Evaluation of the Maximum Design Earthquake for the Tailings Storage Facilities for the Proposed Resolution Copper Mine, Arizona

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LIGHTNING SUMMARY

The U.S. Forest Service has put forward five alternatives for the tailings storage facilities for the proposed Resolution Copper Mine, Arizona, all of which would be designed to withstand the 5000-year earthquake. However, since the failures of the alternatives would endanger the towns of Superior (population 2837), Queen Valley (population 820), Florence (population 26,074), and Dripping Springs (population 235), according to dam safety standards, they should be designed to withstand the Maximum Credible Earthquake, the largest earthquake that is theoretically possible within a particular seismotectonic setting.

ABSTRACT

The U.S. Forest Service has put forward five alternatives for the tailings storage facilities for the proposed Resolution Copper Mine, Arizona, all of which would be designed to withstand the 5000-year earthquake. Four of the alternatives (Peg Leg site, Skunk Camp site, and two at the Near West site) involve the storage of thickened tailings (50-70% solids), while one alternative (Silver King site) involves the storage of filtered tailings (86-89% solids). According to a wide range of dam safety standards, a dam for which the failure would result in the loss of human life should be designed to withstand the Maximum Credible Earthquake (MCE), the largest earthquake that is theoretically possible within a particular seismotectonic setting. Using a statistical model based on previous tailings dam failures, the runouts from the failures of the five alternatives would be in the range 200-370 miles. Although the flow potential of filtered tailings is less than that of thickened tailings, even if the failures of the dams for the filtered tailings caused only slumping of the tailings, they would travel at least 10,400 feet from the Silver King site, and would impact the town of Superior (population 2837) at a minimum distance of 2500 feet. The unincorporated area of Queen Valley (population 820) would be impacted by the failures of either of the Near West facilities (minimum distance 19,000 feet) or of the Silver King facility (minimum distance 8.2 miles). The town of Florence (population 26,074) would be impacted by the failures of the Peg Leg facility (minimum distance 10.3 miles), either of the Near West facilities (minimum distance 16.0 miles), or the Silver King facility (minimum distance 20.5 miles). The unincorporated area of Dripping Springs (population 235) would be impacted by the failure of the Skunk Camp facility (minimum distance 17,000 feet). Dripping Springs, Queen Valley and Superior are all well within what has been called the "self-rescue zone" in recent Brazilian legislation. On the above basis, the tailings storage facilities should be designed to withstand the Maximum Credible Earthquake, rather than the 5000-year earthquake that was proposed by Rio Tinto. It is recommended that anyone interested in investing in the Resolution Copper Mine should enquire as to the additional cost of designing for the MCE.

