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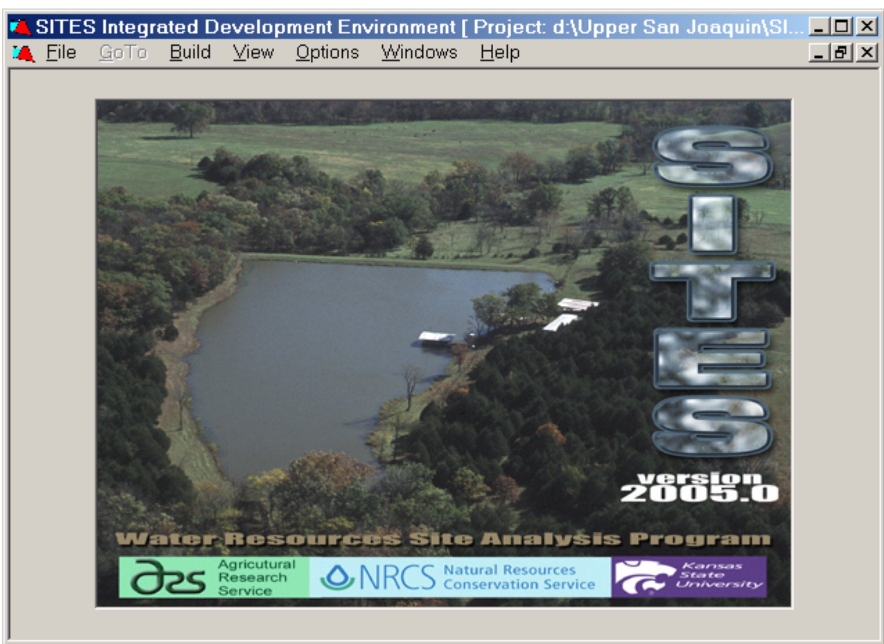
Hydraulic Laboratory Report HL-2008-06

Stability Analysis of Proposed Unlined Spillway Channel for Upper San Joaquin River Basin RM 274 Embankment Dam Alternative



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14. ABSTRACT
Potential headcut erosion of a proposed unlined spillway channel excavated through granitic rock was studied using the SITES water resources site analysis computer program distributed by the USDA. Model runs made using best-estimate values of key material parameters and upper and lower-bound limit values indicated that the spillway channel would not breach due to flows occurring during the probable maximum flood event. Further sensitivity testing showed that extreme values of the detachment rate coefficient, headcut erosion index, or representative material diameter are required for the model to predict a breach of the spillway. Modeling of lower operational flows predicted minimal damage to the spillway channel. The applicability of the model to this situation, uncertainties in model results and the influence of factors that are difficult to include in the analysis are discussed. A novel method for estimating the threshold stresses required to initiate erosion of monolithic rock is also presented.

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Disclaimer

Cover: Right-hand photo shows submerged jet erosion test in progress in test trench at Glendo Dam, Wyoming.

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Introduction and Purpose

Alternative designs for a new dam and spillway are being considered for a site in the Upper San Joaquin river basin, just upstream from Millerton Lake, impounded by Friant Dam. One alternative being considered at river mile 274 (RM 274) is an embankment dam, over 600 ft high, with a spillway excavated in granitic rock passing through the ridge that comprises the left abutment of the proposed dam. As presently proposed, the spillway channel would be unlined, except for a concrete ogee crest control structure. The spillway channel would be approximately 4000 ft long, with the steepest central portion of the channel (the middle 2000 ft) averaging approximately 22% slope. The control section itself would be 1200 ft wide, but with a split crest elevation; the leftmost 800 ft would have crest elevation 985.00 ft and the rightmost 400 ft would have crest elevation 995.00 ft.

To evaluate the feasibility of this spillway concept, a computational model was used to investigate the potential for headcut erosion of the unlined spillway channel under flow conditions that would occur during the Probable Maximum Flood for the site, and lesser operational floods. The PMF event is predicted to discharge approximately 2.67 million acre-feet of water through the spillway over a 34 day period. About 90% of this flow would occur in a 9-day period in which the peak discharge would rise to about 520,000 ft^3/s.

The proposed spillway, if constructed, would be similar in some respects to the spillway for Robert-Bourassa Dam, one element of Hydro Québec's La Grande complex (Fig. 1). This unlined rock spillway channel is 400 ft wide, 4900 ft long, and is designed for a flow of 575,000 ft^3/s. The spillway chute drops about 530 ft in elevation through a series of 33-ft high steps. The structure is a noteworthy tourist destination often described as "The Staircase of the Giants".

Figure 1. — Robert-Bourassa Dam spillway, Québec, Canada.

The SITES Model

Erosion of the proposed spillway channel was evaluated using the one-dimensional SITES water resources site analysis computer model developed by the U.S. Department of Agriculture (USDA) for analysis of hydrologic and hydraulic issues related to embankment dams and their associated features, including free overflow spillways excavated through earthen materials (USDA 1997). The analysis made significant use of only one component of the SITES model: the earth auxiliary spillway evaluation module.

SITES evaluates the stability and integrity of unlined spillway channels using a three-phase simulation of headcut erosion processes. Headcut erosion occurs in a variety of natural materials, especially when cohesion or other internal bonds hold the material together. Headcut erosion is most commonly observed in soil-like materials, but also can occur in rock or in loose granular materials when the presence of moisture creates apparent cohesion. The headcut erosion process begins when concentrated flow causes local erosion that creates a drop in the channel. Energy dissipation downstream from this drop then leads to accelerated erosion at the base of the overfall that undermines the overfall itself. The result is often further deepening and upstream advance of the overfall, or headcut. The objective of the SITES model simulation is to determine whether a headcut will form in the spillway and whether the flow duration will be sufficient to deepen the headcut and cause it to advance upstream through the spillway crest. This would cause a loss of reservoir storage and large outflows, similar to a dam-breach event. Figures 2 and 3 show headcut erosion damage in an earthen spillway, and the aftermath of a spillway breach caused when a headcut advanced into a large reservoir.

The three-phase model used to simulate headcut erosion in SITES is based on a simplification of the erosion process into the following steps:

1. failure of the vegetal cover in the spillway,
2. concentrated erosion that initiates a headcut, and
3. deepening and upstream advance of the headcut.

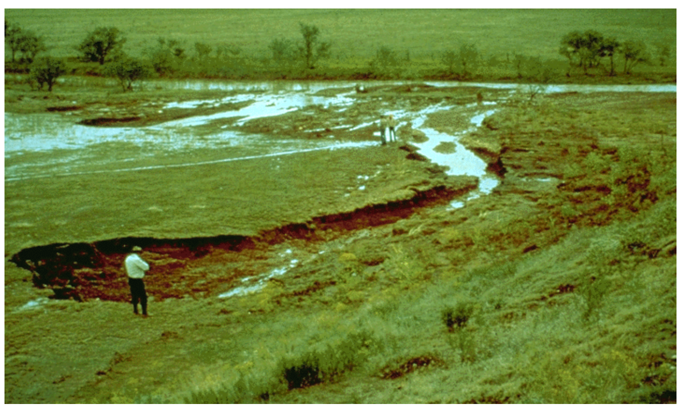

Figure 2. — Headcut damage to a vegetated earthen spillway.

In the case of the proposed spillway for Upper San Joaquin, there will be no significant vegetation in the channel, so only the last two phases of the erosion process need to be considered. For spillways that do have good vegetal cover, failure of the vegetation is modeled by comparing instantaneous and time-integrated hydraulic shear stresses to peak and cumulative threshold values that the vegetation can withstand, with consideration for the influence of cover uniformity and quality.

Phase 2 of the erosion process compares applied hydraulic stresses to the critical shear stress (τ_c) required for initiation of erosion, and estimates the rate of material removal to be proportional to the applied excess stress. The modeling equation is one used to simulate erosion processes controlled by the rate of soil detachment (as opposed to erosion limited by the sediment transport capacity of the flow):

$$\dot{\varepsilon} = k_d\left(\tau - \tau_c\right) \tag{1}$$

where $\dot{\varepsilon}$ is the downward erosion rate (depth/time), and τ is the applied shear stress. The detachment rate coefficient (k_d) determines the rate of deepening per unit of applied excess stress. The critical shear stress, τ_c, is determined as a function of the diameter of the particles to be eroded, utilizing Shields diagram (Vanoni 1975, Cao et al. 2006). The inherent assumption is that the particles are loose and free to be transported by the flow.

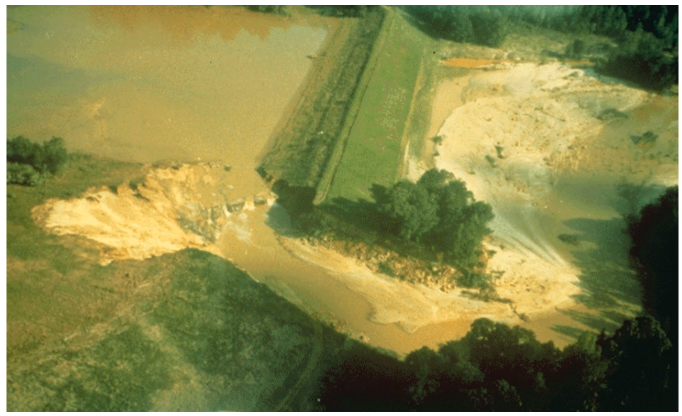

Figure 3. — Example spillway breach caused by headcut erosion.

For cohesive soils, the value of k_d can be estimated as a function of the dry bulk density of the material and the percentage of clay. However, it is preferable to determine values of τ_c and k_d by *in situ* testing with a submerged jet device (Hanson and Cook 2004). This test measures the scour that occurs when a submerged hydraulic jet impinges on the material surface. The test uses a ¼-inch diameter jet, so it is not capable of evaluating the influence of large-scale features such as widely spaced joints and cracks. The mathematical model of erosion in phase 2 and the submerged jet device were both originally developed for application to soil-like materials; for the Upper San Joaquin case, we have attempted to apply them to the rock material expected to be found in the spillway channel excavation.

Phase 3 of the erosion process is the deepening and upstream advance of an existing headcut. The SITES model can track the movement of several headcuts during any model run, and it is possible during phase 3 for one headcut to advance quickly enough that it consumes other upstream headcuts. The model provides detailed output regarding the depth, location, and upstream advance of the deepest and most upstream headcuts. Advance of a headcut during phase 3 is modeled by computing the energy dissipation at the base of the headcut and then making the advance rate proportional to the excess energy dissipation rate beyond a threshold value. In equation form this is written:

$$\frac{dX}{dt} = C(A - A_0) \tag{2}$$

where dX/dt = advance rate, C = advance rate coefficient, A = hydraulic attack (energy dissipation rate), and A_0 = attack threshold. The hydraulic attack is computed as $A=(qH)^{1/3}$, where q is the unit discharge and H is the height of the headcut. If A does not exceed A_0, no movement of the headcut occurs. The threshold for headcut advance, A_0, and the advance rate coefficient, C, are both obtained from empirically-developed relations that depend on a material parameter called the headcut erodibility index, K_h.

Values of K_h are determined by considering a number of geologic factors including material strength, spacing and size of joints, properties of joint filling materials, and orientation of joints (and thereby blocks) relative to the primary flow direction (Annandale 1995; Moore 1997). Values of K_h for the material at the proposed spillway site were estimated from available information, with upper and lower bounds established to indicate the uncertainty in this determination. It should be noted that during phase 3, although the focus is on predicting the upstream advance of headcuts, deepening of headcuts can also continue to occur in the SITES model. This deepening process is modeled using an equation similar to that used for computing concentrated erosion during phase 2 (i.e., deepening is still a function of applied hydraulic stresses and the k_d and τ_c parameters).

