameters, such as Annual Exceedance Probabilities (AEP) of PMP, regional precipitation frequency (PF) climatologies, and Depth-Duration-Frequency (DDF) curves were also derived. Previous PMP projects completed by AWA provide examples which explicitly

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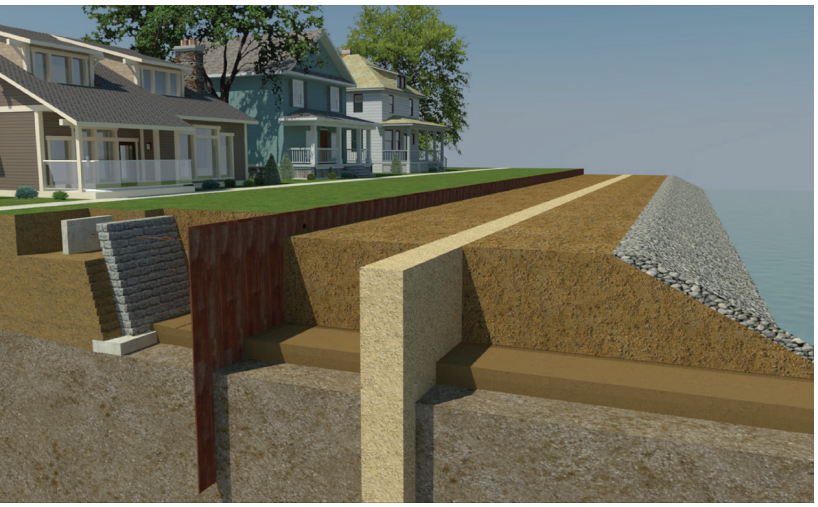

Dean B. Durkee, PhD, PE • ddurkee@gfnet.com
Paul G. Schweiger, PE, CFM • pschweiger@gfnet.com
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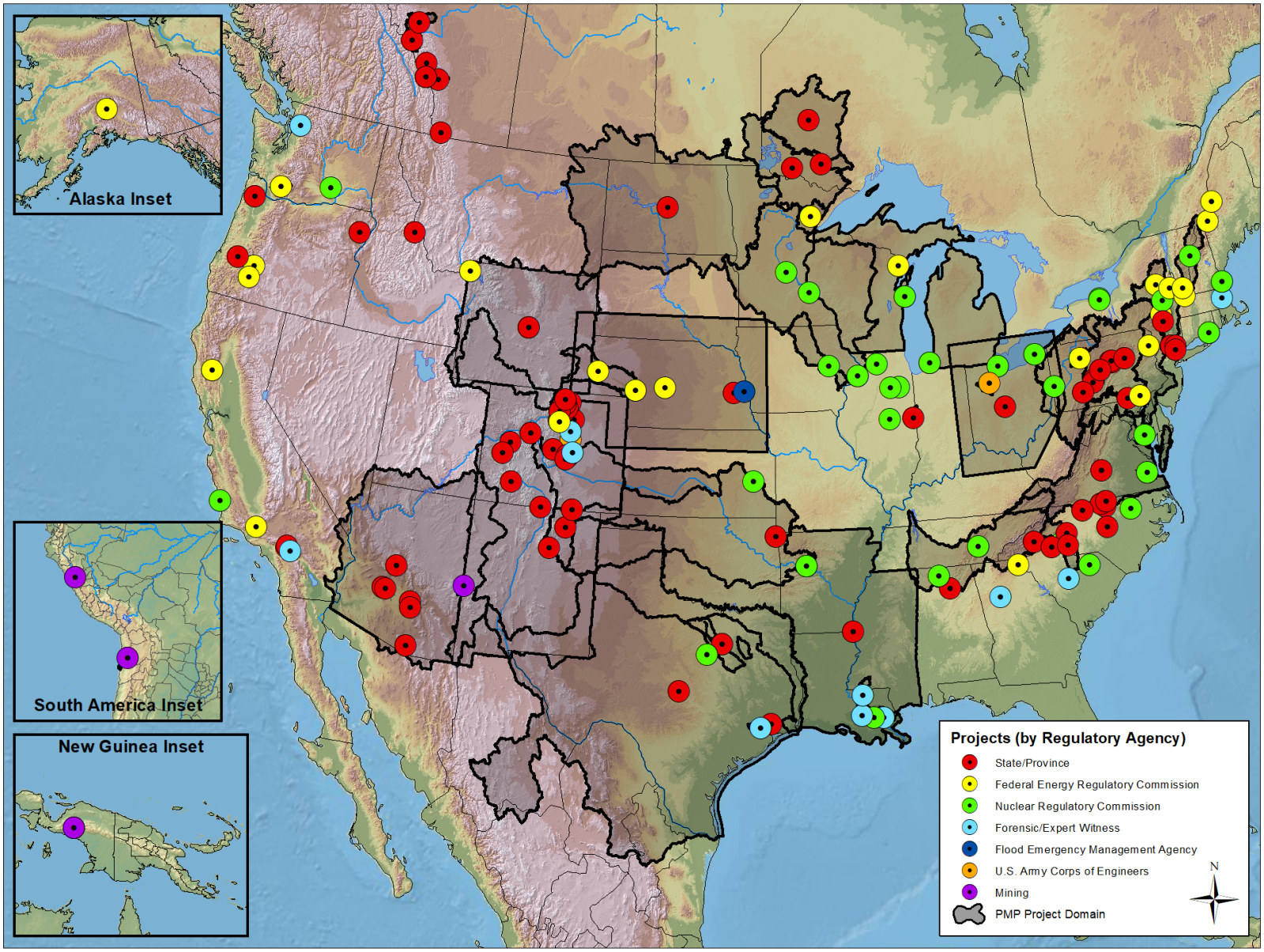

Figure 1. AWA project locations by regulatory agency

considered the topography and meteorological characteristics of each study location. Several of these provided valuable insight about the interaction of extreme precipitation over climatologically similar regions to the mining locations discussed in this paper (Fig. 1). These PMP studies have received extensive review, and the results have been used in computing the Probable Maximum Flood (PMF) for the watersheds and regions covered. The mine locations discussed in this paper were able to leverage those previous studies and follow the same accepted procedures to determine PMP values, to develop the PF database, and calculate other meteorological data for each location.

Mine Site Locations

Each of the locations had previously utilized the Hershfield statistical method (Hershfield, 1961 and Hershfield, 1965) to derive PMP depths. Use of the storm-based approach to derive the updated PMP and other meteorological parameters is a significant improvement over the previously derived estimated PMP depths. The storm-based approach provides more confidence and certainty in the depths used for design of these high hazard infrastructures. In contrast to the Hershfield method, the storm-based approach and utilization of observed rainfall events specifically relevant for a given location, is able to more accurately quantify rainfall accumulation in space, time, and

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The Indonesian mine is located just south of the equator and is the world's largest gold mine and second-largest copper mine (Fig. 2). Due to the topographic setting and extreme elevations, the site can receive snow at the top of the basin at the same time heavy monsoon rainfall is occurring at lower elevations. The region includes tropical glaciers above the mine site with tropical rainforest throughout the majority of the basin, ending with an ocean interface (Mealey, 1996). Terrain plays a key role in defining the PMP storm type and PF development, the magnitude of rainfall accumulations, and their associated spatial and temporal distributions. These factors were explicitly accounted for during the updated PMP and PF development processes.