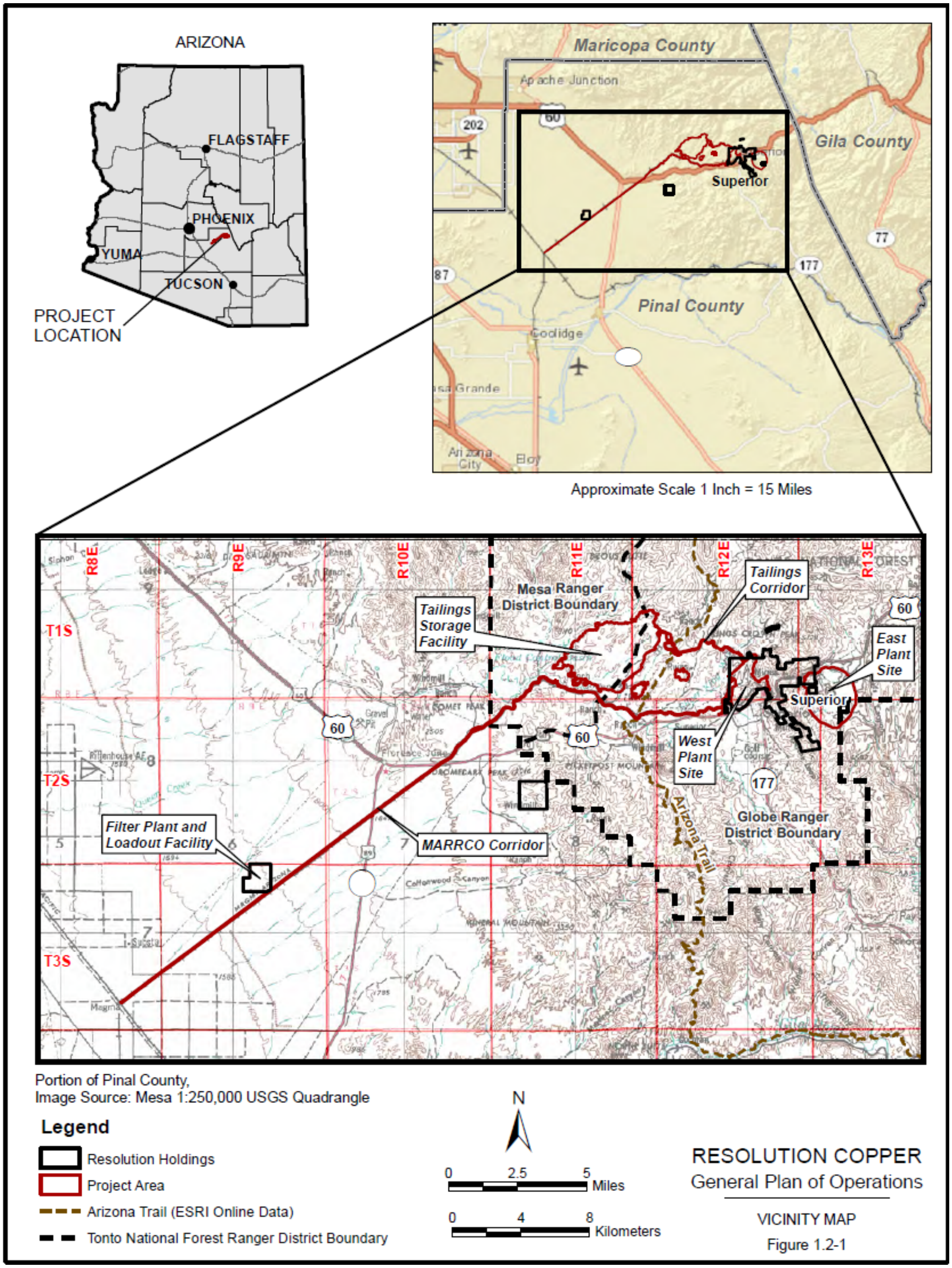

Figure 1. Rio Tinto has submitted a proposal for an underground copper mine, called the Resolution Copper Mine, within a mix of federal public land (Tonto National Forest), Arizona state trust land, and private land, which would process 120,000 metric tons of ore per day with a maximum processing rate of 150,000 metric tons per day from an ore body that lies 5000-7000 feet below the surface. Figure from Resolution Copper Mining (2014b).

INTRODUCTION

Rio Tinto has submitted a proposal to the U.S. Forest Service for an underground copper mine in Arizona, called the Resolution Copper Mine (see Fig. 1). The porphyry copper deposit occurs 5000-7000 feet beneath the surface and has an inferred resource of 1790 million tons with a copper grade of 1.47% and molybdenum grade of 0.037% (Houston et al., 2010; Cherry, 2011; Hehnke et al., 2012). The ore processing rate is predicted to be 120,000 metric tons per day with a maximum processing rate of 150,000 metric tons per day. Process improvements over the anticipated 40-year life of the project could increase the ore processing rate by up to 25%, for a maximum throughput of 187,500 metric tons per day (Resolution Copper Mining, 2014a-c).

The proposed mine is located within a mix of federal public land (Tonto National Forest), Arizona state trust land, and private land (Resolution Copper, 2018a). The proposal includes an exchange of 5344 acres of land privately held by Rio Tinto for 2422 acres of the Tonto National Forest (Resolution Copper Mining, 2014a). The Arizona Mining Reform Coalition and 15 other organizations have submitted scoping comments to the U.S. Forest Service that describe a wide range of detrimental social and environmental impacts of the proposed copper project (Arizona Mining Reform Coalition et al., 2016). Those social and environmental impacts will not be reviewed or further developed in this study.

As part of the preparation of the Environmental Impact Statement (EIS), the U.S. Forest Service has put forward five alternative plans for the tailings storage facilities for the proposed mine (USDA, 2017a-b). These alternatives have been summarized in five two-page "snapshots" (USDA, 2018a-e) and in a comparative matrix format by SWCA Environmental Consultants (2018). By EIS conventions, Alternative #1 is the "no-action" alternative. Alternative #2, the preferred alternative that was presented in the General Plan of Operations (Resolution Copper Mining, 2014a-c) involves storing tailings thickened into a slurry (65% solids for scavenger tailings, 50% solids for cleaner tailings) at the Near West site behind a 520-foot-high tailings dam (see Fig. 2). Alternatives #2 and #3 are nearly spatially coincident at the Near West site, but Alternative #3 extends slightly farther in the northeast direction (see Fig. 2). Alternative #3 involves slightly thicker scavenger tailings (70% solids) and a slightly lower dam (510 feet). Alternative #4 would involve the storage of filtered tailings (86-89% solids) at the Silver King site to a height of 1040 feet (see Fig. 2, Table 1). The dam for the Silver King site would be a "structural zone" of tailings built around the perimeter (SWCA Consultants, 2018) and would be the tallest tailings dam ever constructed. (The current tallest tailings dam in the world is the 650-foot-high Quillayes Dam at the Los Pelambres Mine in Chile (Campaña et al., 2015)). Alternative #5 involves the storage of thickened tailings (60% solids for scavenger tailings, 50% solids for cleaner tailings) behind a 310-foot-high tailings dam at the Peg Leg site (see Fig. 2, Table 1). The final Alternative #6 involves the storage of similarly thickened tailings (60% solids for scavenger tailings, 50% solids for cleaner tailings) behind a 490-foot-high tailings dam at the Skunk Camp site (see Fig. 2, Table 1). The total volumes of stored tailings have been predicted as 1315.45 million cubic yards for the sites storing thickened tailings and 1188.98 million cubic yards for the site storing filtered tailings (see Table 1; USDA, 2017b).

The most important aspect of the design of the tailings dam, or any other component of a tailings storage facility, is the choice of the correct safety criteria, one of which is the Maximum Design Earthquake (MDE). According to Rio Tinto, the tailings storage facilities will be designed to withstand an earthquake with a return period of 5000 years, corresponding to an earthquake with an annual exceedance probability of 0.02%, or a 1% probability of exceedance in 50 years (Resolution Copper Mining, 2014a,c). That choice of the 5000-year earthquake has never been justified in any document produced by Rio Tinto.