The empirical relations used to predict the headcut advance rate coefficient and headcut advance threshold were established through analysis of real headcut erosion events, primarily in earthen spillway channels associated with USDA dams (Temple and Moore 1997). The advance threshold was established from analysis of 46 headcuts in materials with K_h values ranging from about 0.03 to 3000. For the advance rate coefficient, detailed investigations of advancing headcuts were carried out in which applied stream power and advance rates were determined from field measurements and hydrologic records, and a relation between the advance rate coefficient and K_h was developed. The most resistant material in the data set of advancing headcuts had a K_h value of about 20, so the developed relation included a minimum value for the advance rate coefficient to prevent extrapolation of lower advance rate coefficients for higher values of K_h than those represented in the data set. Overall, the approach taken was quite conservative and was designed to produce overprediction of headcut advance rates more often than underprediction, although underprediction is still possible (Temple and Moore 1997).

Modeling Adjustments

SITES offers several simulation options, including two alternate methods for running a simulation of an auxiliary spillway operation event. The **special auxiliary spillway analysis** is meant to be used when flood routing calculations take place outside of the SITES model. It utilizes a direct input of the flow hydrograph through the spillway, and thus seems at first to be well-suited to this situation.

The **single event analysis** performs a simple level-pool routing of a single inflow flood to the reservoir, and carries out a stability and integrity analysis of the auxiliary spillway that is similar to the special auxiliary spillway analysis option. One additional feature of the single event analysis is the ability to define the location of a barrier wall in the spillway that will stop the upstream advance of any headcut. Due to an oversight during program development (personal communication, Darrel Temple, retired USDA-ARS), this option is not available when using the special auxiliary spillway analysis.

To keep the option of the barrier wall analysis available and avoid the need to fully describe the reservoir area-capacity curve and other factors that influence the flood routing, a hybrid modeling option was used. The single event analysis option was selected, but the reservoir inflow given to the model was the outflow hydrograph through the spillway, determined separately. To obtain the correct outflow hydrograph through the spillway, the reservoir was defined in the model to be of miniscule volume, causing the outflow hydrograph to be essentially equal to the provided inflow hydrograph with minimal attenuation. This method of model operation was tested and it was verified that the model correctly translated the inflow directly to outflow with reasonable simulated reservoir water surfaces and was stable in its operation.

The SITES model was developed to satisfy the needs of USDA and accommodates only relatively simple spillway geometries. In particular, it does not allow for an ogee crest control shape, tapered spillway channel widths (width reducing in the downstream direction), or spillways with dual crest elevations, all of which are features being considered for the Upper San Joaquin spillway. As a result, the following modeling simplifications were made:

- The ogee crest control structure was modeled as a simple broad-crested weir with the same control elevation as the lowest segment of the ogee crest. The channel immediately downstream from the crest was modeled as a constant-slope chute intersecting the planned excavated channel invert at the downstream end of the proposed crest structure apron.

- In runs designed to analyze the influence of tapered spillway channels, the entire spillway width was reduced to the minimum width at the downstream end of the tapered section, and the hydrograph through the spillway was maintained. SITES allows one to specify the rating curve for the spillway as a function of the reservoir elevation, irrespective of the modeled width of the spillway, so this approach maintained the same flow rates through the narrowed spillway, thus producing higher unit discharges over the full length of the spillway. Slight differences in depth of flow at the start of the spillway were caused by the approach, but these differences are believed to be insignificant considering the 600+ ft drop in the spillway channel.

- To examine the effect of a crest with different control elevations on the left and right side, runs were made with only the flow through the low side of the crest passed through a spillway channel that was artificially modeled to be the same width as the low section of the crest. This is a conservative approach that assumes that the flow over the lower portion of the crest does not spread as it moves downstream in the spillway channel; thus higher unit discharges are maintained over the full length of the channel.

Material Parameters

The SITES model requires several data inputs related to the erodibility of the materials in the spillway channel. The model also allows multiple material layers to be defined, but for this work only one layer was used. The three parameters needed for each material are:

- headcut erodibility index, K_h
- representative diameter of material
- detachment rate coefficient, k_d

The critical shear stress, τ_c, which appeared in the erosion equation discussed earlier, is determined internally in the SITES model from the Shields diagram for incipient sediment motion, making use of the material diameter input (USDA 1997).

Values of the first two parameters, K_h and representative material diameter (D_{75} value if a gradation curve were available), were determined in consultation with the design team, through a review of geologic design data. The K_h parameter combines numerical estimates for the contribution to erodibility of four geotechnical parameters: mass strength; block size; properties of discontinuities, joints, and the material filling them; and orientation of the material structure to the flow direction. Field investigations and modeling by USDA (1997) and others have shown that values of K_h can vary over more than 6 orders of magnitude (0.01 for loose sand up to 35000 for massive rock [ryolite]). Table 1 shows the best estimate and upper and lower limit values of K_h and the representative material diameter for the Upper San Joaquin spillway material. Material diameters were computed by determining the equivalent spherical particle diameter having the same volume as the rectangular block size shown in the table.

Table 1. — Material properties used for SITES analysis.

	K_h	**Block size** (ft)	**Representative diameter** (ft / inches)
Best estimate	2657	15 x 12 x 6	12.73 ft = 153 in.
Lower limit	1281	10 x 8 x 4	8.47 ft = 102 in.
Upper limit	7317	20 x 16 x 8	16.97 ft = 204 in.

Values of the detachment rate coefficient were estimated by engineering judgment using several different information sources. First, Figure 4 shows the range of k_d values obtained by Hanson and Simon (2001) from an extensive set of submerged jet tests performed on cohesive streambed sediments from loess areas of the midwestern USA. The figure identifies five erodibility classes, with k_d values for the "very resistant" class spanning the range of 0.001 to 0.03 cm/s/(N/cm^2). It should be kept in mind that these were conducted on cohesive soil-like materials found in streambeds, not rock.

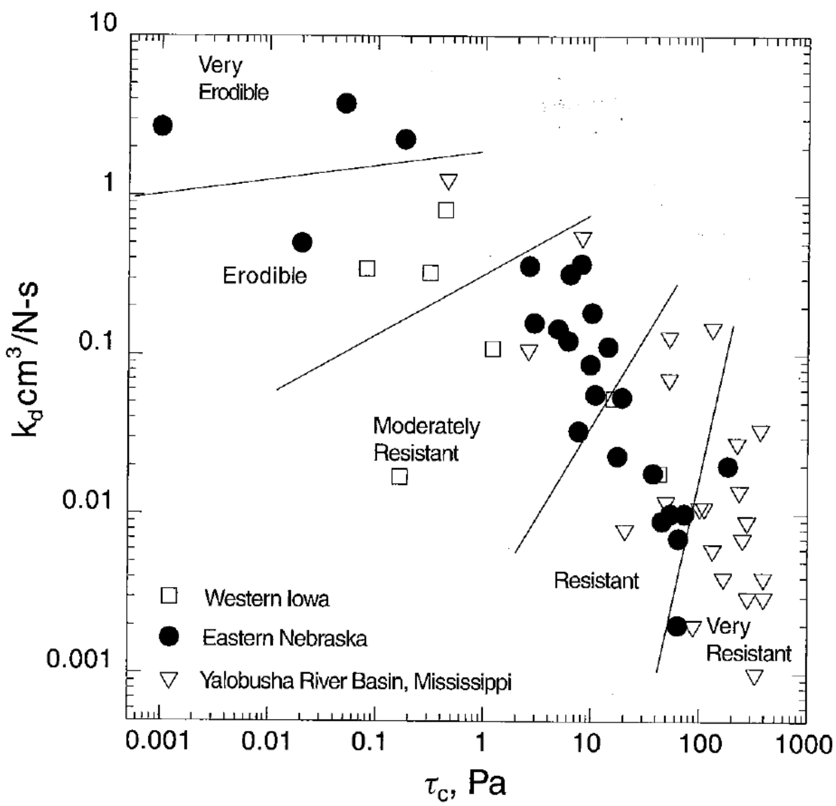

Figure 4. — Critical shear stress, τ_c, and erodibility rate coefficient, k_d, determined by submerged jet testing of streambed sediments in loess areas of the midwestern USA (Hanson and Simon 2001).

Second, a pair of *in situ* submerged jet tests were performed by Reclamation in 2007 at the site of a proposed spillway for Glendo Dam, Wyoming. The material at this site was a siltstone with headcut erodibility indices estimated at 0.85

(weathered) to 75 (unweathered). This was an unusual material that slakes and weathers very rapidly (in a matter of minutes when exposed to dry air). Although it was technically a rock material, it also exhibited enough soil-like tendencies to make it feasible to perform a jet test. One jet test performed at a location that weathered somewhat during site preparation yielded a k_d value of 0.14 cm/s/(N/cm^2). A second test performed at a position that was carefully protected from weathering yielded a k_d value of 0.008 cm/s/(N/cm^2), in the midst of the previously cited range for very resistant streambed sediments.

It should be expected that values of k_d for the Upper San Joaquin rock would be even lower than the values obtained from the Glendo tests or those reported by Hanson and Simon (2001) for erosion-resistant streambed sediments. Although there are no established relations between k_d and K_h values, one would expect that materials that are more resistant to headcut advance (a function of K_h in phase 3 of the SITES model) would also be similarly more resistant to downward erosion (a function of k_d in both phases 2 and 3). Given the dramatic difference in K_h values for the Upper San Joaquin and Glendo materials, it should not be surprising if k_d values for the Upper San Joaquin rock were one or more orders of magnitude lower.

Despite these arguments, because k_d cannot actually be measured for the Upper San Joaquin material and because no accepted methods exist for relating k_d and K_h, the best estimate for the k_d value of the Upper San Joaquin rock was taken to be the value from the test of the unweathered material at Glendo Dam, and the upper and lower limits were taken to be the Hanson and Simon (2001) values for very resistant streambed sediments. The resulting k_d values are 0.001, 0.008, and 0.030 cm/s/(N/cm^2) (low limit, best estimate, and upper limit, respectively). In the English units used by SITES, the values are 0.00057, 0.0045, and 0.017 ft/hr/(lb/ft^2). Higher values of k_d were also examined, because it is an important parameter affecting the performance of the model and considerable judgment was applied to develop these values.

Table 2. — Significant values of k_d used for SITES analysis.

Description	$\boldsymbol{k_d}$ (cm/s)/(N/cm^2)	$\boldsymbol{k_d}$ (ft/hr)/(lb/ft^2)
Lower limit (least erodible)	0.001	0.00057
Best estimate (jet test of unweathered siltstone at Glendo Dam)	0.008	0.0045
Upper limit (most erodible)	0.03	0.017

Erosion Modeling Results

A base-condition run of the SITES model was made and additional runs then considered variations of the three material parameters just discussed, as well as changes in spillway channel geometry. Each material parameter was changed individually to the lower and upper limit values, and in some cases additional runs were made with even more extreme values representing one or two orders of magnitude of additional erodibility. Three runs were also made that combined lower, upper, and extreme values of all three material parameters. These are described as best-case, worst-case, and extreme worst-case scenarios.

The hydrograph used for all initial runs was the PMF spillway outflow with a peak discharge of 519,000 ft^3/s at time 523 hours, shown in Figure 5. Most runs analyzed the full width of the spillway, distributing the flow evenly over the full width, but one run was made with only the hydrograph for the left (lower) side of the crest used (peak discharge of 410,000 ft^3/s), and with the spillway width set to 800 ft (the width of the lower left side of the crest). For all model runs the Manning's *n* roughness coefficient for the spillway channel was set to 0.030. The spillway profile entered into the model was a good approximation of the design profile, but was limited somewhat by the model's ability to use no more than 20 points to define the profile and a requirement that no points be separated vertically by more than 50 ft.

Table 3 summarizes the results of each PMF run. For most runs the table shows the depth and upstream advance of both the most upstream and deepest headcuts; in some cases they are the same headcut. For those runs that predicted a breach of the spillway, the time at which the breach occurred is shown (model computations stop once a headcut advances through the spillway crest). Plots depicting headcut erosion for each of the runs shown in Table 3 are included in Appendix A.