The mine in Peru is located in a mountainous region near the headwaters of the Marañón

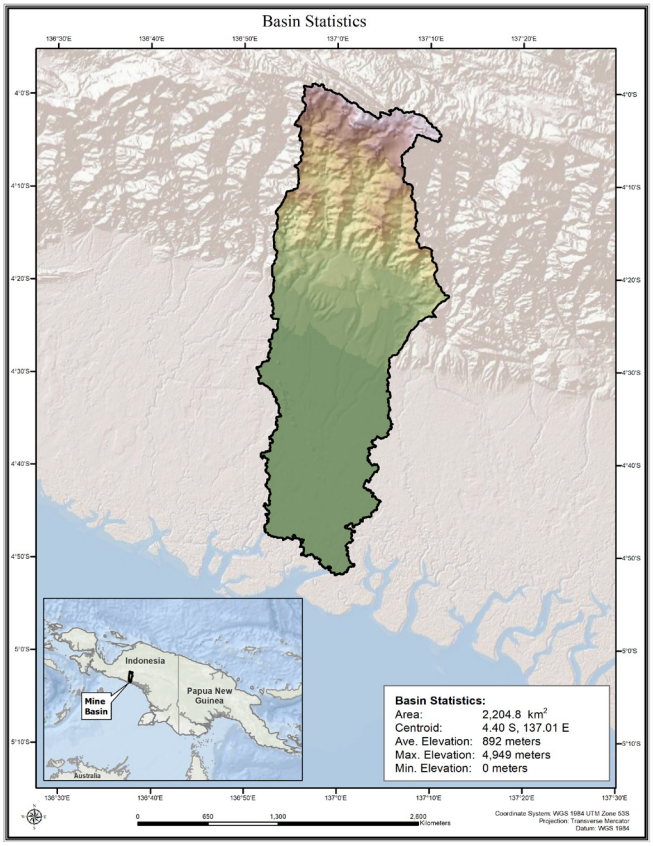
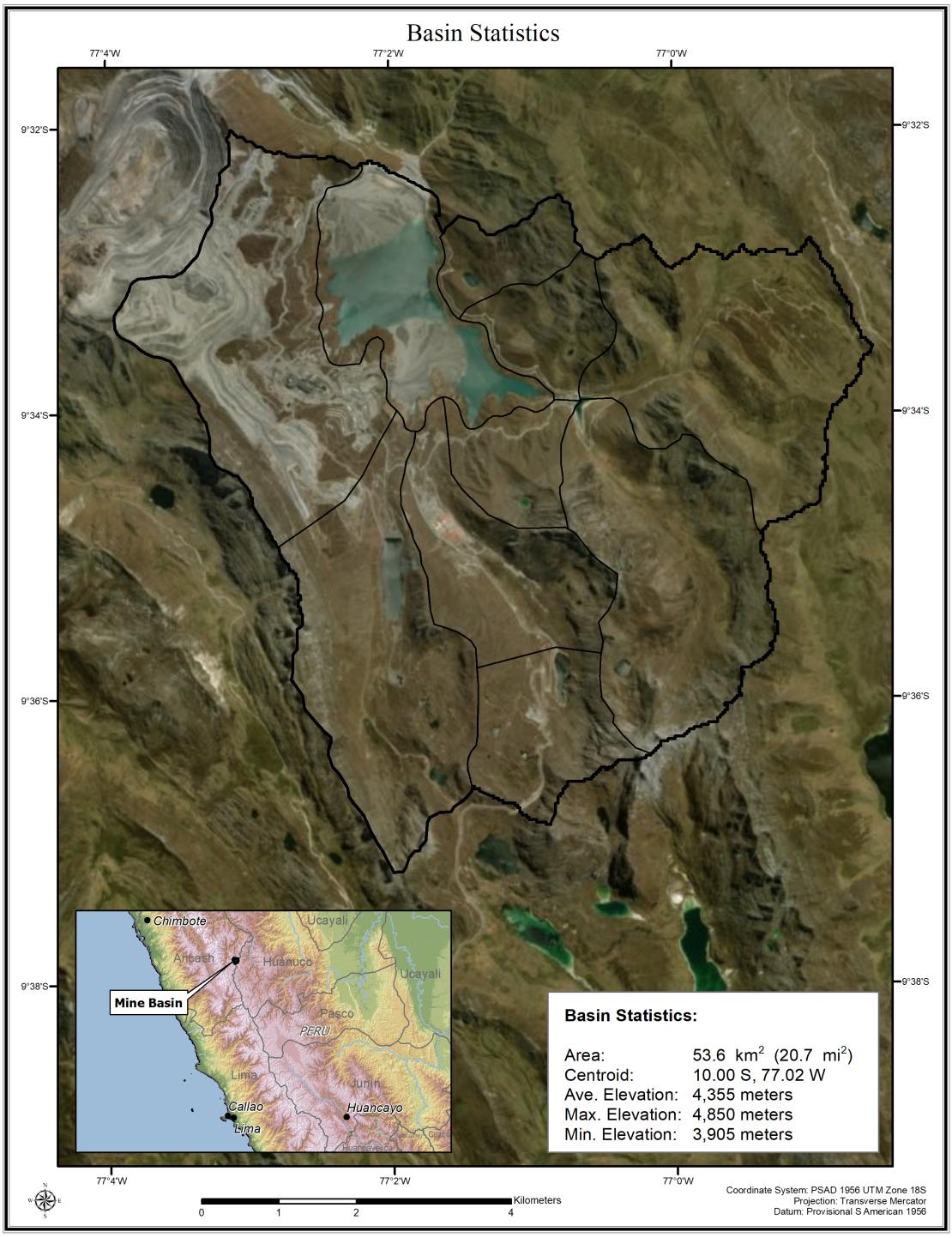


Figure 2. Indonesian mine site, topography, and regional setting

Figure 3. Peruvian mine site, topography, and regional setting



River and the headwaters of the Amazon River at elevations ranging from 3900 m (12,795 ft) to 4850 m (15,912 ft) (Fig. 3). This location plays a significant role in precipitation development; hence, PMP values must be considered explicitly. In addition, the basin is located in a transitional region between the humid upper Amazon basin to the east and the dry coastal regions to the west. Finally, significant topographical barriers exist both to the immediate west and east of the basin, limiting moisture availability. These factors were not accounted for using the Hershfield method but were explicitly accounted for using the storm-based PMP and PF development process.