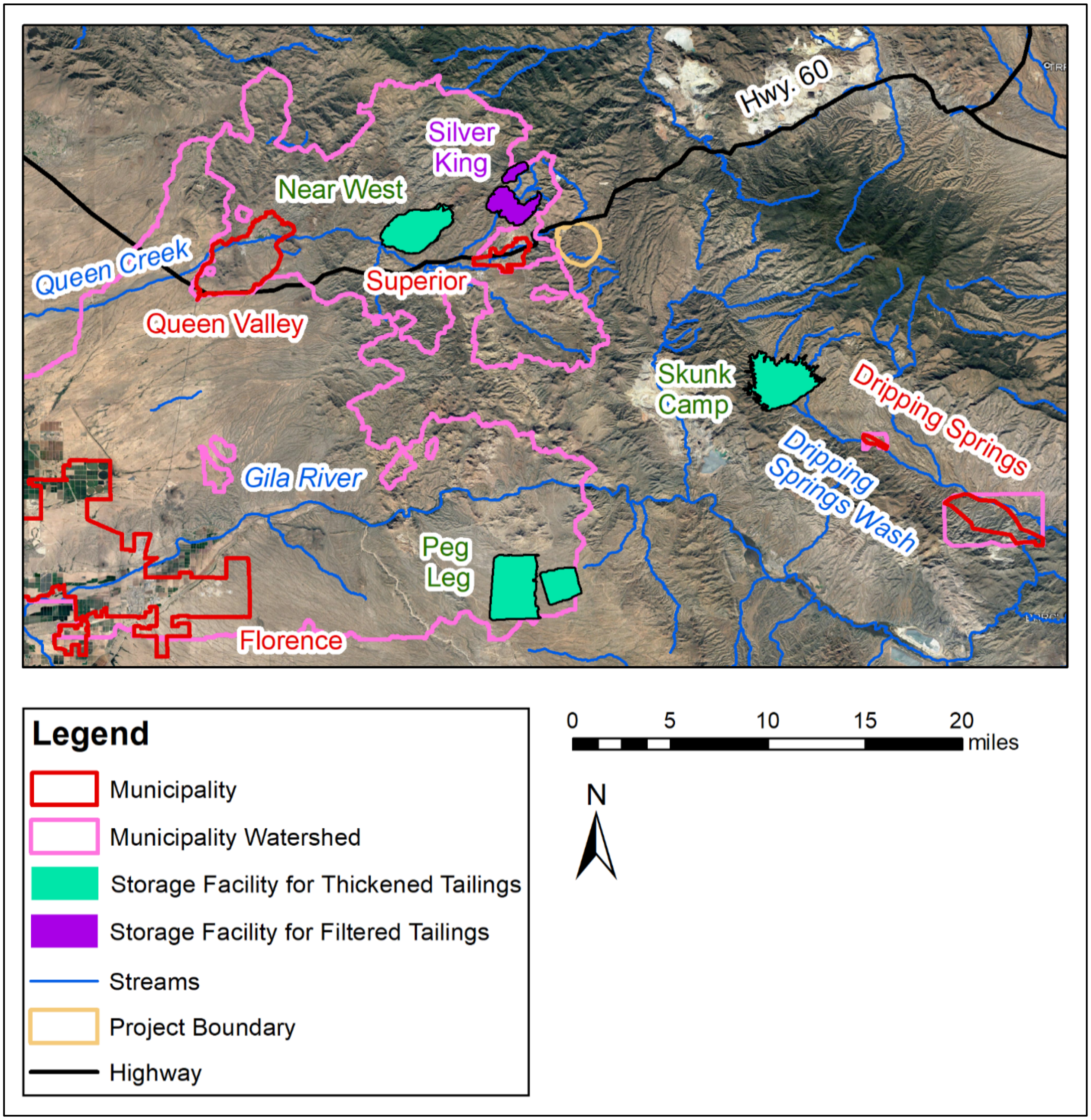

Figure 2. Out of the five alternatives for the tailings storage facilities for the proposed Resolution Copper Mine, four would store thickened tailings, while one would store filtered tailings. Two alternatives at the Near West site are nearly spatially coincident, with the alternative with thickest tailings being slightly larger. Failure of the Silver King facility would impact the town of Superior (population 2837). The unincorporated area of Queen Valley (population 820) would be impacted by the failures of the Silver King or either of the Near West facilities. The town of Florence (population 26,074) would be impacted by the failures of the Peg Leg, Silver King, or either of the Near West facilities. The unincorporated area of Dripping Springs (population 235) would be impacted by the failure of the Skunk Camp facility. On the above basis, the tailings storage facilities should be designed to withstand the Maximum Credible Earthquake, rather than the 5000-year earthquake, as proposed by Rio Tinto. Background combines Google Earth imagery from December 6, 2014, January 13, 2018, and April 6, 2018.

A common choice for the seismic design criterion is the Maximum Credible Earthquake (MCE), defined as “the largest earthquake magnitude that could occur along a recognized fault or within a particular seismotectonic province or source area under the current tectonic framework” (FEMA, 2005). According to the U.S. Army Corps of Engineers, “for critical features, the MDE is the same as the MCE” (USACE, 2016). In a similar way, according to the Federal Emergency Management Agency, “for high-hazard potential dams, the MDE usually is equated with the controlling MCE” (FEMA, 2005). The same federal agency has clarified that “dams assigned the high hazard potential classification are those where failure or misoperation will probably cause loss of human life” (FEMA, 2013). Perhaps most relevant are the recommendations of the Arizona Department of Environmental Quality (n.d.), which state “where human life is potentially threatened, the maximum credible earthquake (MCE) should be used.”

Table 1. Predicted Runout following Tailings Dam Failure

Alternative	Name	Tailings Type	Impounded Volume[1] (million yd^3)	Dam Height[2] (ft)	Spill Volume[3] (million yd^3)	Runout[3] (mi)
2	Near West	Thickened	1315.45	520	309.1	266.7
3	Near West	Thickened	1315.45	510	309.1	263.9
4	Silver King	Filtered	1188.98	1040	280.8	370.3
5	Peg Leg	Thickened	1315.45	310	309.1	201.2
6	Skunk Camp	Thickened	1315.45	490	309.1	258.2

[1]Impounded volumes from USDA (2017b).
[2]Dam heights from SWCA Environmental Consultants (2018).
[3]Spill volume and runout calculated from statistical model in Larrauri and Lall (2018).