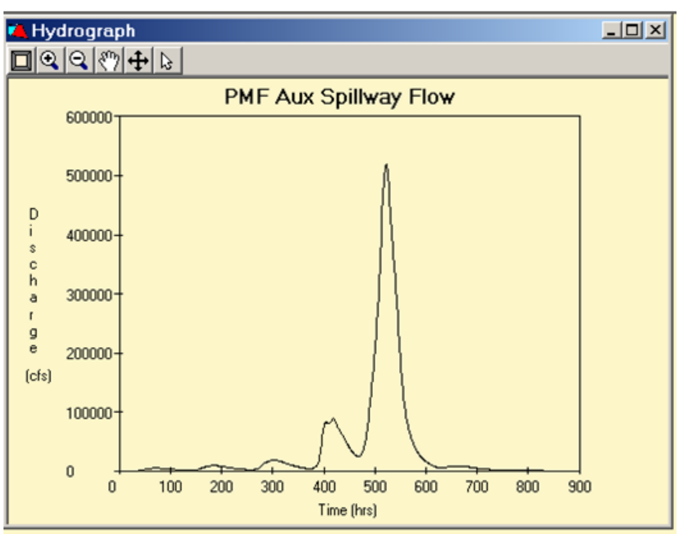

Figure 5. — PMF hydrograph through the full spillway (1200 ft wide).

Table 3. — Results of SITES model runs.

		Input Parameters			Results - Headcut Depth and Station (Spillway Crest = Station 2000)						
		Representative diameter of material in headcut	Headcut Index, K_h	detachment rate coefficient, k_d							
		inches		*ft/hr/psf*							
	Parameter range	102 - 204	1281 - 7317	0.00057 - 0.017	Most upstream			Deepest			
	Best estimate	153	2657	0.0045	Depth	Initial Station	Advanced to Station…	Depth	Initial Station	Advanced to Station…	
Figure	**Case Name**				*ft*	*ft*	*ft*	*ft*	*ft*	*ft*	Comment
A-1	Base case (combined best-estimate values)	153.	2657.	0.0045	0.6	2700	2700	43.6	3200	3162	
A-2	Repr diam 204	**204.**	2657.	0.0045	25.7	3200	3200	<—— Same as most upstream headcut			
A-3	Repr diam 102	**102.**	2657.	0.0045	11.6	2700	2700	58.6	3200	3125	
A-4	Repr diam 12	**12.**	2657.	0.0045	21.0	2010	2008	119.2	3200	2903	Cascading headcuts along length of spillway
A-5	Repr diam 1	**1.**	2657.	0.0045	25.7	2010	2008	125.1	3200	2907	Cascading headcuts along length of spillway
A-6	K_h high	153.	**7317.**	0.0045	0.6	2700	2700	36.0	3200	3200	
A-7	K_h low	153.	**1281.**	0.0045	0.6	2700	2700	91.0	3300	3097	
A-8	K_h = 100	153.	**100.**	0.0045	174.4	3300	2584	<—— Same as most upstream headcut			
A-9	K_h = 10, Value of K_h that demonstrates a breach	153.	**10.**	0.0045	204.3	3300	2000	409.8	4850	2976	**BREACHED at 565 hours (Q_{peak} @ 523 hours)**
A-10	k_d low (e.g., most resistant streambed sediments tested by Hanson and Simon 2001)	153.	2657.	**0.00057**	3.9	3200	3200	<—— Same as most upstream headcut			Minimal erosion
A-11	k_d high (e.g., well-compacted Lean Clay, 30% clay, PI=24, Std. Proctor compaction [25 blows/layer])	153.	2657.	**0.017**	1.0	2700	2700	110.7	3200	2931	
A-12	k_d very high	153.	2657.	**0.2**	264.0	3200	2480	<—— Same as most upstream headcut			
A-13	Value of k_d that causes a breach	153.	2657.	**2.**	416.6	2700	2000	491.6	3200	2000	**BREACHED at 558 hours (Q_{peak} @ 523 hours)**
A-14	Combined best-case values	**204.**	**7317.**	**0.00057**	1.7	3200	3200	<—— Same as most upstream headcut			Minimal erosion
A-15	Combined worst-case values	**102.**	**1281.**	**0.017**	0.5	2010	2010	161.4	3200	2637	
A-16	Combined extreme worst-case values	**12.**	**100.**	**0.2**	29.2	2010	2000	585.0	3200	2000	**BREACHED at 425 hours (Q_{peak} @ 523 hours)**
A-17	Base case narrowed 200 ft	153.	2657.	0.0045	1.9	2700	2700	90.9	3300	3107	
A-18	Base case narrowed 400 ft	153.	2657.	0.0045	9.8	2700	2700	139.9	3300	2870	
A-19	Base case, analyzing only left side of spillway (higher unit q)	153.	2657.	0.0045	1.9	2700	2700	103.7	3300	3046	

***Bold** entries are values different from the best-estimate (base case)*

Shaded entries are extreme values outside of established reasonable parameter range

Base Case and Effect of Varying Material Parameters

Table 3 shows that the base case run and all runs made with material parameters varied within the established upper and lower bound limits predicted some headcut erosion, but no breach of the spillway. Headcuts most often originated at spillway stations 3200, 3300, 2700, and 2010 ft (spillway crest at station 2000 ft). These are locations at which breaks in slope occur in the profile that was entered into the model, so they are most susceptible to the initiation of erosion. The predicted erosion changed the most in response to setting the value of k_d to its upper or lower limit and least in response to setting the representative material diameter to its upper or lower limit. This is not surprising, since the ranges of the upper-to-lower limit values of the three parameters were about 0.3 orders of magnitude for the representative diameter, 0.6 orders of magnitude for K_h, and 1.5 orders of magnitude for k_d.

Setting all three parameters together to the most erodible of the upper/lower limit values (worst-case scenario) produced significant headcutting well downstream from the spillway control structure, but due to the length of the spillway and the duration of time required for a headcut to advance upstream, the model still indicated no breach into the reservoir. Changing each material parameter individually by one additional order of magnitude beyond the upper/lower limit value also did not produce a breach, but changing *kd* or K_h by two orders of magnitude or changing all three parameters together by one order of magnitude (extreme worst-case scenario) did produce breaches. It should be kept in mind that the k_d values chosen for this analysis may have been quite conservative (more erodible than reality), since they represent the erodibility of erosion-resistant soils or weak rock materials, not strong rock such as that found at this site.

Effect of Changing Spillway Geometry

The last three runs shown in Table 3 examined the effect of tapering the spillway channel by either 200 or 400 ft, or of assuming that the higher unit discharge of the left side of the spillway (due to the 10 ft lower crest height) persisted down the full length of the spillway. These alternatives were analyzed by reducing the spillway width to either 1000 or 800 ft, since SITES does not specifically allow for a tapered spillway channel. The effects of these changes were relatively small compared to the changes observed when the material parameter values were set to their upper and lower limit values. Again, this was expected since the change in spillway width from 1200 to 800 ft represents a width change of only about 0.18 orders of magnitude, less than the variation of all three material parameters.

Operational Flood Results

Following the completion of the PMF runs, several smaller floods were considered to determine the erosion that might take place during operational use of the spillway. Spillway outflow hydrographs were available for floods with return intervals of 2, 10, 25, 50, 100, 200, and 500 years. These hydrographs had similar duration as the PMF (about 34 days), but lower peak flow magnitudes and volumes as shown in Table 4.

Table 4. — Spillway outflow hydrograph characteristics.

Return Period (years)	Peak Flow (ft^3/s)	34-day volume (ac-ft)
2	5,030	143,000
10	15,500	324,000
25	24,500	402,000
50	32,900	487,000
100	58,000	601,000
200	96,800	734,000
500	143,000	940,000
PMF	519,000	2,670,000

The great majority of the flows for these lesser floods would pass over the low (left) side of the spillway crest, so these model runs were all made with the spillway width set at 800 ft. In addition to runs that considered single events at these return intervals, a series of runs was made that evaluated the cumulative effect of multiple events smaller than the 500-yr flood. Arbitrarily assuming an operational life of 500 years, the expected number of events during that time period at each return interval was computed as N=500/T_r, where T_r is the return interval in years. The duration of the individual event hydrograph was then scaled up (stretched in time) by the factor N to produce a hydrograph representing the cumulative volume of flow to be expected in a 500 year time period from floods having the one specified return interval. Thus, for the 100-yr event, the scaling factor was N=5, and the duration of the cumulative event was increased from 34 days to about 170 days.

The operational flood runs were all made using the base-case material parameters, K_h=2657, k_d=0.0045 ft/hr/(lb/ft^2), and representative diameter=153 inches. Note that for the PMF hydrograph, these parameters produced a predicted a 44-ft deep headcut that initiated at station 3200 and advanced 38 ft upstream. For the 500-yr flood event, the deepest and most upstream headcut was predicted to be only 11.7 ft deep, initiating at station 3200 ft, and the model predicted that this headcut would not advance upstream. Given the size of this spillway, this level of damage to a roughly excavated rock channel would be unlikely to affect future spillway operations or require repair.

For the single-event 200-yr flood, the cumulative 200-yr flood, and all smaller floods and cumulative floods, the model predicted no development of headcuts anywhere in the spillway, although some localized concentrated erosion of surface materials should still be expected.

Alternative Method for Modeling Rock Erodibility

The approach taken in the runs described thus far was to model headcut development and deepening in phases 2 and 3 using the detachment-limited erosion equation (eq. 1), with the critical shear stress, τ_c, determined from the geologic estimate of the rock block size and the detachment rate coefficient, k_d, estimated using values obtained from Reclamation's Glendo Dam jet test and from jet tests by Hanson and Simon (2001) on erosion-resistant cohesive streambed sediments. However, an argument can be made that the mechanisms of rock erosion may be fundamentally different from those of cohesive soil erosion, and that it might be more appropriate to consider that intact, massive rock might have a greater resistance to the initiation of erosion (i.e., a higher critical shear stress than one would determine based on block size alone), due to the interlocking of blocks with one another. However, once the critical shear threshold is exceeded and rock blocks are broken free from the surrounding rock mass, the rate of material removal might also be quite high, since whole blocks could be transported as intact units. Thus, k_d, the rate of material detachment per unit of excess stress above the threshold, might have a relatively high value, comparable to values for loose granular materials like sand and gravel. The lower k_d values of cohesive soils might be justified on the basis of their more plastic behavior, illustrated by their ability to deform without breaking.

On the basis of this conceptual description, the SITES user manual suggests modeling rock materials by not specifying a k_d value, but instead by specifying that the material contains 0% clay. This causes SITES to compute its own value for k_d as a function of the clay content and bulk density of the material. The resulting value of k_d is quite high when the clay content is zero, 2.1 ft/hr/(lb/ft^2) in our case, comparable to the value we used previously that was two orders of magnitude more erodible than the upper limit we initially established.

The key to this modeling approach is that the critical shear stress value becomes the primary factor determining whether erosion occurs and the rate at which it occurs (since the rate coefficient is only applied to the excess stress above the critical value). The critical shear stress is not specified directly as an input to SITES, but is determined internally from the user-specified representative material diameter, using the Shields diagram, which applies to the incipient motion of loose, granular material. In order to give some credit for the fact that intact rock should have a higher threshold for movement than loose rock, the representative diameter should be adjusted up to a value greater than the true block size.

Adjusting the Representative Diameter

To determine this adjusted material diameter, a multi-step process was used. First, the headcut erodibility index was used to determine the critical stream power required to initiate erosion, using a relation developed by Annandale (1995) for the prediction of initiation of surface erosion, $P_c=K_h^{0.75}$, where P_c is the critical stream power in kW/m^2. Next, recognizing that the applied stream power is the product of the shear stress and the flow velocity, the required critical stress to obtain this stream power was computed for the reach of the spillway having the highest velocity, as indicated in the SITES output. For the PMF case, this velocity was about 95 ft/s. The resulting stress was then used with Shields diagram to determine the particle diameter that should be provided as input to SITES. This process was applied for the lower limit, best-estimate, and upper limit values of K_h. For the PMF case, the resulting particle diameters were 398, 689, and 1472 inches, respectively, about 4 to 6 times greater than the sizes estimated from the observed rock joint spacing. The same procedure was also applied to the 500-yr flood event. For that event, since flow velocities are lower, more shear stress is required to achieve a similar critical stream power. As a result, the inferred particle diameters were an additional 42% larger (567, 980, and 2094 inches, respectively).