The mining complex in Chile is located in one of the driest regions on the planet (Houston, 2006; Garreaud and Aceituna, 2001) with a significant portion of the overall region in the Atacama Desert (Fig. 4). The overall mining area extends from the coast to the High Andes. Therefore, a wide range of meteorological and topographical environments are encountered, including various seasonality and magnitudes of precipitation (Garreaud, 2010). Some locations in this region receive less than 1 mm (0.01 in.) of precipitation per year with several locations in the central and western regions going without any measurable precipitation for more than a decade. Conversely, as elevation increases towards

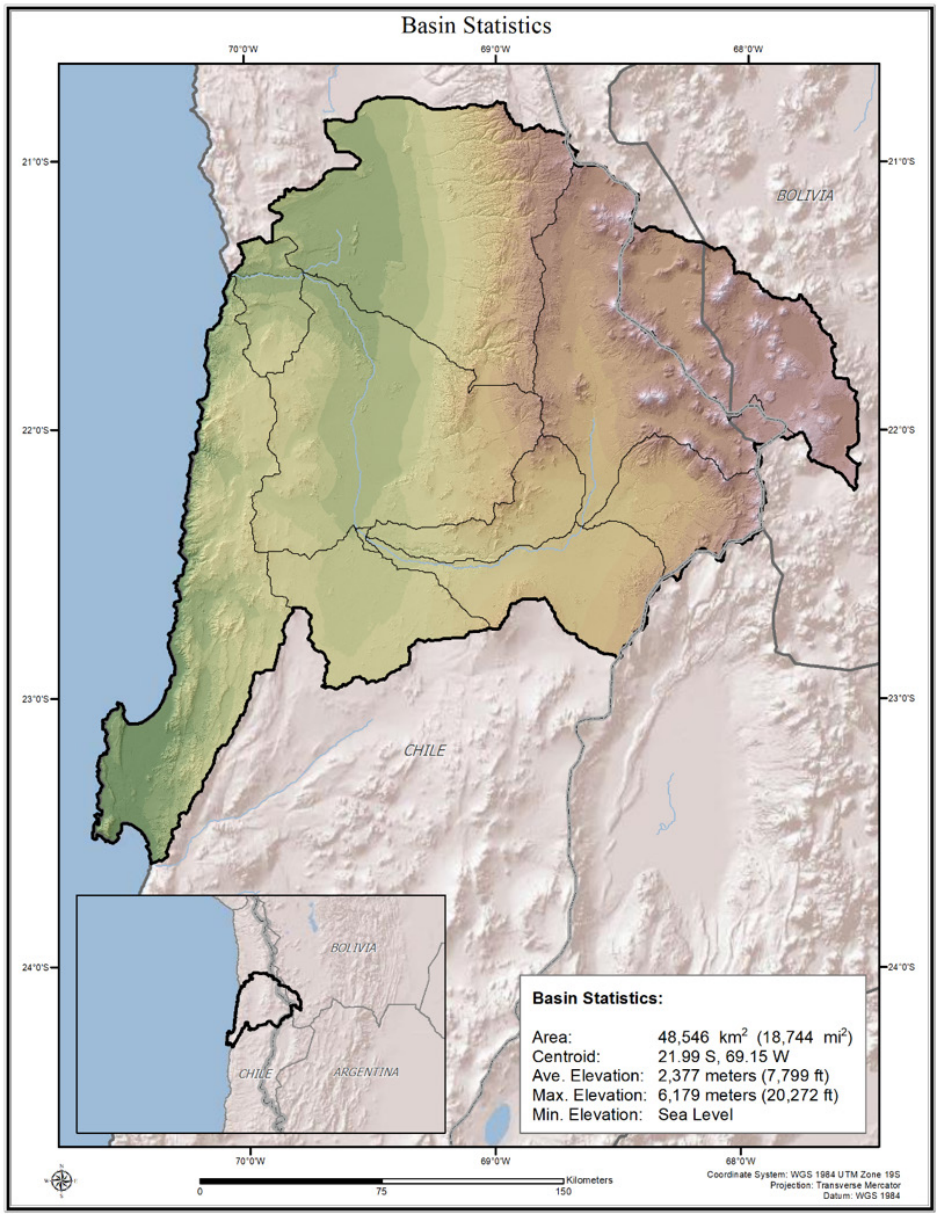


Figure 4. Chilean mining complex, topography, and regional setting

the foothills of the Andes and into the Andes themselves, annual precipitation increases as well, reaching over 750 mm (29.5 in.) per year over the highest peaks, including snowfall. These factors were explicitly accounted for during the PMP and PF development process.

PMP Development Process

The storm-based approach utilized by AWA in these studies requires that explicit precipitation data be analyzed which represent PMP-type storm events that have or could occur over the location of interest. Therefore, AWA performed extensive data mining and analysis to identify the storm type(s), region of similar meteorology and topography, and individual extreme precipitation events. AWA's Storm Precipitation Analysis System (SPAS) was used to analyze all storms. SPAS produces hourly gridded precipitation data, as well Depth-Area-Duration (DAD), mass curves (hyetographs), total storm isohyetal images, AEP maps, and several other standard outputs. In addition, AWA derived climatological data sets that are used to adjust individual storms. These include development of 100-year recurrence interval dew point climatologies, sea surface temperature climatologies, and 100-year recurrence interval precipitation frequency estimates.

Statistical procedures for estimating PMP can be used if sufficient period of record precipitation data are available and are particularly useful for making quick estimates of PMP when more detailed meteorological data are limited. The Hershfield method is used mostly for making quick estimates for basins of no more than about 400-mi^2 (Hershfield, 1961; Hershfield, 1965; Koutsoyiannis, 1999). This method is convenient in that it requires considerably less time to apply than other meteorological or storm-based approaches and doesn't require meteorologists to develop the

	PMP storm-based	PMP Hershfield $k_m = 5$	PMP Hershfield $k_m = 17.5$
21-mi² 24-hr (inches)	4.66	2.59	6.16
Fractional Difference	-	0.56	1.32

Table 1
Comparison of Hershfield method to storm-based method for estimating basin PMP

statistics. A major limitation of the Hershfield method is that it yields only point values of PMP and thus requires area-reduction curves for adjusting the point values to basin area sizes. A second problem is in determining the appropriate frequency factor value to use. The Hershfield method is calculated as:

$$PMP = \overline{X}_n + k_m * \sigma_n$$

$$k_m = \frac{X_M - \overline{X}_{n-1}}{\sigma_{n-1}}$$

where, X_M, X_n and σ_n are the maximum value, the mean, and the standard deviation, respectively, for a series of n annual maximum rainfall values of a given duration. $\overline{X}_{n-1}$ and σ_{n-1} are, respectively, the mean and the standard deviation for this series excluding the highest value from the series, and k_m is a frequency factor.

The Hershfield method is extremely sensitive to the frequency factor (k_m). To evaluate the frequency factor (k_m), Hershfield (1961) initially analyzed a total of 95,000 station-years of annual maximum rainfall belonging to 2645 stations and found the frequency factor k_m varied between 1.00–14.99 with k_m, ranging between 13.00 and 14.49 for only four stations. Hershfield (1961) concluded that an estimate of the PMP amount could be estimated by setting $k_m = 15$. Later studies by Hershfield (1965) proposed that k_m varies with the rainfall duration and the mean X_n, stating that a $k_m = 15$ is too high for areas with heavy rainfall and for rain durations shorter than 24 hours, and too low for arid areas (Koutsoyiannis, 1999). It was concluded that the k_m value should vary between five and 20 depending on duration and the mean (Hershfield, 1965; WMO, 1986). From a probabilistic perspective: the Generalized Extreme Value (GEV) distribution fit the annual maximum data better than a Gumbel distribution, and the k_m value of 15 (considered PMP) equates to return frequency of about 60,0000 years (Vivekanandan, 2015).