The MCE is simply the largest earthquake that is theoretically possible at a given location, with no defined return period or probability of occurrence (USACE, 2016). However, some insight into the difference between the 5000-year earthquake and the MCE can be gained by considering the guidelines of the Canadian Dam Association (2013). These guidelines classify dams into five categories, based upon the consequences of failure. The three dam classes with the highest failure consequences are high, very high and extreme, corresponding to loss of life of 10 or fewer persons, 100 or fewer persons, and more than 100 persons, respectively (Canadian Dam Association, 2013). These guidelines use two approaches for determining the safety criteria for dam design. Using a risk-informed approach, dams in the very high- and extreme-consequence categories should be designed to withstand a 10,000-year event. Using a standards-based approach, dams in the extreme-consequence category should be designed to withstand either the MCE or the 10,000-year earthquake (Canadian Dam Association, 2013). The above suggests an equivalence between the MCE and the 10,000-year earthquake, although the same guidelines emphasize that the MCE has no associated return period (Canadian Dam Association, 2013). On the other hand, in the context of discussing criteria for determining the MCE at a particular location, FEMA (2005) states, “For high-hazard potential dams, movement of faults within the range of 35,000 to 100,000 years BP is considered recent enough to warrant an ‘active’ or ‘capable’ classification.” In summary, it is important to note that the MCE can be much stronger than the 5000-year earthquake and can be as rare as a 100,000-year earthquake, with a corresponding annual exceedance probability of 0.001%.

The objective of this report is to answer the following question: Is the ability to withstand the 5000-year earthquake the appropriate design criterion for the tailings storage facilities at the proposed Resolution Copper Mine? Based on the discussion above, the question is equivalent to the following: Would the failure of the tailings dams at the Resolution Copper Mine result in the probable loss of at least one human life? Although this study has been prepared at the request of the Arizona Mining Reform Coalition, the intended audience is individuals or companies who might wish to invest in the copper project or the companies managing the copper project. For context, Resolution Copper Mining is owned 55% by Resolution Copper, a Rio Tinto subsidiary, and 45% by BHP Copper, a BHP-Billiton subsidiary (Rio Tinto, 2018). It might be assumed that the possible failure of a tailings dam and the resulting loss of human life are more of a human rights issue than a financial issue. However, for the purpose of this report, it will be assumed that Rio Tinto would not actually construct tailings dams that would endanger human life, so that the issue is whether Rio Tinto, at this point, has correctly taken into account the real cost of constructing and maintaining tailings storage facilities at the appropriate safety level. Previous reports concerning the financial viability of the Resolution Copper Mine include evaluations of the impact of the discovery of geothermal water on the mining project (Emerman, 2018a), the projected electricity and water consumption of the project (Emerman, 2019), and the impact of the land subsidence that would be caused by the project on the sacred lands of the Apache.

METHODOLOGY

The objective of this report could be subdivided into the following questions:

1) What is the predicted runout of mine tailings following the failure of the tailings dams at each of the alternatives for the tailings storage facilities?
2) Will the runout impact a population center, such that there will be a probable loss of human life?

The runout refers to the distance traveled by the initial surge of mine tailings that is propelled by the collapse of the dam. After the cessation of the initial surge, the tailings can be transported even farther downslope or downstream by colluvial or fluvial processes. In cases where mine tailings have been spilled into rivers, it can be difficult to distinguish between the initial surge and the subsequent transport by normal fluvial processes. The runouts were predicted using a statistical model based on the history of tailings dam failures (Larrauri and Lall, 2018). According to this model, the best predictor of runout is the dam factor H_f, defined as

$$H_f = H\left(\frac{V_F}{V_T}\right)V_F \tag{1}$$

where H is the dam height (meters), V_T is the total impounded volume of tailings and water (millions of cubic meters), and V_F is the spill volume (millions of cubic meters). The spill volume and runout D_{max} (kilometers) are then calculated using

$$V_F = 0.332 \times V_T^{0.95} \tag{2}$$

$$D_{max} = 3.04 \times H_f^{0.545} \tag{3}$$

Total impounded volumes and dam heights were obtained from USDA (2017b) and SWCA Environmental Consultants (2018), respectively.

The impact of the tailings flow on the local population was then addressed by determining whether the watersheds of local population centers intersected the footprint of the proposed tailings storage facilities within a distance that was at least as great as the predicted runout. The local population centers included the incorporated towns of Superior (population 2837) and Florence (population 26,074), and the unincorporated census-designated places of Queen Valley (population 820) and Dripping Springs (population 235) (see Fig. 2). Watersheds were calculated using ESRI ArcMap 10.6.1 Spatial Analyst with one-degree digital elevation models (DEMs) from WebGIS (2019). Other geographical information included municipal boundaries (MapCruzin, 2019a), highways (MapCruzin, 2019b), streams (USGS, 2019), and footprints of proposed tailings storage facilities (USDA, 2018a-e).

RESULTS

Predicted Runouts

Predicted runouts due to failure of the tailings dams at each of the five alternative tailings storage facilities range from 201 miles (Peg Leg site) to 370 miles (Silver King site; see Table 1). Although the predicted runouts may seem surprisingly large, it should be noted that, compared to past tailings dam failures, the impounded volumes and dam heights are "off the charts." For the Resolution Copper Mine, the impounded volumes are either 1315.45 million cubic yards for thickened tailings or 1188.98 million cubic yards for filtered tailings (USDA, 2019b; see Table 1). By contrast, the largest volume of impounded tailings at any tailings dam that has failed thus far was 97 million cubic yards at the Mount Polley Mine in British Columbia that failed in 2014 (Larrauri and Lall, 2018). Moreover, the tallest tailings dam that has failed thus far was the 295-foot-high Fundão Dam at the Samarco Mine in Brazil that failed in 2015 (Larrauri and Lall, 2018), which was not as tall as any of the proposed tailings dams for the Resolution Copper Mine (see Table 1). Predicted spill volumes, which depend only upon the impounded volume (see Eq. 2) are either 309.1 million cubic yards for thickened tailings or 280.8 million cubic yards for filtered tailings (see Table 1). Again, by contrast, the largest tailings spill that has occurred thus far was 42 million cubic yards from the failure of the Fundão Dam (Larrauri and Lall, 2018).