Results for Alternative Method

When the SITES model was run with these input data, the model predicted no headcut development for any of the cases. Next, to explore the sensitivity of the model and the proximity to the threshold for headcut development, the PMF and 500-yr flood event models were run repeatedly with lower representative diameters specified until headcutting occurred. For the PMF case, headcutting occurred when the diameter was reduced to 305 inches (no headcutting with diameter = 306 inches), and for the 500-yr flood case, headcutting occurred when the diameter was reduced to 192 inches. Because the detachment rate coefficient was high for these cases (the value internally computed by SITES assuming 0% clay content), when the threshold for headcut development was exceeded, the depth of headcutting and computed headcut advance were very large. Using the lower limit value of K_h=1281 for phase 3, the PMF produced a 333-ft deep headcut that advanced from station 3200 to 2431 ft. The 500-yr flood event produced a 169-ft deep headcut that advanced from station 3200 to 2972 ft. While the size of these headcuts is sobering, it should be kept in mind that we had to significantly reduce the erosion threshold (as determined from the representative diameter input) in both cases in order to have the model indicate any headcut erosion at all. These results help to illustrate that this approach to the modeling of rock erosion is almost an all-or-nothing scenario. If the threshold is not reached, there is no erosion, but once the threshold is exceeded, the predicted amount of erosion can immediately be enormous. In contrast, the initial approach predicted gradually increasing erosion over a broader range of material properties. It is most notable that both modeling approaches predicted no breach of the spillway using input data that were believed in advance to reasonably represent reality. We only obtained large amounts of erosion when we provided extreme values of input data, beyond the respective lower or upper limit values that we established prior to running the model.

Discussion of Other Factors

Although the SITES spillway erosion model depends upon only three primary parameters, it is clear from the preceding discussion that the judgments that must be made when determining input data and evaluating program output are considerable, and there are complex interactions of the three primary inputs. In addition, other factors need to be given some consideration: potential cavitation damage, abrasion damage, and the effects of non-uniform materials.

Considering the height of the spillway and likely flow velocities, there is potential for cavitation damage of the rock that might then initiate headcut erosion, although natural entrainment of air into the flow would probably minimize this as a source of damage. Cavitation is typically a serious concern for concrete-lined spillway chutes where the initiation of erosion can lead to damage to larger areas and the exposure of underlying erodible materials. However, in this case, minor cavitation damage to a roughly excavated surface having good erosion resistance probably would not be a serious issue.

Similarly, there is some potential for abrasion erosion if the outlet channel from any individual headcut allowed recirculation of trapped "particles". Like cavitation, this is unlikely to be a significant issue.

Non-uniformity of the rock materials in the spillway channel may be significant and may strongly affect the results of this study; the analysis is thus far based on geologic information obtained from preliminary site investigations that included only two drill holes in the vicinity of the spillway. Materials were assumed to be uniform within the modeled area, but the presence of localized weak zones and layers could accelerate erosion processes.

Conclusions

The SITES model predicts significant headcut erosion in the spillway channel under PMF flows, but using material parameter inputs that are believed to be reasonable to conservative, no breach of the spillway is predicted. Setting material parameter inputs to extreme values (2 orders of magnitude more erodible for individual parameters or 1 order of magnitude more erodible for all parameters simultaneously) does produce a predicted breach during the PMF event, but the material represented by these extreme values is much different from that which we expect to encounter at this site. More frequent operational floods were also studied, and predicted headcut erosion was slight for the 500-yr flood and zero for the 200-yr and smaller floods.

Two approaches to the modeling of rock erosion were considered. The majority of the reported results were obtained by using detachment rate coefficients comparable to those of very erosion-resistant clay materials or soft rock. Model runs were also made with much higher detachment rate coefficients and adjusted material diameters that are intended to reflect the additional initial erosion resistance of intact, tightly jointed rock and the potential for more rapid downward erosion once the critical shear stress threshold is exceeded. These model runs indicated no headcut erosion until material diameters were decreased well below the range of reasonable values determined by rational analysis.

It should be kept in mind that the SITES model was originally developed for the analysis of headcut erosion in spillways primarily composed of soil materials, and its empirical elements were calibrated against real headcuts in real spillways, including some in weaker sedimentary rock materials. For application to more resistant rock, conservative approaches were taken by the developers when extending empirical relations to materials that are more erosion resistant than those represented in USDA's real-world spillway headcut database. The results of this study are encouraging for this spillway, but although SITES is thought to be the best available tool at this time for modeling headcut erosion in rock, many uncertainties still exist with regard to material parameter input data and the applicability of the model specifically to problems of rock erosion.

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Appendix A: Selected SITES Graphical Output

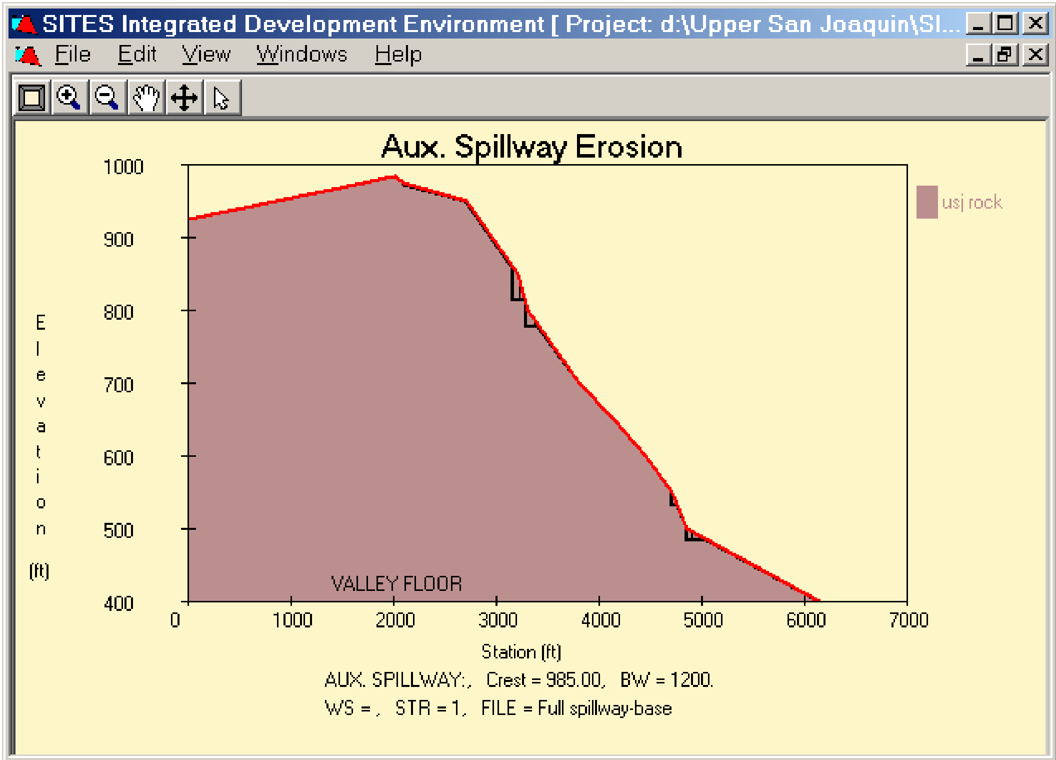

Figure A-1. SITES erosion results for base case, full-width spillway.
Diam. = 153 inches, K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum depth = 43.6 feet.

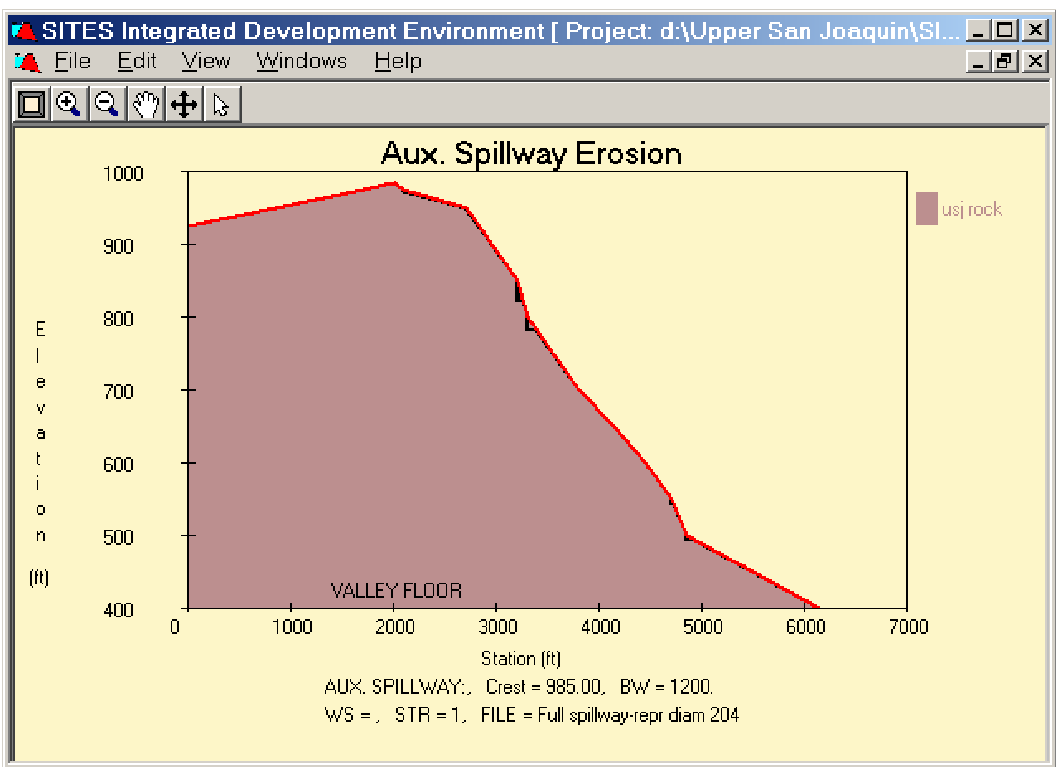

Figure A-2. SITES erosion results with representative diameter = 204 inches.
K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 25.7 feet.

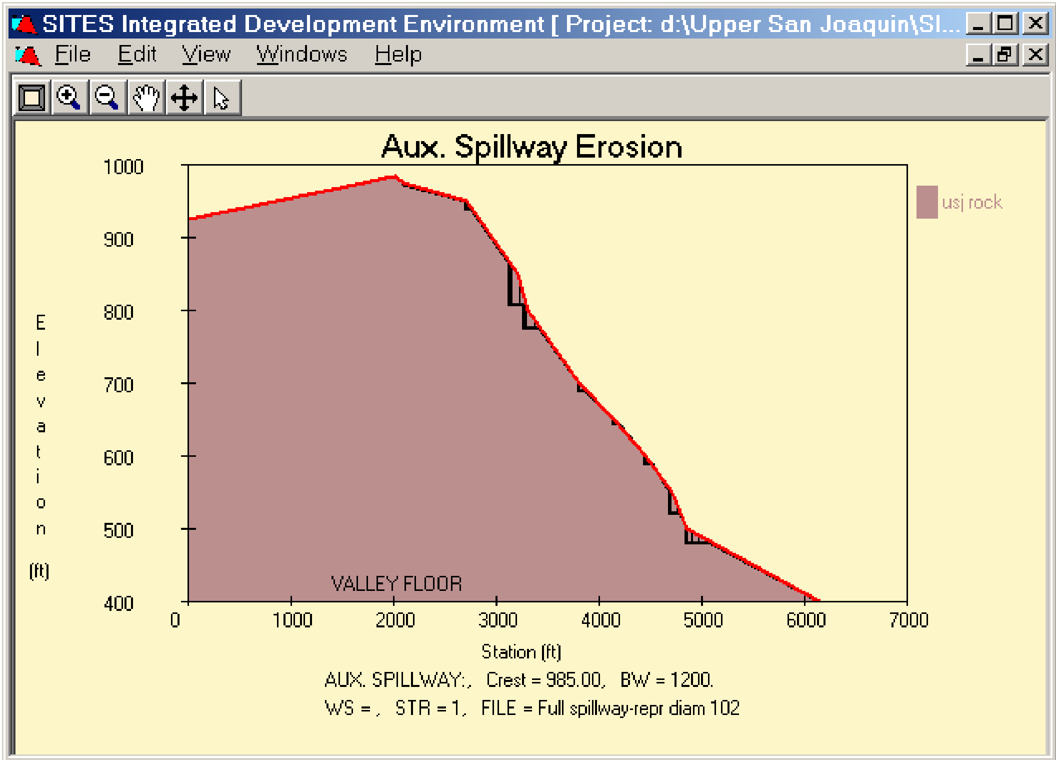

Figure A-3. SITES erosion results with representative diameter = 102 inches. K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 58.6 feet.