A comparison of the Hershfield method to storm-based PMP calculations for the 21-mi² Antamina basin in Peru is provided as an example. The storm-based 21-mi² 24-hr PMP is 4.66 inches. The Hershfield method was calculated on four stations within the basin using the following assumptions:

- k_m values calculated at four stations; results were less than 5 so k_m values set to Hershfield recommended minimum value of 5
- k_m based on Hershfield duration and mean annual value charts and set to 17.5
- areal reduction factor of 0.92 used to convert point estimates (1-mi²) to basin (21-mi²) estimates

PMP estimates based on the Hershfield method are presented in Table 1. Results illustrate the sensitivity of the frequency factor k_m on PMP estimates using the Hershfield method and also the fractional difference from the storm-based PMP estimate for the same basin.

These limitations and the large uncertainty associated with the Hershfield method is one of the main reasons that more detailed PMP analyses are needed at so many locations. However, without sufficient data, the storm-based approach would not be possible for many of these data-limited regions. Fortunately, ground-based meteorological observations are now able to be supplemented with remote sensing data such as satellite precipitation estimates. These remote sensing technologies provide global coverage that can supplement and fill in areas with limited surface observations. Unfortunately, remote sensing data have a more limited period of record, generally since the 1980s, and a lower spatial and temporal resolution. In addition, the accuracy of the remote sensing data is lower than ground-based observations (Zambrona-Bigiarini et al., 2017 and Derin et al., 2016). However, by combining the best aspects of both data sets, a more complete picture can be realized. This then becomes the foundation for calculating PMP in these data limited regions.

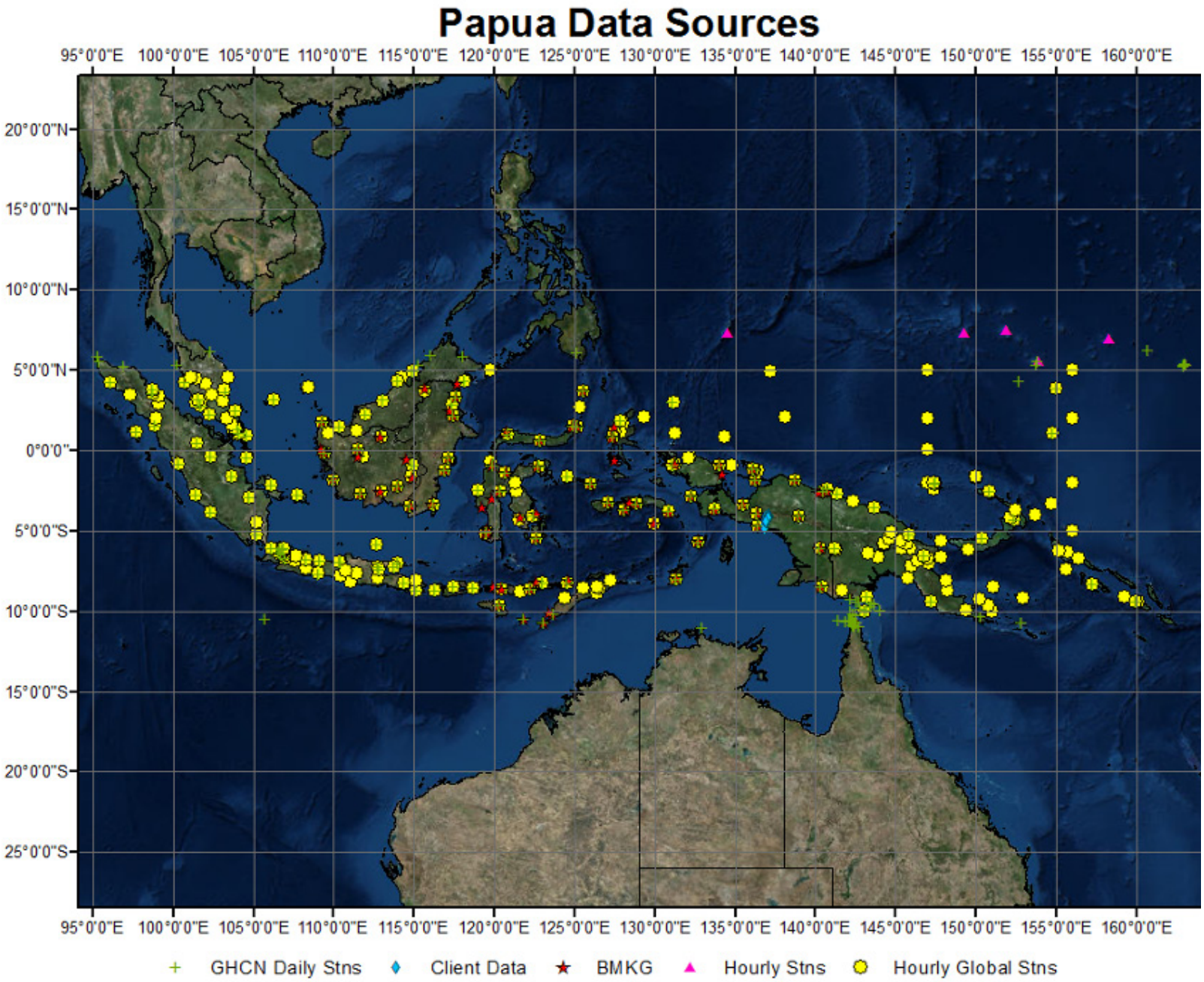


Figure 5. Storm search domain with all stations that were investigated

Indonesian Data Mining

A search domain of 94°E, 10°N, 10°S and 165°E was determined to be a similar region of meteorological, climatological, and topographic characteristics where all storms within this domain could be considered transpositionable to the location. Hundreds of rainfall events which occurred in this region were investigated to identify potential events for final analysis, as well as gaining insight into the PMP storm types that are important (Fig. 5).

The storm search was conducted by comparing the magnitude and frequency of the individual storm events by duration. Several storm durations were used and investigated: 1-hour, 6-hour, 24-hour, 72-hour, and 120-hour. The 100-year values derived from the PF analysis were utilized as an initial cut-off for identifying potential PMP-type storm events that required further evaluation. For the 120-hour duration, higher total depth thresholds were

used. The surface station storm search resulted in several thousand-storm events being identified. In general, storms included in the long list all exceed the 100-year return frequency value for specified durations at the station location or are associated with known extreme floods. The resulting long storm list was extensively controlled to ensure that only the highest storm rainfall values for each event were selected. Storms were then grouped by storm location and duration for further analysis.

Ground-based observational data are sparse in time and space in this region. Therefore, other observational data were incorporated to capture extreme events that may not have been observed at a recording location. Asian Precipitation – Highly- Resolved Observational Data Integration Towards Evaluation (APHRODITE) daily data from 1985 to 2007 was investigated, and Tropical Rainfall Measuring Mission (TRMM) satellite data from 2008 to 2016 were analyzed to flag any daily pixels over 124mm (4.88 in.), which was roughly equivalent to the 24-hour, 100-year rainfall recurrence interval in the region. APRHODITE data search resulted in 90 storms being identified, and the TRMM data resulted in 84 storms being identified. These storms constituted the intermediate storm list against which further investigations were completed. These day/multi-day composites of precipitation storm centers were validated with surface station data from AWA's database to confirm the occurrence of extreme rainfall in the region of interest and to compare remotely sensed amounts to rain gauge observations.