The important point is that tailings dam failures could have very wide-ranging impacts, extending over hundreds of miles, and that the previously-mentioned local population centers are simply the "front line" of affected populations. It could be argued that the statistical model based upon past tailings dams failures does not apply to the Silver King site, which will store filtered tailings. Based upon their lower water content, filtered tailings will have much less ability to mobilize into a flow slide than more conventional unthickened or thickened tailings. Moreover, none of the data points used by Laurarri and Lall (2018) seem to have involved dams that stored filtered tailings. However, a collapse of filtered tailings could potentially evolve into a flow slide if the tailings mixed with enough water following collapse, and the Silver King site sits on the flow path of King Wash, a tributary of Queen Creek (see Fig. 2). Even in the best-case scenario, a failure of the tailings dam at the Silver King site would result in the slump of the filtered tailings that would extend for a distance of roughly ten times the dam height or 10,400 feet (Klohn Crippen Berger, 2017).

Impacts on Population Centers

All of the local population centers include at least one proposed tailings dam in its watershed, so that the failure of each of the five alternatives has the potential to result in the loss of human life. It has already been shown that the predicted runouts are so large that the ability of a tailings spill to reach a local population center is not a factor. The watershed of Superior includes the Silver King site at a minimum distance of 2500 feet (see Fig. 2). Even a slump of filtered tailings with no added water would nearly cover the entire town of Superior. The unincorporated area of Queen Valley would be impacted by the failures of either of the Near West facilities (minimum distance 19,000 feet) or of the Silver King facility (minimum distance 8.2 miles; see Fig. 2). The town of Florence would be impacted by the failures of the Peg Leg facility (minimum distance 10.3 miles), either of the Near West facilities (minimum distance 16.0 miles), or the Silver King facility (minimum distance 20.5 miles; see Fig. 2). Based on the DEMs, the watershed of Dripping Springs does not include the Skunk Camp facility. However, Dripping Springs sits on the bank of Dripping Springs Wash, which would be quite likely to overflow following a tailings spill from the Skunk Camp site, a minimum distance of 17,000 feet from Dripping Springs (see Fig. 2). It should be noted that, based upon the populations of Superior, Queen Valley, Florence, and Dripping Springs, all of the proposed tailings dams should be placed into the extreme-consequence category (more than 100 persons at risk), using the classification system of the Canadian Dam Association (2013).

Following the failure of the tailings dam at the Córrego do Feijão Mine in Brazil on January 25, 2019, which resulted in 308 people missing or confirmed dead, the new Brazilian mining regulations and legislation introduced the concept of "*zonas de autossalvamento*," which are literally the "self-rescue zones" or the zones in which no rescue is possible (Agência Nacional de Mineração [National Mining Agency], 2019; Assembleia Legislativa de Minas Gerais [Legislative Assembly of Minas Gerais], 2019). This "self-rescue zone" has been defined as either 10 kilometers (6.2 miles) along the course of the valley or the portion of the valley that can be reached by the tailings flow within 30 minutes, whichever is greater (Assembleia Legislativa de Minas Gerais, 2019). In the Brazilian state of Minas Gerais, it is currently illegal to construct a tailings dam where there is a population residing in the "self-rescue zone" (Assembleia Legislativa de Minas Gerais, 2019). It should be noted that the town of Superior and the unincorporated areas of Dripping Springs and Queen Valley are all well within this "self-rescue zone." Although of course the U.S. Forest Service would not be bound by any legislation passed in Brazil, the proposal for a mining project in Arizona that would be illegal in a developing country should be a cause for pause and reflection.

At this point, it is appropriate to ask how quickly the local population centers could be overrun by mine tailings following the failure of a tailings dam. There have not been many measurements of the velocities of tailings flow slides, but they have ranged from 20-160 km/h (12-100 mph) (Jeyapalan, 1981). (The lower limit of 20 km/h apparently accounts for the equivalence between 10 km and 30 minutes in the Brazilian legislation.) According to Petley (2019), the tailings flow slide following the recent failure of the dam at the Córrego do Feijão Mine accelerated to 120 km/h (75 mph) and then slowed to 66 km/h (41 mph). Using the most conservative value of 12 mph and the above minimum distances between local population centers and tailings storage facilities, the tailings flood would arrive at Superior in 2.4 minutes, at Dripping Springs in 16 minutes, at Queen Valley in 18 minutes, and at Florence in 51.5 minutes.

DISCUSSION

It should now be abundantly clear that, due to the probable loss of human life that would result from failure of the tailings dams, the Maximum Credible Earthquake (MCE), and not the 5000-year earthquake, is the appropriate design criterion for the proposed tailings storage facilities. The only remaining question is the additional cost of construction and operation of the facilities that would be necessary to accommodate the strengthened safety standard. The higher safety standard is not a minor change. Based on calculations presented in Table 3 of Appendix I in Resolution Copper Mining (2014c), at the Near West site, the predicted acceleration that would result from a 10,000-year earthquake is considerably greater (factor of 1.16-1.34 over the range 0.01-10 seconds for periodicity of seismic shaking) than what would result from a 5000-year earthquake (see Fig. 3). In fact, the predicted accelerations show no signs of approaching an asymptotic limit as the earthquake return period is increased from 100 years to 10,000 years (see Fig. 3).