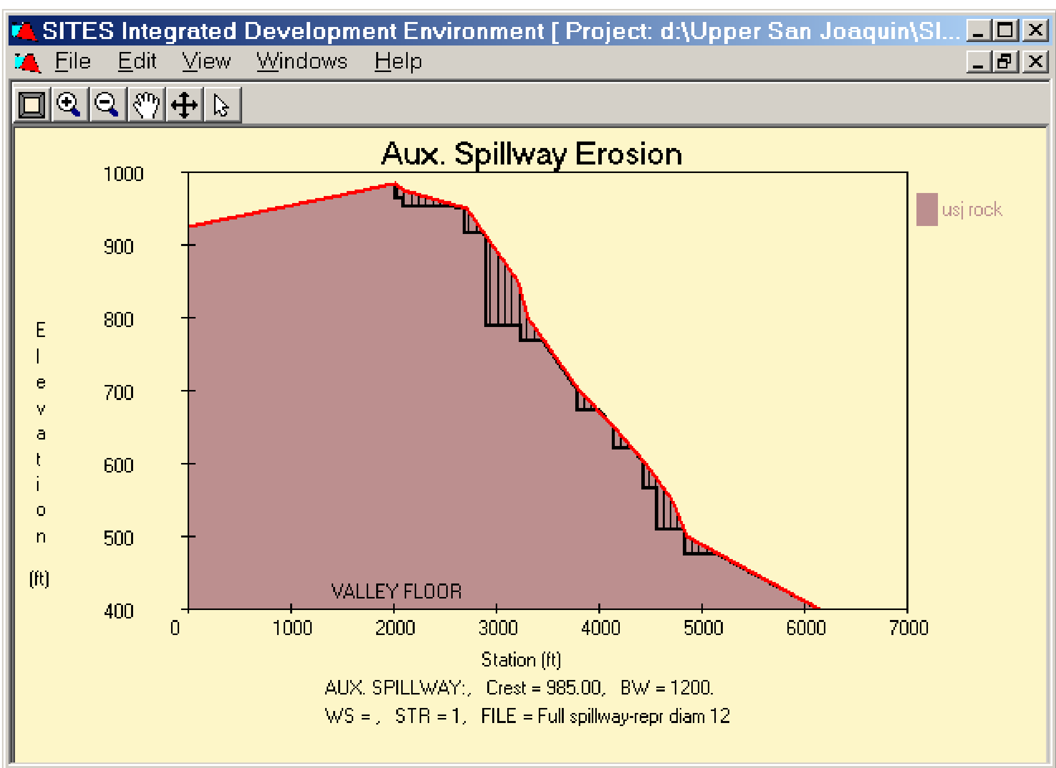

Figure A-4. SITES erosion results with representative diameter = 12 inches. K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 119 feet.

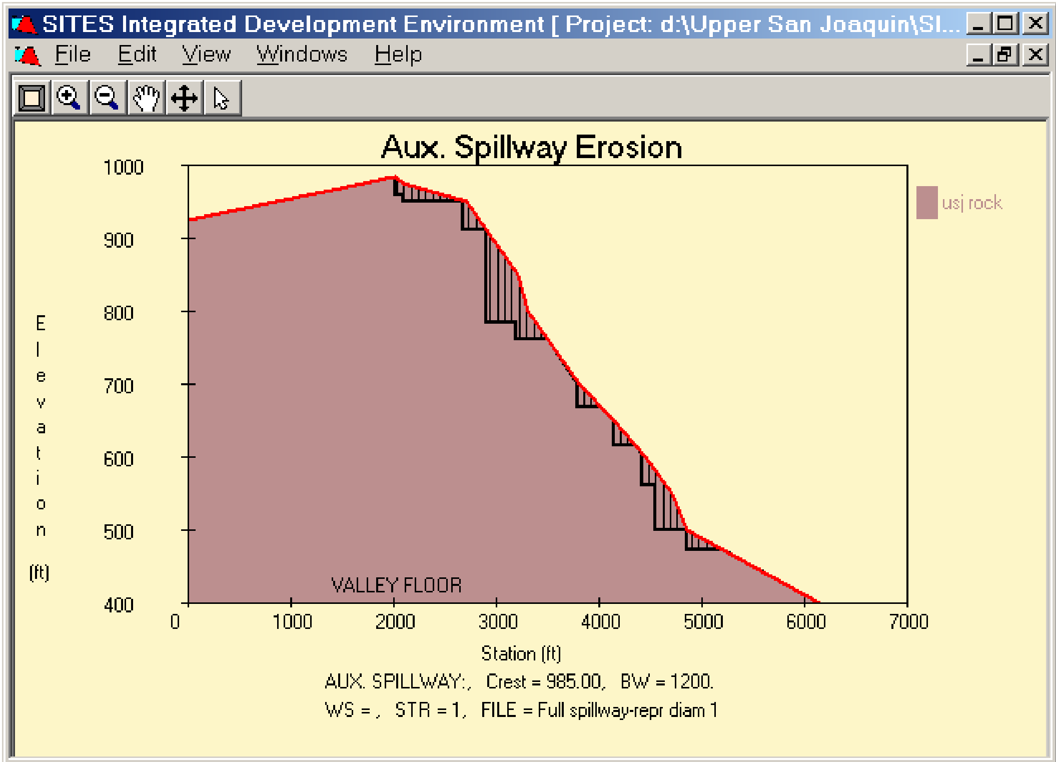

Figure A-5. SITES erosion results with representative diameter = 1 inch.
K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 125 feet.

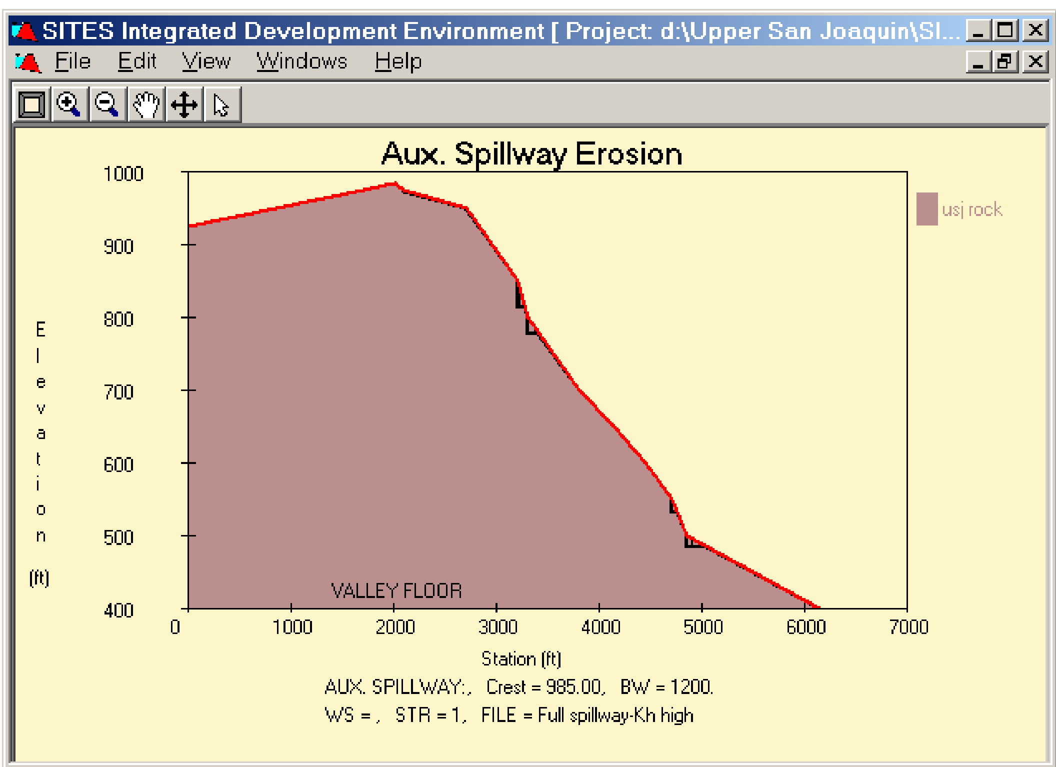

Figure A-6. SITES erosion results with K_h = 7317.
Diam. = 153 inches, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 36.0 feet.

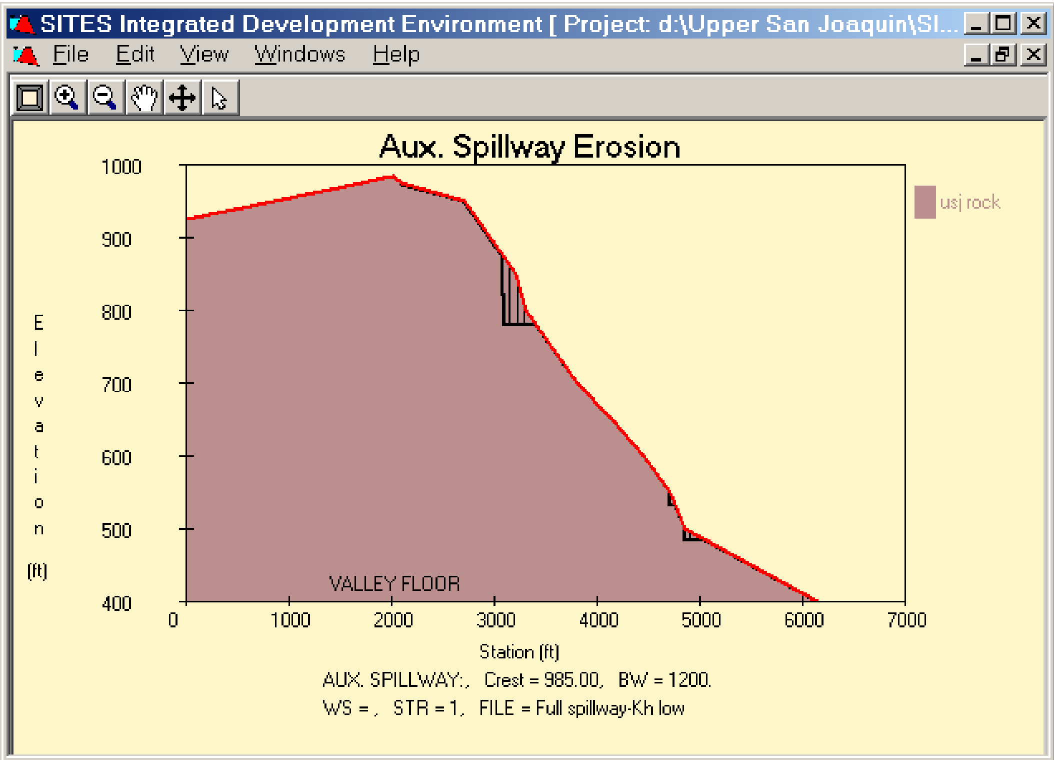

Figure A-7. SITES erosion results with K_h = 1281.
Diam. = 153 inches, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 91.0 feet.