Consideration was given to each storm's transpositionability to the basin and each storm's relative magnitude compared to other similar storms on the list. Figure 6 shows the locations of storms used for PMP development and data analysis. Each of these storms was extensively evaluated to determine which storms were needed for final SPAS analysis and PMP development. Storms were evaluated from both a meteorological and topographic perspective to determine if they occurred in regions of similar characteristics as the basin. If so, they are considered to be transpositionable to one or more locations within the basin (e.g. HMR 51, Section 2.4.1, 1978 and Kappel et al., 2019). Storms considered transpositionable were then compared to other similar storms to determine the

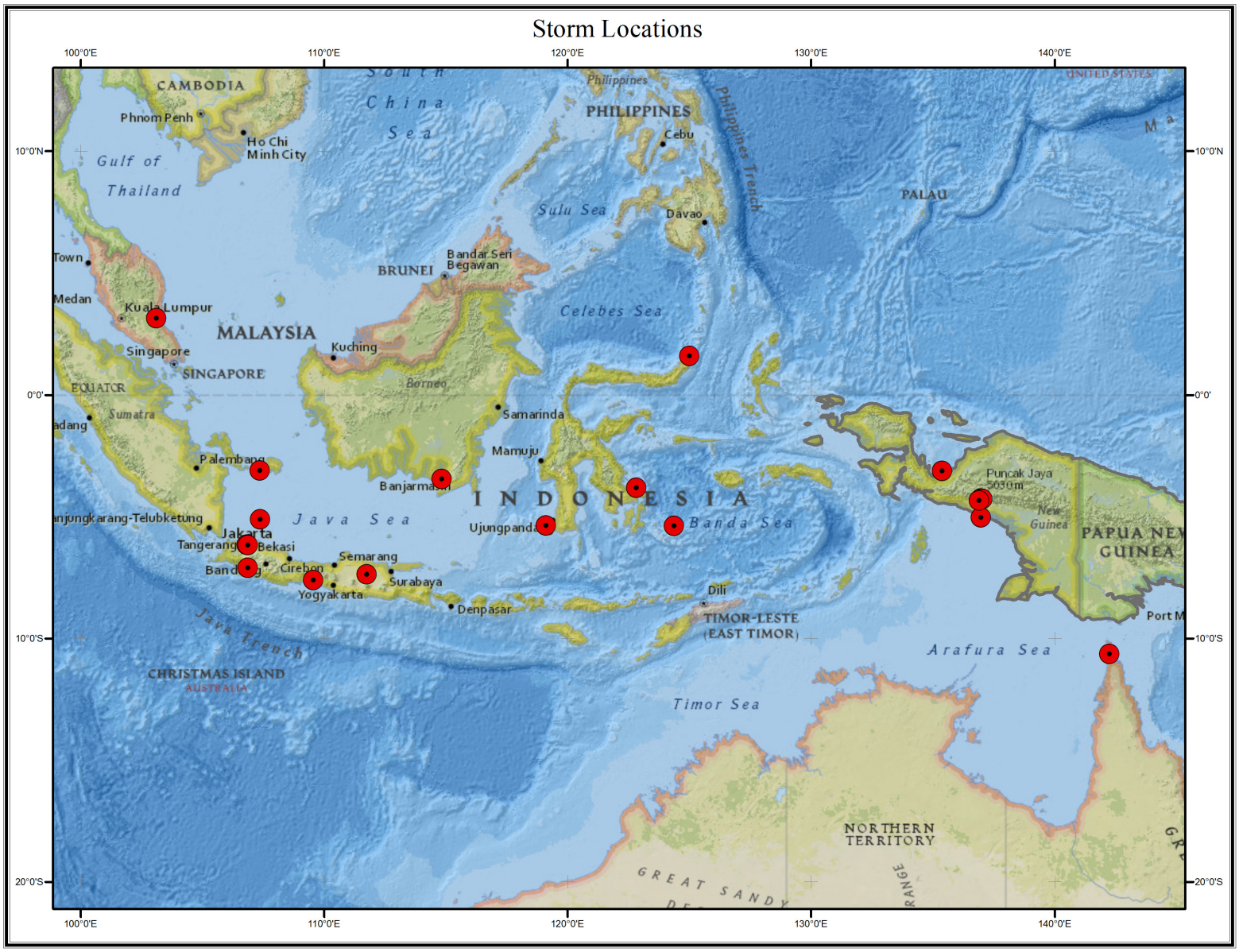


Figure 6. Final storms used for PMP development and meteorological analysis

largest of the transpositionable storms. Durations of storms were also considered to ensure that several storms important for short (one day or less) and long (multi-day) durations were included. The final list of storms was determined after all evaluations were completed and this list included 15 distinct storm centers. These covered a wide region geographically and included storms ranging from short duration, intense rainfalls to long duration rainfall with several bursts of rainfall occurring over several days.

Peruvian Data Mining

A storm search domain covering the Altiplano and interior high elevation regions of Peru, from approximately 8°S to 16°S and 69°W to 78°W, was determined to be similar to the basin in regard to meteorological and topographical environments (Fig. 7). This storm search domain evaluated the important characteristics related to precipitation development over the basin. Moisture inflow from the upper Amazon basin and local recycled moisture are most important for rainfall in this basin. This is unique to this area because of extreme topography both to the west and east of the location. Therefore, the storm search domain encompassed other regions that represent the same transition zone between moisture inflow from the east/northeast (upper Amazon basin) and the west/southwest from the Pacific Ocean and regions that are influenced by similar topography.