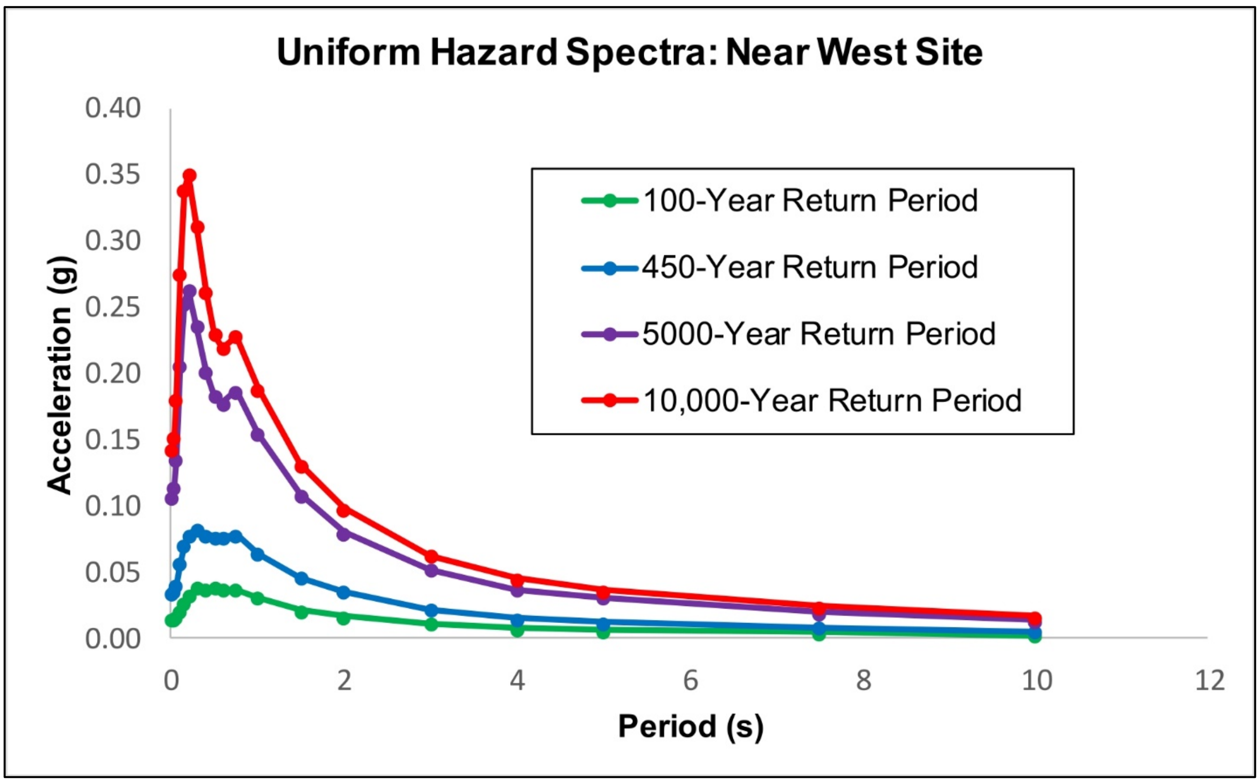

Figure 3. At the Near West site, the predicted acceleration that would result from a 10,000-year earthquake is considerably greater (factor of 1.16-1.34) than what would result from a 5000-year earthquake. Graph created from calculations in Table 3 of Appendix I in Resolution Copper Mining (2014c).

The additional costs should be considered in light of the common causes of failures of tailings dams during earthquakes. Most failures are a result of some form of liquefaction of either the foundation, the tailings dam, or the tailings stored behind the dam. Under normal circumstances, although there is water in the pores between the solid particles within the soil, tailings or tailings dam, the particles are touching one another, so that the overlying load is carried by the solid particles (and partially by the water). However, during seismic shaking, the particles can separate, so that they are no longer touching one another, and all of the load is carried by the interstitial water. Since water has no shear strength, the soil or the mass of tailings and water behaves as if it were a liquid. Regardless of the method of dam construction, the foundation could be potentially liquefiable during an earthquake. If that is the case, the foundation might require appropriate compaction prior to dam construction, or the liquefiable foundation material might need to be removed and replaced with more appropriate material, or it might be necessary to choose a different site.

Aside from the foundation, the potential for liquefaction for each alternative, and the cost of preventing liquefaction are a function of the proposed methods of dam construction. According to SWCA Environmental Consultants (2018), the current plans are for dam construction using the modified centerline method for both alternatives at the Near West site and for the use of the true centerline method at the Peg Leg and Skunk Camp sites. In all cases, the dams would be constructed out of the coarser (sand-sized) fraction of the same tailings that would be confined behind the dam. The important difference is that, in the modified centerline method, the tailings dam is partially underlain by the softer, uncompacted tailings that are confined by the dam (Haile and Brouwer, 1994). The result is that the dam could fall into the liquefied tailings below, even if the dam maintained its own structural integrity. For both types of construction, seismic liquefaction would need to be avoided by maintaining a sufficiently low water table, both within the dam and the tailings pile. This would involve the installation and maintenance of appropriate internal drainage systems. In addition, there would be a need for appropriate operational procedures that would avoid mixing of sands and finer-sized particles (called slimes) within the tailings pile in order to keep the permeability of the sands high enough so that water could escape. Moreover, the rate of addition of new tailings to the facility would have to be sufficiently slow so as to allow enough time for dewatering and consolidation of tailings. Finally, the likelihood of all forms of liquefaction failure could be reduced by decreasing the outward slope of the dam, which requires more construction material. Although the plan is to construct the dam out of the tailings themselves (SWCA Environmental Consultants, 2018), if there were insufficient coarser tailings for this purpose, it would be necessary to purchase or quarry construction material, thus further increasing the cost.

The additional cost of strengthening safety standards also applies to the dam at the Silver King site that would store only filtered tailings, especially considering that, at 1040 feet, this would be the tallest tailings dam ever built by an extra 390 feet. In the matrix of alternatives, SWCA Environmental Consultants (2018) wrote in the category “Tailings Embankment” for the Silver King site, “None. Structural zone of filtered tailings built around perimeter.” This is simply a choice of vocabulary, since a wall of filtered tailings that is intended to confine other filtered tailings still has the same safety function of a dam. Although liquefaction is much less likely for filtered tailings, it is still necessary to prevent slumping of the dam during an earthquake, which would require reducing the outward slope of the structural zone of filtered tailings, thus requiring additional construction material. Moreover, infrastructure is required to prevent the addition of water to the tailings pile, such as appropriate upstream diversions and dams, and this infrastructure must also be able to withstand the MCE (since its failure could result in the failure of the tailings dam).