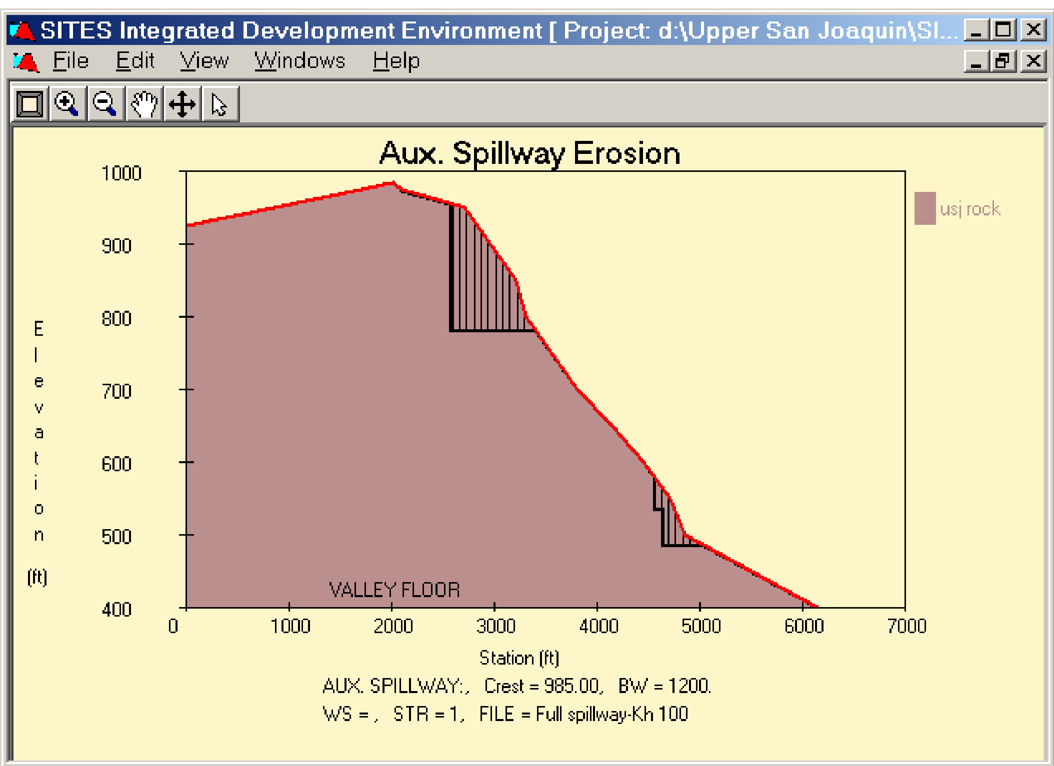

Figure A-8. SITES erosion results with K_h = 100.
Diam. = 153 inches, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 174 feet.

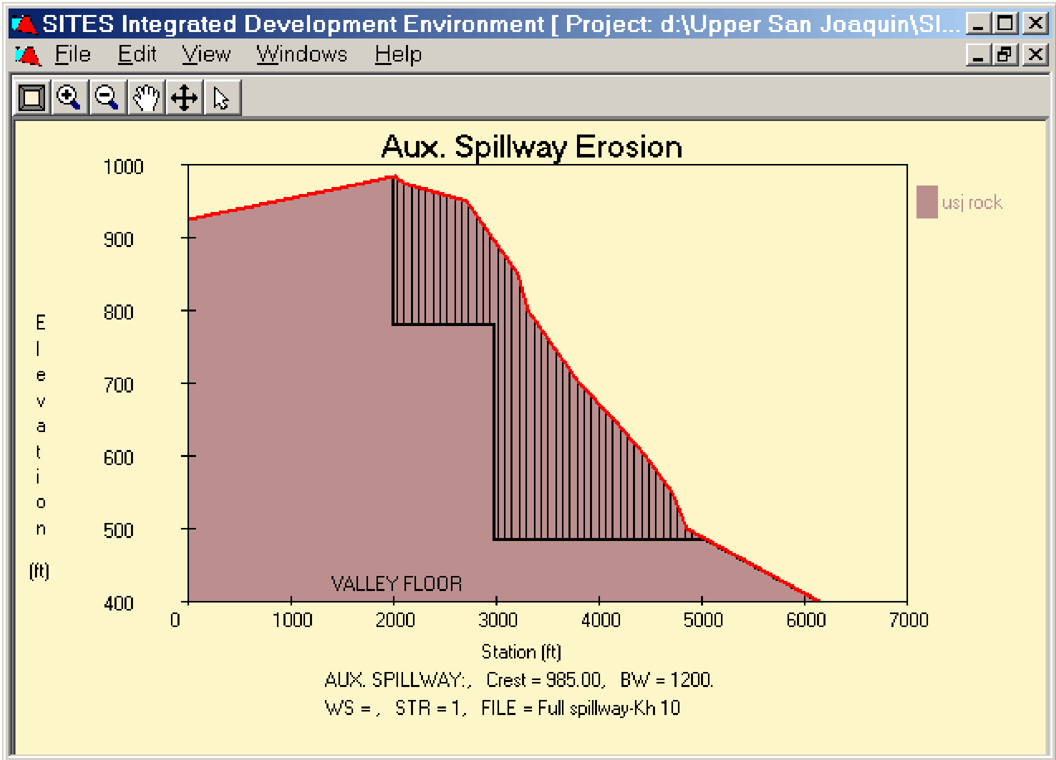

Figure A-9. SITES erosion results with K_h = 10. Spillway breached at 565 hrs. Diam. = 153 inches, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 410 feet.
This run uses input data that represent extreme erodibility compared to expected conditions.

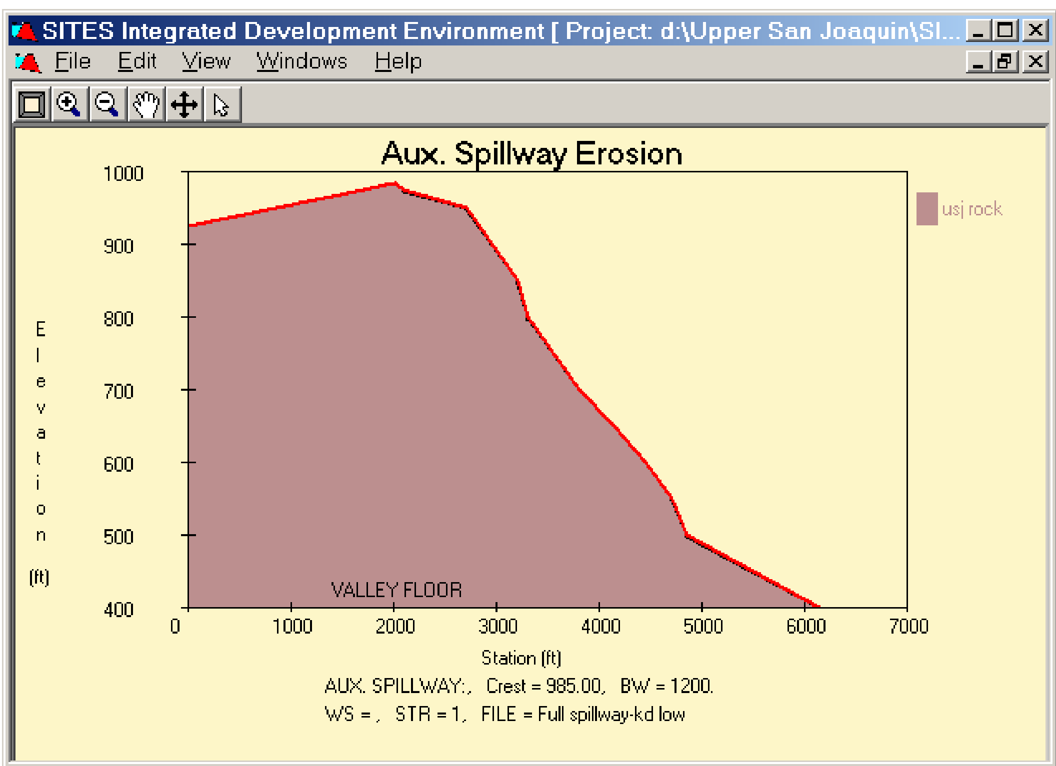

Figure A-10. SITES erosion results with k_d = 0.00057 ft/hr/(lb/ft^2). Diam. = 153 inches, K_h = 2657, maximum headcut depth = 3.9 feet.

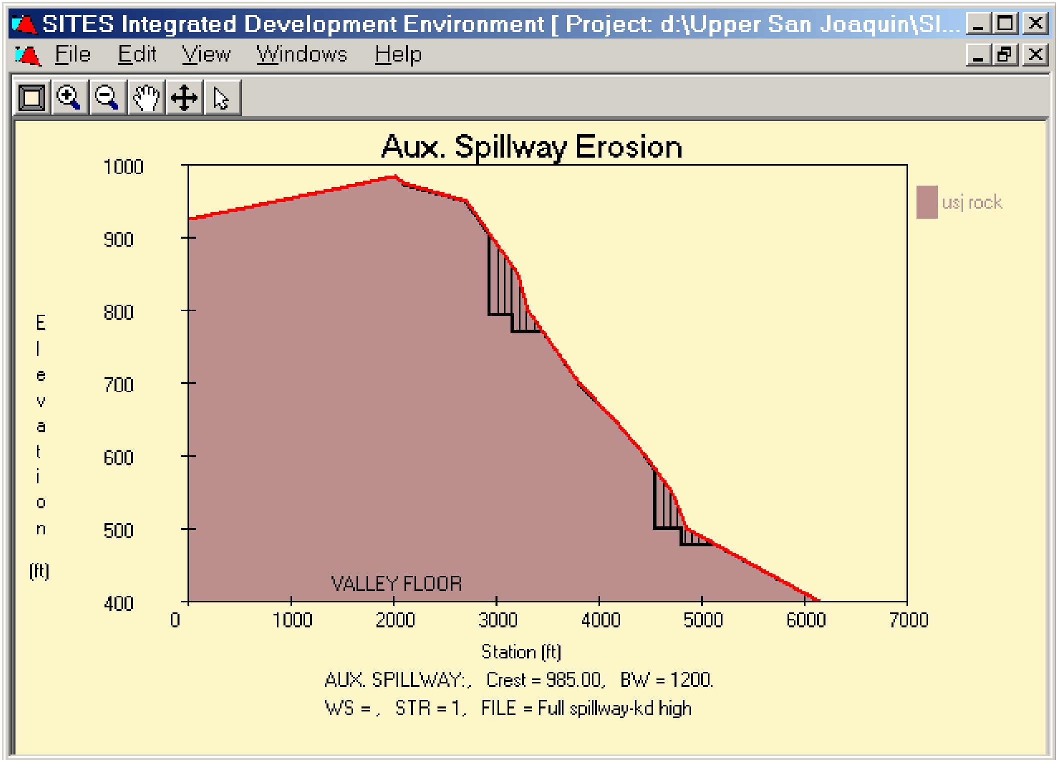

Figure A-11. SITES erosion results with k_d = 0.017 ft/hr/(lb/ft^2).
Diam. = 153 inches, K_h = 2657, maximum headcut depth = 111 feet.