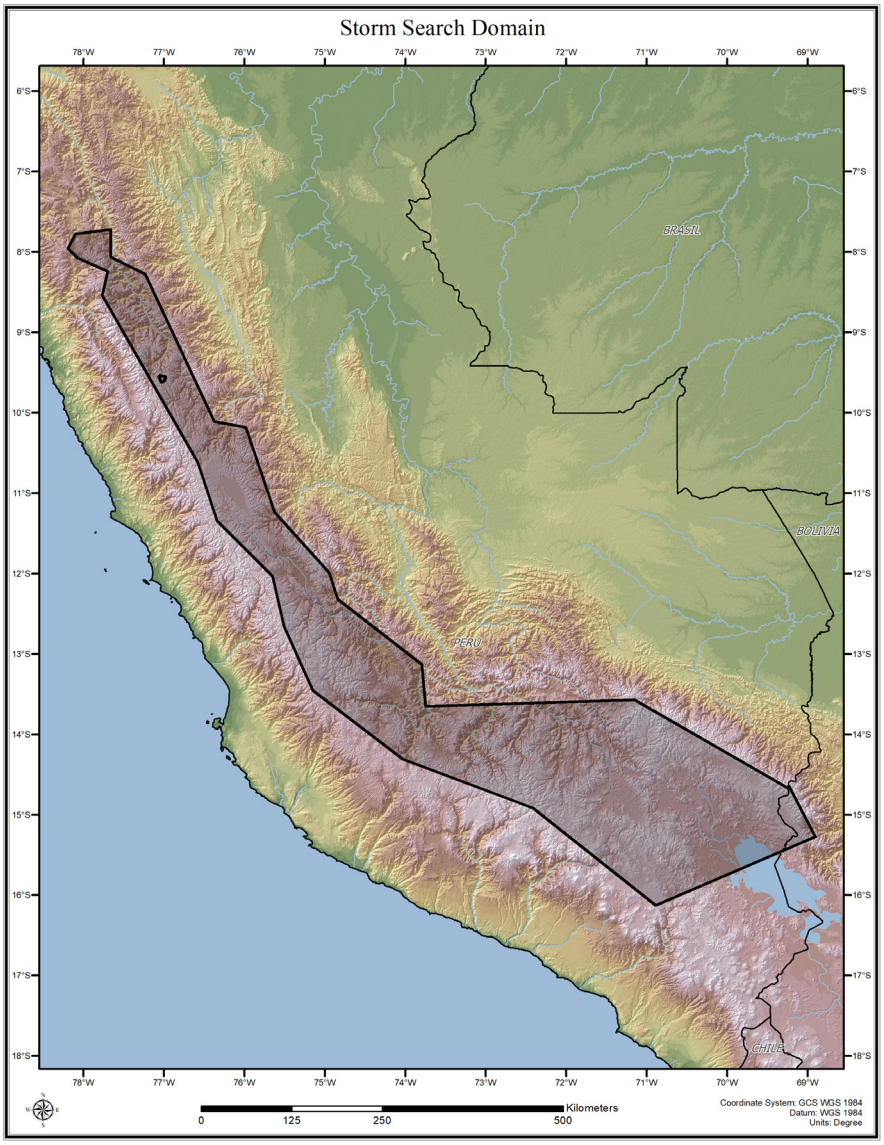


Figure 7. Storm search domain used for the Peruvian mine location

Specific interactions of topography and moisture availability were considered and evaluated against surrounding regions. This included evaluating rainfall accumulation data provided by the client to determine the specific wet season period for the basin and comparing that to similar rainfall climatologies in other areas considered. This demonstrated that areas further south towards the Altiplano of southern Peru have a shorter wet season, signifying a different meteorological pattern from that over the basin. Therefore, rainfall patterns and individual storm events south of 16°S are not the same as would occur over the basin and are, therefore, not transpositionable.

In addition, elevation differences were explicitly considered. The high elevation of the basin, generally between 3500m and 5000m, results in unique weather patterns and storm development characteristics in the basin. The high elevation of the basin means there is less total atmospheric column moisture to work with, as the lower 3500 meters of the atmosphere, where most of the moisture and instability are located, are not available for storm development. This results in significantly lower amounts of total moisture availability and, hence, much lower total precipitation accumulations. No storms were used that occurred in regions less than 2500m in elevation because of these elevation considerations.

The storm search was conducted by comparing the magnitude of individual storm events by duration and location. Several storm durations were used and investigated: 1-hour, 6-hour, 24-hour, and 72-hour. The 100-year values, derived as part of this analysis, were used to quantify initial levels to investigate. These were utilized as an initial cut-off for identifying potential PMP-type storm events that required further evaluation. Several hundred-storm events were identified. These storm events constituted the long list of storms to be further investigated and from which to derive the final list of storms used for PMP development. Remote sensing data were also used to supplement

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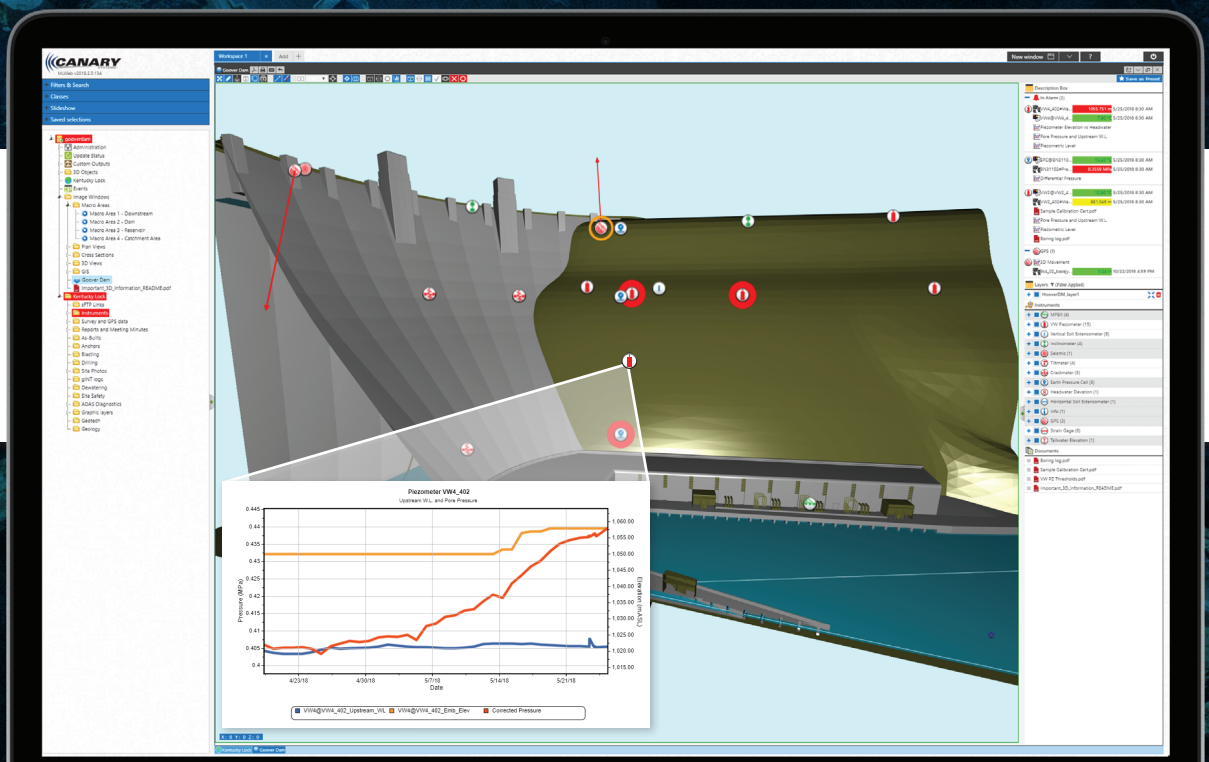