It is impossible to estimate the additional cost of strengthening safety standards for the proposed tailings storage facilities without further information. In fact, none of the documents that have been made available by Rio Tinto have provided any information about the costs of construction and operation of the proposed tailings storage facilities, even under the weaker safety standard. However, if the Environmental Impact Statement, when it is released, is still calling for design for the 5000-year earthquake, the proposed mining project should and probably will be rejected by the U.S. Forest Service out of hand, without any consideration of costs.

CONCLUSIONS

The conclusions of this report can be summarized as follows:

1) Using a statistical model based on previous tailings dam failures, the predicted runouts from the failures of the five alternative tailings storage facilities would be in the range 200-370 miles.
2) Although the flow potential of filtered tailings is less than that of thickened tailings, even if the failures of the dam for the filtered tailings (Silver King site) caused only slumping of the tailings, they would travel at least 10,400 feet, and would impact the town of Superior (population 2837) at a minimum distance of 2500 feet.
3) The unincorporated area of Queen Valley (population 820) would be impacted by the failures of either of the Near West facilities (minimum distance 19,000 feet) or of the Silver King facility (minimum distance 8.2 miles).
4) The town of Florence (population 26,074) would be impacted by the failures of the Peg Leg facility (minimum distance 10.3 miles), either of the Near West facilities (minimum distance 16.0 miles), or Silver King facility (minimum distance 20.5 miles).
5) The unincorporated area of Dripping Springs (population 235) would be impacted by the failure of the Skunk Camp facility (minimum distance 17,000 feet).
6) Dripping Springs, Queen Valley and Superior are all well within what has been called the "self-rescue zone" (where no rescue is possible) in recent Brazilian legislation.
7) Since the failure of any the proposed tailings storage facilities would result in the probable loss of human life, the tailings storage facilities should be designed to withstand the Maximum Credible Earthquake, rather than the 5000-year earthquake that was proposed by Rio Tinto.

RECOMMENDATIONS

It is recommended that potential investors in the Resolution Copper Mine seek clarification from Rio Tinto on the following questions:

1) Why has Rio Tinto proposed designing the tailings storage facilities for the 5000-year earthquake, rather than the Maximum Credible Earthquake, even though all proposed sites are clearly upslope from local population centers?
2) What is the response of Rio Tinto to recent Brazilian legislation that forbids the construction of tailings dams where there is a population residing within 10 kilometers (6.2 miles) downslope from the dam?
3) What would be the additional cost of constructing and operating tailings storage facilities to meet the safety standard of the Maximum Credible Earthquake, as opposed to the 5000-year earthquake?

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REFERENCES

Agência Nacional de Mineração [National Mining Agency], 2019. Resolução Nº 4, de 15 de Fevereiro de 2019 [Resolution No. 4 of February 15, 2019], 1 p. Available online at: http://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/63799094/do1-2019-02-18-resolucao-n-4-de-15-de-fevereiro-de-2019-63799056

Arizona Department of Environmental Quality, n.d. Arizona mining guidance manual BADCT [Best Available Demonstrated Control Technology)]: Publication No. TB 04-01, 298 p. Available online at: http://static.azdeq.gov/wqd/badctmanual.pdf

Arizona Mining Reform Coalition et al., 2016. Scoping comments for the Resolution Copper Mine DEIS, 166 p. Available online at: http://www.azminingreform.org/sites/default/files/docs/scoping%20comments%20FINAL%20with%20attachments.pdf

Assembleia Legislativa de Minas Gerais [Legislative Assembly of Minas Gerais], 2019. Legislação Mineira (Lei 23291, de 25/02/2019) [Mining Legislation of February 25, 2019]. Available online at: https://www.almg.gov.br/consulte/legislacao/completa/completa.html?tipo=LEI&num=23291&ano=2019

Campaña, J., L. Valenzuela, and A. Figueroa, 2015. The Quillayes sand tailings dam in Chile—design and operation: Proceedings Tailings and Mine Waste 2015 Vancouver, BC, 14 p. Available online at: https://open.library.ubc.ca/cIRcle/collections/59368/items/1.0320846

Canadian Dam Association, 2013. Dam safety guidelines 2007 (2013 edition), 88 p.

Cherry, J., 2011. It seems like mining is the easy part; addressing societal issues as part of developing the Resolution copper mine in Arizona: Abstracts with Programs – Geological Society of America Annual Meeting, v. 43, p. 355.

Emerman, S.H., 2018. Potential impact of geothermal water on the financial success of the Resolution Copper Mine, Arizona: Report to Arizona Mining Reform Coalition, 14 p. Available online at: https://www.azminingreform.org/sites/default/files/docs/Arizona_Mining_Reform_Coalition_Report.pdf

Emerman, S.H. 2019a. Projected consumption of electricity and water by the proposed Resolution Copper mine, Arizona: Report to Arizona Mining Reform Coalition, 13 p.

Emerman, S.H., 2019b. Evaluation of predictions of land subsidence due to panel caving at the Resolution Copper Mine, Arizona: Report to Arizona Mining Reform Coalition, 17 p.

FEMA (Federal Emergency Management Agency), 2005. Federal guidelines for dam safety—Earthquake analyses and design of dams: FEMA-65, 75 p. Available online at: https://www.ferc.gov/industries/hydropower/safety/guidelines/fema-65.pdf

FEMA (Federal Emergency Management Agency), 2013. Selecting and accommodating inflow design floods for dams: FEMA-94, 38 p. Available online at: https://www.fema.gov/media-library-data/1386108128706-

02191a433d6a703f8dbdd68cde574a0a/Selecting_and_Accommodating_Inflow_Design_Floods_for_Dams.PDF

Haile, J.P. and K.J. Brouwer, 1994. Modified centerline construction of tailings embankments: Third International Conference on Environmental Issues and Waste Management in Energy and Mineral Production, August 1994, Perth, Australia, 7 p. Available online at: http://mssi.nrs.gov.bc.ca/1_CIMMountPolley/DOC1535.pdf

Hehnke, C., G. Ballantyne, H. Martin, W. Hart, A. Schwarz, and H. Stein, 2012. Geology and exploration progress at the Resolution porphyry Cu-Mo deposit, Arizona, *in* Hedenquist, J.W., M. Harris, and F. Camus (eds.), Geology and genesis of major copper deposits and districts of the world; a tribute to Richard H. Sillitoe: Special Publication (Society of Economic Geologists, CD-ROM), v. 16, pp. 147-166.