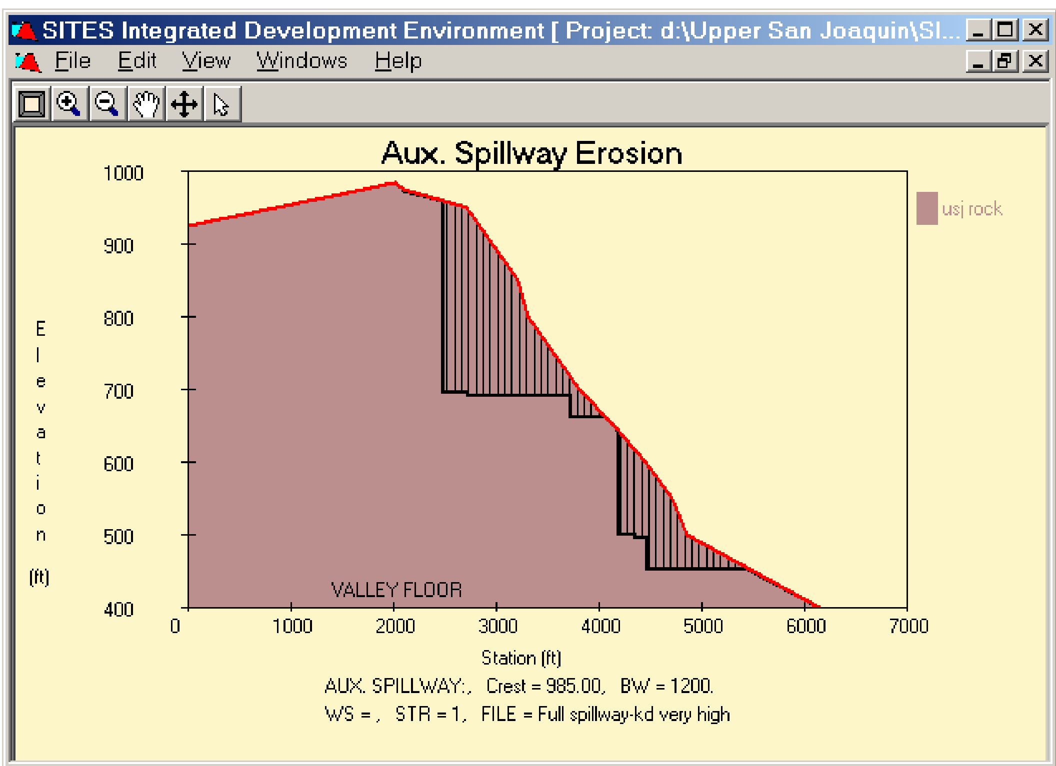

Figure A-12. SITES erosion results with k_d = 0.2 ft/hr/(lb/ft^2).
Diam. = 153 inches, K_h = 2657, maximum headcut depth = 264 feet.

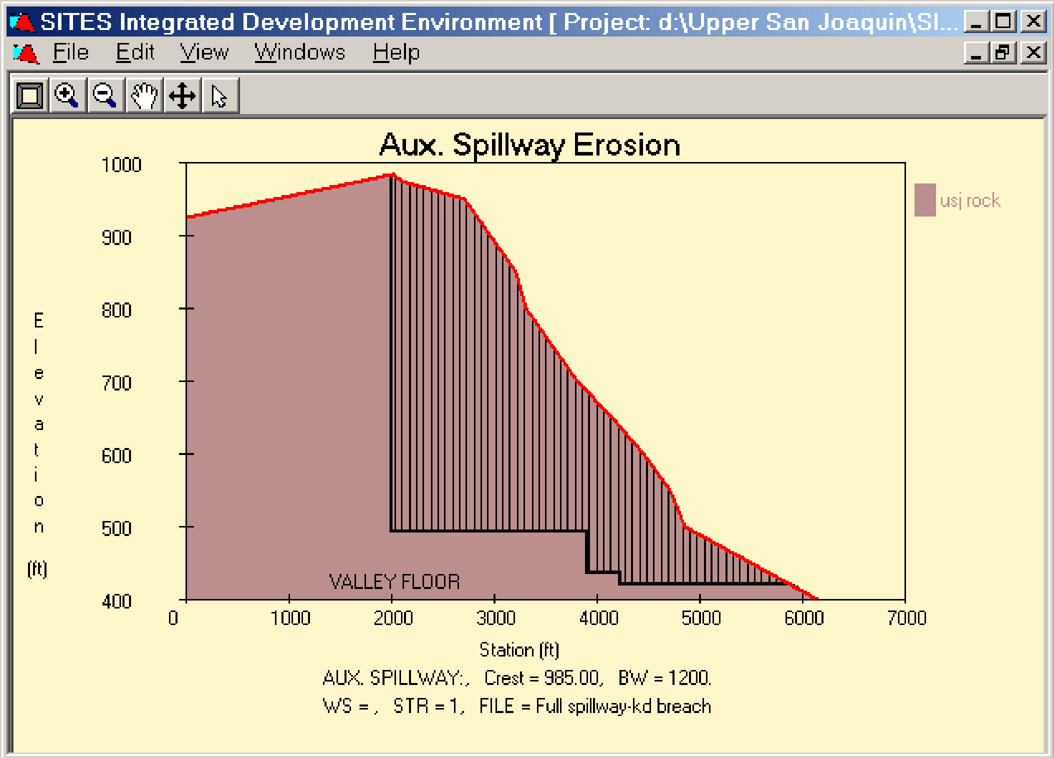

Figure A-13. SITES erosion results with k_d = 2.0 ft/hr/(lb/ft^2). Spillway breached at 558 hrs. Diam. = 153 inches, K_h = 2657, maximum headcut depth = 492 feet.
This run uses input data that represent extreme erodibility compared to expected conditions.

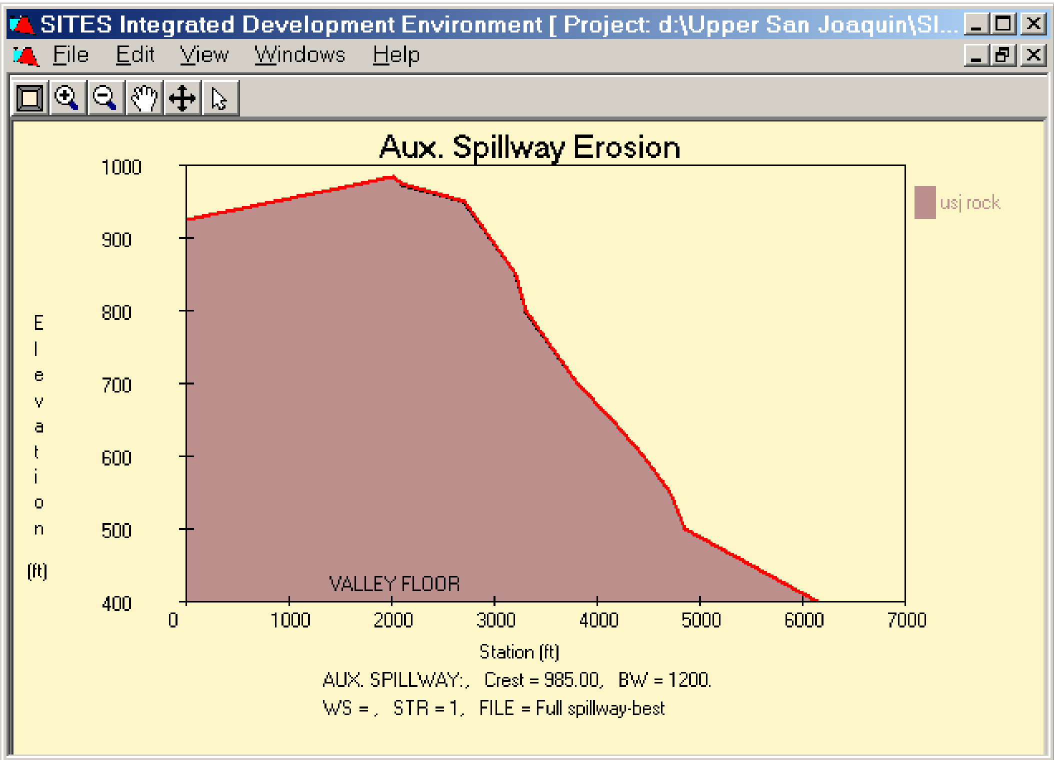

Figure A-14. SITES erosion results with combined best-case material parameters.
Diam. = 204 inches, K_h = 7317, k_d = 0.00057 ft/hr/psf, maximum headcut depth = 1.7 feet.

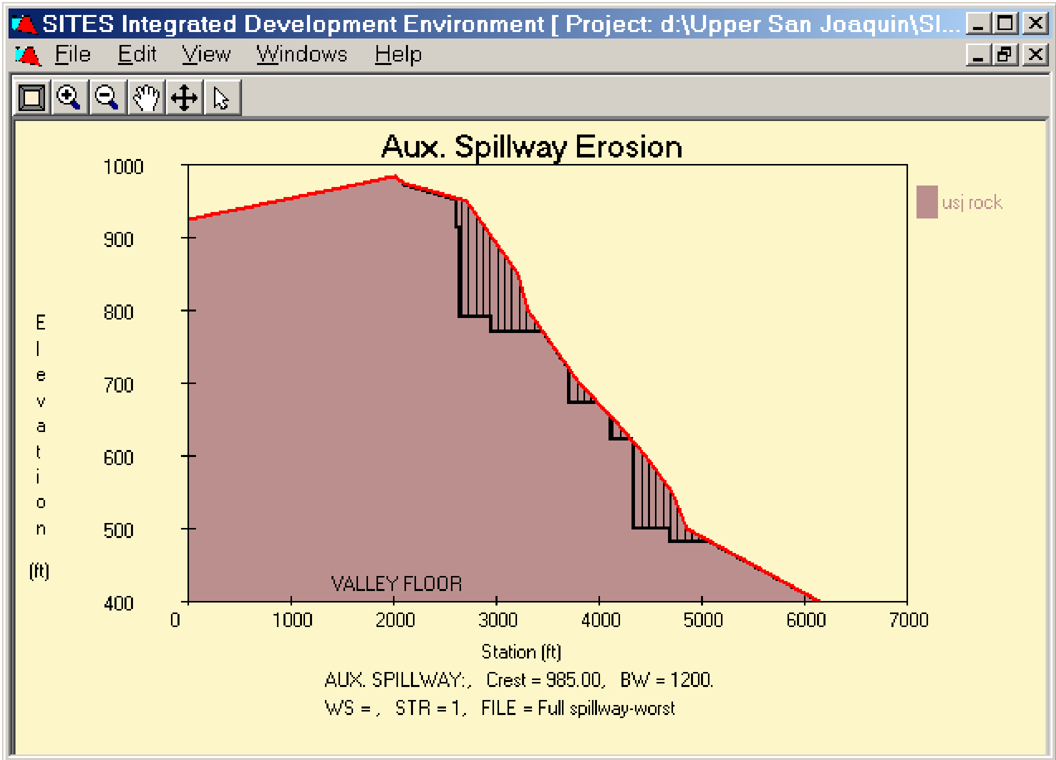

Figure A-15. SITES erosion results with combined worst-case material parameters. Diam. = 102 inches, K_h = 1281, k_d = 0.017 ft/hr/psf, maximum headcut depth = 161 feet.

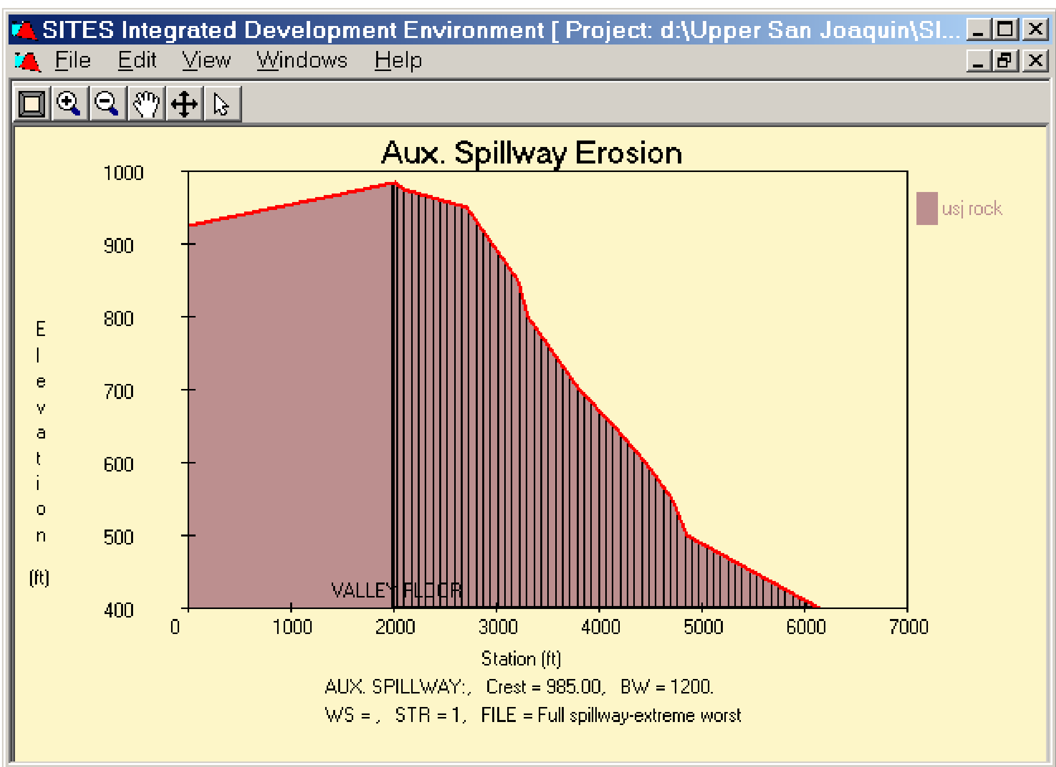

Figure A-16. SITES erosion results with combined extreme worst-case material parameters. Diam. = 12 inches, K_h = 100, k_d = 0.2 ft/hr/psf, maximum headcut depth = 585 feet.
This run uses input data that represent extreme erodibility compared to expected conditions.