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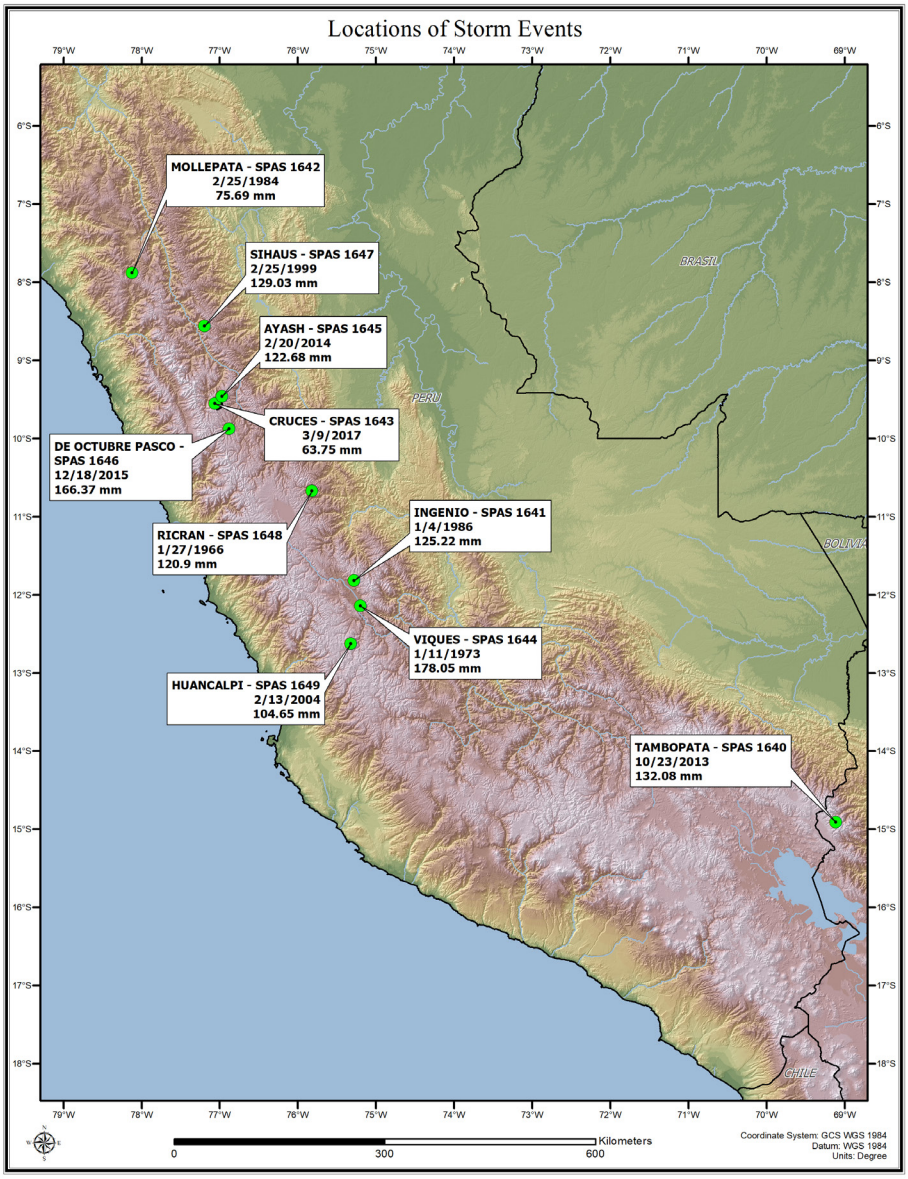

Figure 8. Storms used for PMP development and meteorological analysis for the Peruvian mine site

individual station data. Satellite-derived precipitation data from the Center for Hydrometeorological and Remote Sensing (CHRS) were analyzed to flag any daily pixels that represented extreme precipitation accumulations from the long list. Station data and CHRS data (Adler et al., 2003; Ceccherini et al., 2015) were taken into consideration when the final short storm list was created and when a SPAS analysis was performed on the storm.

Consideration was given to each storm's transpositionability to the basin and each storm's relative magnitude compared to other similar storms on the list by location and duration. Figure 8 provides locations of the storms on the final storm short list. Durations were also considered to ensure that several storms important for various durations were included. The short list was finalized after all evaluations and included 10 unique storm events. These covered a geographically wide region within the overall storm search domain and included storms ranging from short duration rainfalls to long duration rainfalls covering several days.

Chilean Data Mining

The storm search domain for this study extended from southern Peru through central Chile and encompassed regions from the High Andes to the Pacific Coast. This large and diverse region was required to ensure that storms representing all meteorological settings and storm types were evaluated (Fig. 9). This was the result of the mining complex domain extending from the High Andes to the Pacific Coast, encompassing all meteorological and topographic settings in the region. This included regions that represent the Andean Cordillera, the hyper-arid interior, and coastal regions. Therefore, storms had to be considered which could within one or more of these diverse meteorological and topographical regions which could also occur over one or more locations within the overall mining complex region.