Houston, S., W.X. Chavez, and A.R. Campbell, 2010. Investigation of supergene processes at the Resolution copper deposit: Abstracts with Programs – Geological Society of America Annual Meeting, v. 42, p. 582.

Jeyapalan, J.K., 1981. Flow failures of some mine tailings dams: Geotechnical Engineering, v. 12, pp. 153-166.

Klohn Crippen Berger, 2017. Study of tailings management technologies: Report to Mine Environment Neutral Drainage (MEND) Program, MEND Report 2.50.1, 164 p. Available online at: http://mend-nedem.org/wp-content/uploads/2.50.1Tailings_Management_TechnologiesL.pdf

Larrauri, P.C. and Lall, U., 2018. Tailings dams failures—Updated statistical model for discharge volume and runout: Environments, v. 5. Available online at: doi:10.3390/environments5020028.

MapCruzin, 2019a. Arizona Administrative Boundaries GIS Shapefile. Available online at: https://mapcruzin.com/free-united-states-shapefiles/free-arizona-arcgis-maps-shapefiles.htm

MapCruzin, 2019b. Arizona Highway GIS Shapefile. Available online at: https://mapcruzin.com/free-united-states-shapefiles/free-arizona-arcgis-maps-shapefiles.htm

Petley, D., 2019. The speed of the Brumadinho tailings dam landslide: AGU100 Blogosphere—The Landslide Blog, February 4, 2019. Available online at: https://blogs.agu.org/landslideblog/2019/02/04/brumadinho-tailings-dam-landslide/

Resolution Copper Mining, 2014a. General plan of operations, vol. 1, 337 p. Available online at: http://www.resolutionmineeis.us/sites/default/files/project-files/resolution-copper-gpo-vol-1-20160509.pdf

Resolution Copper Mining, 2014b. General plan of operations, vol. 2, 97 p. Available online at: http://www.resolutionmineeis.us/sites/default/files/project-files/resolution-copper-gpo-vol-2-figures-20160509.pdf

Resolution Copper Mining, 2014c. General plan of operations, vol. 3, 1961 p. Available online at: http://www.resolutionmineeis.us/sites/default/files/project-files/resolution-copper-gpo-vol-3.pdf

Rio Tinto, 2018. Resolution. Available online at: https://www.riotinto.com/copperanddiamonds/resolution-4682.aspx

SWCA Environmental Consultants, 2018. Final range of alternatives for detailed analysis in draft EIS: Report to U.S. Forest Service, 19 p.

USACE (U.S. Army Corps of Engineers), 2016. Earthquake design and evaluation for civil works projects: ER 1110-2-1806, 28 p. Available online at: https://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1110-2-1806.pdf

USDA (U.S. Department of Agriculture), 2017a. Resolution Copper Project and Land Exchange Environmental Impact Statement—DRAFT alternatives evaluation report—Tonto National Forest, 74 p. Available online at: https://www.resolutionmineeis.us/sites/default/files/project-files/usfs-tonto-alternatives-evaluation-report-draft-final-201711.pdf

USDA (U.S. Department of Agriculture), 2017b. Resolution Copper Project and Land Exchange Environmental Impact Statement—DRAFT alternatives evaluation report—Appendices—Tonto National Forest, 165 p. Available online at: https://www.resolutionmineeis.us/sites/default/files/project-files/usfs-tonto-alternatives-evaluation-report-draft-final-appendices-201711.pdf

USDA (U.S. Department of Agriculture), 2018a. Snapshot—Resolution Copper Project – Tailings alternative—#2: Near West – wet {modified proposed action}, 2 p. Available online at: https://www.resolutionmineeis.us/sites/default/files/project-files/usfs-tonto-snapshot-alternative-2-20180817.pdf

USDA (U.S. Department of Agriculture), 2018b. Snapshot—Resolution Copper Project – Tailings alternative—#3: Near West – dry{modified proposed action}, 2 p. Available online at: https://www.resolutionmineeis.us/sites/default/files/project-files/usfs-tonto-snapshot-alternative-3-20180817.pdf

USDA (U.S. Department of Agriculture), 2018c. Snapshot—Resolution Copper Project – Tailings alternative—#4: Silver King – filtered, 2 p. Available online at: https://www.resolutionmineeis.us/sites/default/files/project-files/usfs-tonto-snapshot-alternative-4-20180817.pdf

USDA (U.S. Department of Agriculture), 2018d. Snapshot—Resolution Copper Project – Tailings alternative—#5: Peg Leg, 2 p. Available online at: https://www.resolutionmineeis.us/sites/default/files/project-files/usfs-tonto-snapshot-alternative-5-20180817.pdf

USDA (U.S. Department of Agriculture), 2018e. Snapshot—Resolution Copper Project – Tailings alternative—#6: Skunk Camp, 2 p. Available online at: https://www.resolutionmineeis.us/sites/default/files/project-files/usfs-tonto-snapshot-alternative-6-20180817.pdf

USGS (U.S. Geological Survey), 2019. USGS National Hydrography Dataset (NHD) Best Resolution 20190222 for Arizona State or Territory Shapefile Model Version 2.2.1. Available online at: https://www.sciencebase.gov/catalog/item/5a96cda0e4b06990606c4d0f

WebGIS, 2019. PINAL – Arizona—Terrain Data – 7.5 DEM. Available online at: http://www.webgis.com/terr_pages/AZ/dem75/pinal.html