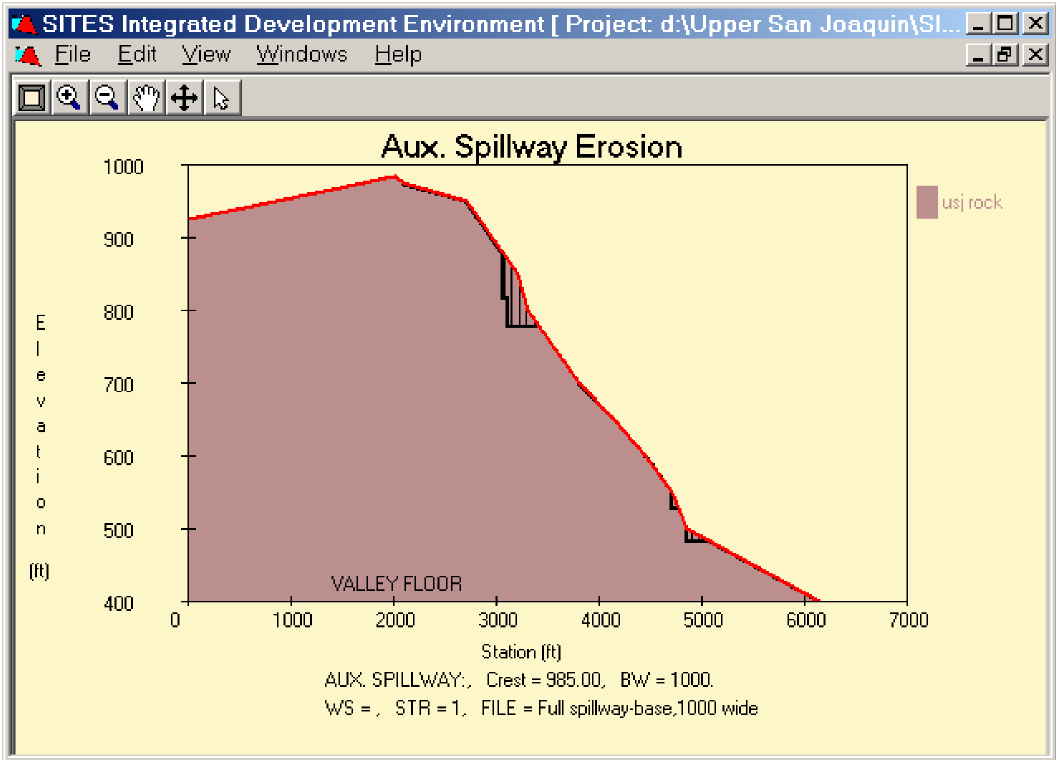

Figure A-17. SITES erosion results with channel narrowed by 200 ft.
Diam. = 153 inches, K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum depth = 90.9 feet.

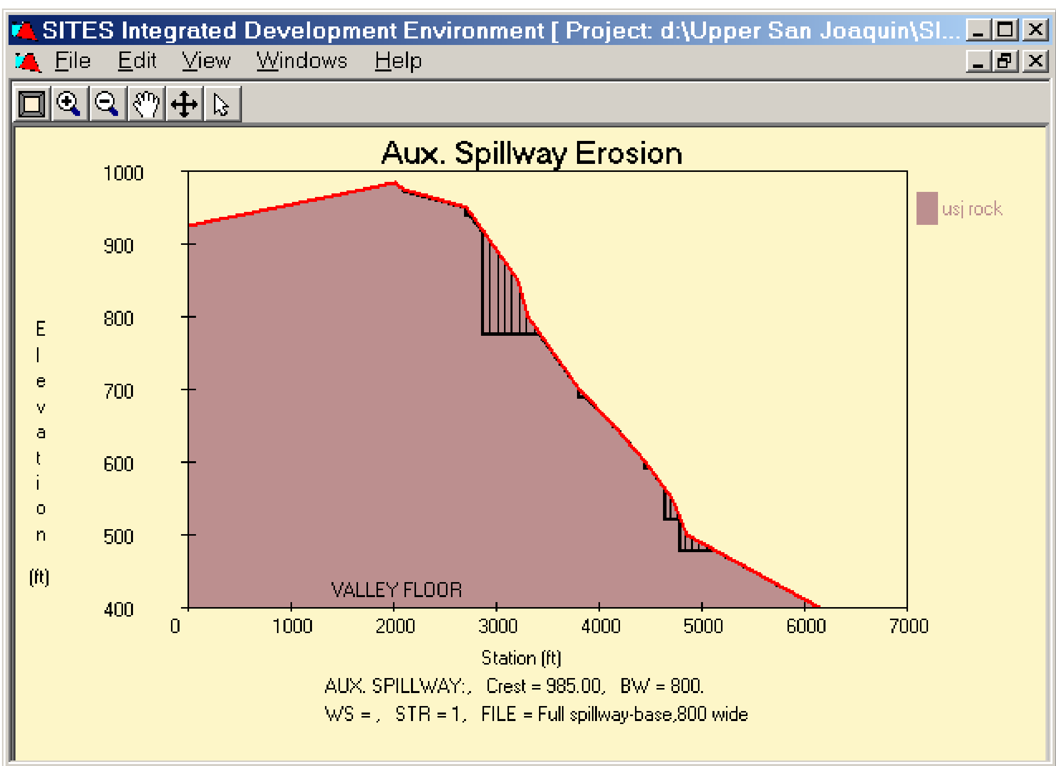

Figure A-18. SITES erosion results with channel narrowed by 400 ft.
Diam. = 153 inches, K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum depth = 140 feet.

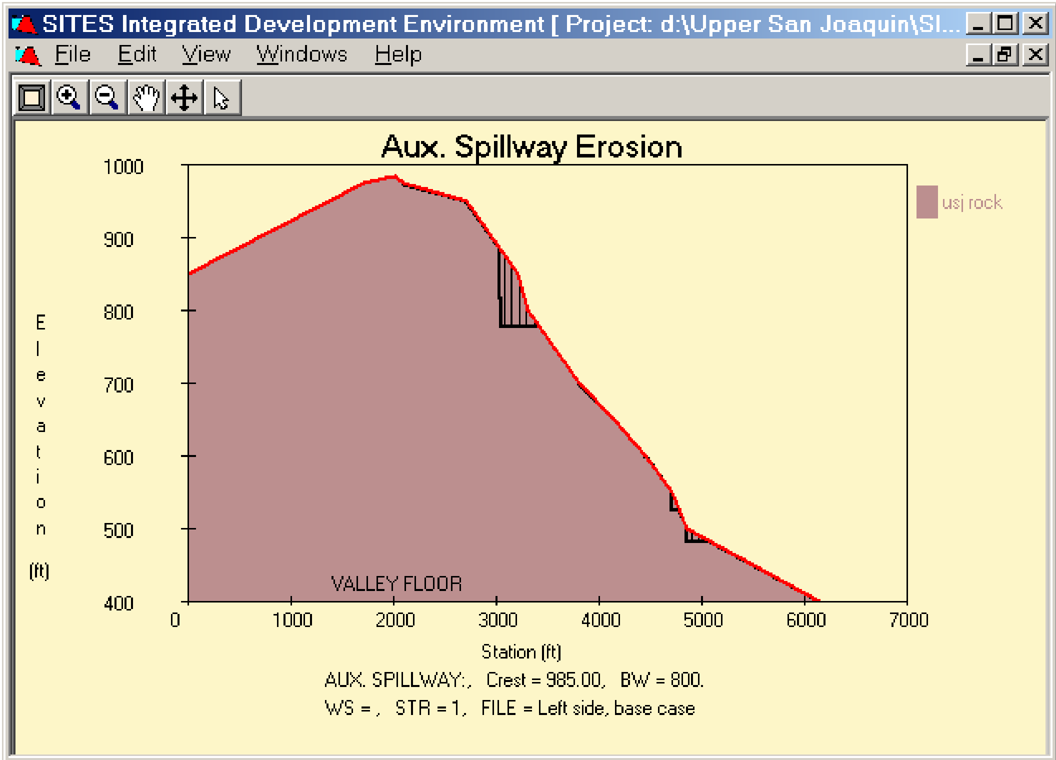

Figure A-19. SITES erosion results considering only flow through the left side of the channel (lowest section of the dual-height ogee crest). Diam. = 153 inches, K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum headcut depth = 104 feet.

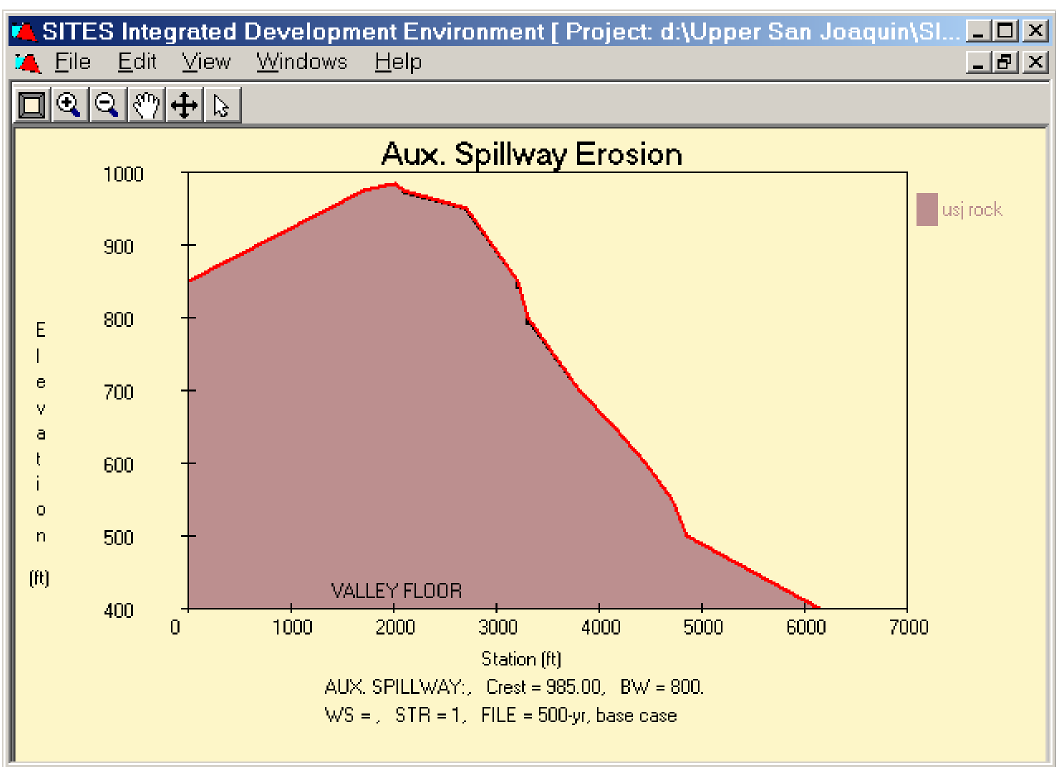

Figure A-20. SITES erosion results for base case during the 500-yr flood. Diam. = 153 inches, K_h = 2657, k_d = 0.0045 ft/hr/psf, maximum depth = 11.7 feet.