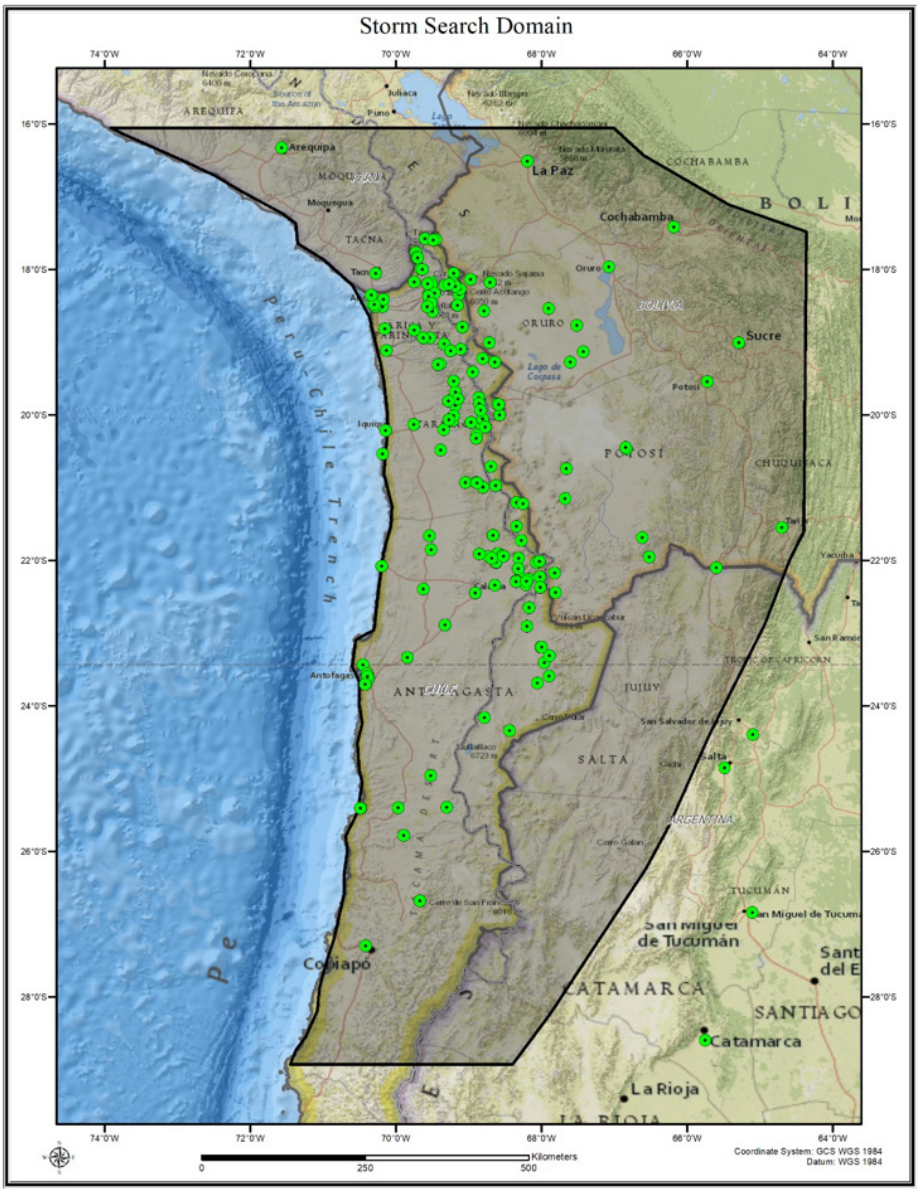

Figure 9. Storm search domain with all stations that were investigated

AWA completed detailed evaluations of the topography and moisture availability in the region, noting how this varied significantly moving from the Pacific Coast through the Andean Cordillera. The Chilean Meteorological Service archives an extensive database of meteorological information. This was supplemented by data provided by the client. Remote sensing data were also used to supplement individual station data. PERSIANN satellite data (Ashouri et al, 2015) were analyzed to flag any daily and hourly extreme precipitation accumulations, and these were investigated using ground-based observations to determine if a significant storm had occurred which could be analyzed. These remote sensing data were also used to help spatially distribute rainfall accumulations between ground observation locations. Combining data from all these sources helped to define the climate characteristics of the region, capture the variations, and define transition regions that were reflected in the PMP and PF depths.

The storm search was conducted by comparing the magnitude of individual storm events by duration and location. Because there was a wide variety of precipitation mechanisms and seasonality across the overall region, several storm durations were used and investigated: 1-hour, 6-hour, 24-hour, and 72-hour. In addition, different storm types were evaluated, with convective storms dominating from the mine site through the Andean Cordillera and frontal systems dominating along the coastal region. Several hundred-storm events were identified. These storm events constituted the long list of storms to be further investigated and from which to derive the final list of storms used for PMP development.

Consideration was given to each storm's magnitude versus other storms in the same region and of the same storm type. The number of storms affecting each climate region was also considered to ensure we had sufficient data from which to develop PMP and PF depths. Figure 10 provides locations of the storms on the final

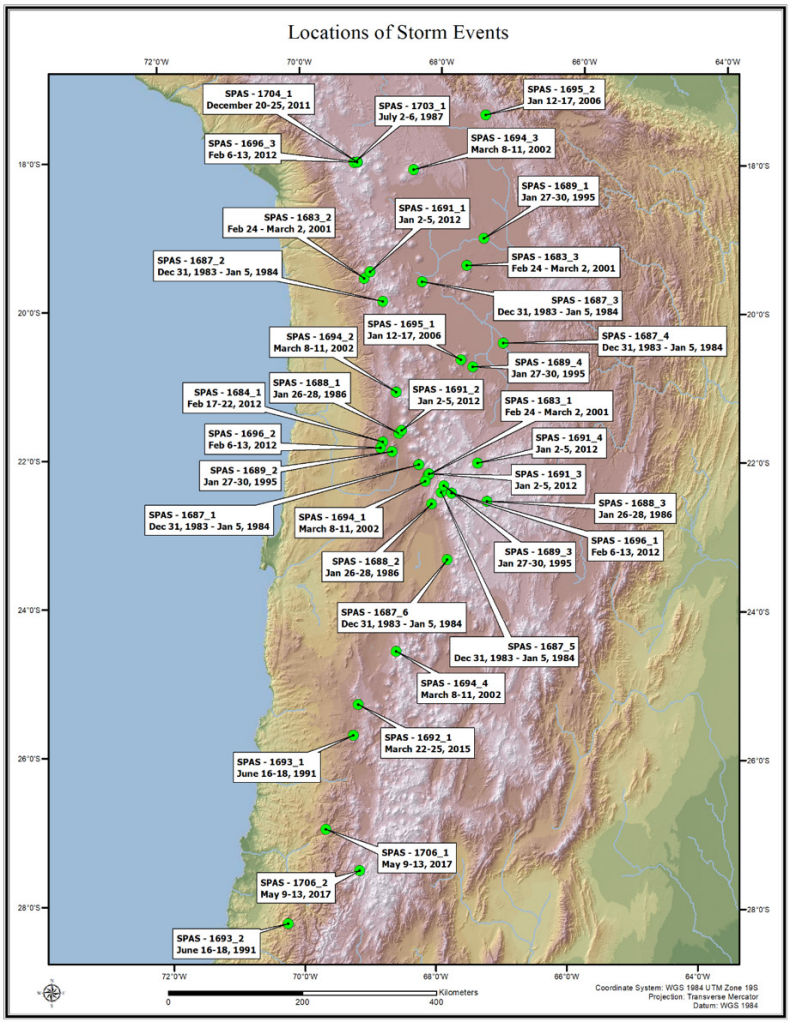

Figure 10. Storms used for PMP development and meteorological analysis for the Chilean mine site

storm short list. The short list was finalized after all evaluations and included 38 unique storm centers. These covered a wide region geographically within the overall storm search domain and included storms ranging from short duration rainfalls to long duration rainfalls covering several days.

Conclusion

Each of these studies resulted in a more accurate set of PMP depths that were explicitly quantified based on the meteorological and topographical characteristics unique to each location. PMP depths were provided at various area sizes and durations, from one to thousands of square kilometers and from one through 120 hours. This provided more robust and representative rainfall accumulation data for hydrologic model input.

AWA's results were a significant improvement over the previous rainfall information available from the Hershfield method which only provided point data for a single duration and, therefore, does not represent the unique spatial and temporal variances.

As with all AWA PMP studies, the objective is not to lower the PMP depths but instead to get them as accurate as the data will support and reduce uncertainty. This was accomplished in each of these studies through the use of multiple data sets, application of AWA's experience dealing with extreme meteorological and topographical settings, coordination and communication with the mine operations personnel.

AWA utilized the storm-based approach to develop PMP depths, PF depths, and other meteorological data for three unique mine locations across the world. Limited surface observational data were supplemented by incorporating remote sensing data. Each location is affected by unique meteorological and topographic settings. Data supplied by the client/mining companies, local governmental entities, internal AWA database, and remote sensing observations were investigated to develop the information needed to calculate the results. Changes in climate were included in the analysis by utilizing data from the entire period of record (50 - 100 years) and applying appropriate storm adjustments to derive the final values.

Each of these studies demonstrated that development of accurate and scientifically defensible PMP depths and other meteorological data using the storm-based approach are now possible even in the most remote locations in the world. This is achieved through AWA's experience and knowledge.

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Bill Kappel

President/Chief Meteorologist, Applied Weather Associates

PO BOX 175, Monument, CO 80132

719-964-3395 • billkappel@appliedweatherassociates.com

Bill Kappel is president and chief meteorologist of Applied Weather Associates. Bill has been the project manager and technical lead for more than 100 Probable Maximum Precipitation studies over the last 15 years covering just about every meteorological setting possible. Mr. Kappel has also been involved in more than 700 storm analyses using the Storm Precipitation Analysis System (SPAS) since 2002. These results have been used to calculate PMP values, used for model calibration, in forensic meteorological investigations, and in various climatological and precipitation frequency analyses. Prior to joining AWA, Mr. Kappel was an on-air meteorologist at several TV stations across the country.