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Hydrologic, Hydraulic and Sediment Transport Evaluation for Fossil Springs Dam Site Management Scenario Options

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January 17, 2003

NAU Project # EGR39DV

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1. INTRODUCTION

Fossil Creek is a tributary of the Verde River in north-central Arizona. An ephemeral watercourse above Fossil Springs, Fossil Creek was, historically, a perennial stream below the springs, with a base flow of nearly 43 cubic feet per second (cfs). Until the early 1900's, the steady Fossil Springs base flow, with high concentrations of calcium carbonate, provided for travertine formation in reaches of the perennial stream below the springs. This perennial flow below Fossil Springs was interrupted in the early 1900's, due to construction of the Childs-Irving hydropower facility, which led to the diversion of the base flow.

A key element of the Childs-Irving hydroelectric system is the Fossil Springs diversion dam. Prior to the construction of this diversion, the spring-derived base flow traveled nearly 14 miles to reach the Verde River. Since its construction, the diversion dam has been used to capture and send the majority of the nearly 43 cfs baseflow through a series of flumes, open channels, pressure pipes, tunnels, intermediate diversions and power plants, with discharge at Childs, on the Verde River, upstream of the confluence of Fossil Creek with the Verde. During the past 85 years, streamflow at the Fossil Springs diversion dam in excess of 43 cfs, originating seasonally from spring snowmelt and rain-on-snow events, and summer monsoonal storm events, has flowed over the top of the diversion dam and down the creek.

APS, as owner and manager of Childs-Irving, signed a Settlement Agreement (Agreement in Principle) on November 12, 1999 with a group including American Rivers, Center for Biological Diversity, the Yavapai-Apache Nation, the Northern Arizona Audubon Society, the Nature Conservancy – Arizona Chapter, and the Sierra Club – Grand Canyon Chapter. Key elements of the agreement are as follow:

- Cessation of electrical power generation at Childs-Irving, return of full flows to Fossil Creek and surrender of the project license by December 31, 2004;
- Site restoration to be completed by December 31, 2009.

APS is faced with a variety of challenges related to decommissioning and restoration in the watershed and stream corridor areas impacted by the existing facilities and their operation. *Of primary concern for this evaluation is the impact of dam removal, full or partial, on the geomorphology of the stream channel and the adjoining riparian areas.*

On April 30, 2002, APS (2002) submitted a license surrender application, to the Federal Energy Regulatory Commission (referred to herein as FERC). FERC responded (2002) with a request for additional information.

> In this request for information, FERC (2002, item 2b) sought information on the "staging" and release of sediments that have accumulated behind the Fossil Springs dam for the latter two of the following three possible future management scenarios, which are:

1) no action (dam and sediment upstream of structure remain in place);
2) removal of the top 6 feet of the dam (sediment upstream of dam remains);
3) full removal (sediment upstream of dam remains).

Of concern to FERC (2002) was the timing of sediment release relative to the sensitive life cycle stages of the most important aquatic species – as identified by resource agencies.

> Additionally, FERC (2002, item 10) requested an evaluation of erosion and water surface impacts to the channel environment above the dam for sediment release under management scenarios 2) and 3), above.

In order to address the above two questions posed by FERC, we have completed an evaluation of hydraulics and sediment transport in the area of the Fossil Springs dam site for a variety of hydrologic conditions (inflow hydrographs). We considered a nearly 1,200-ft reach of Fossil Creek in the immediate vicinity of the damsite – approximately 950 ft upstream and 350 ft downstream. These upstream and downstream limits were chosen based on our field observations and to establish suitable locations for establishing the boundary conditions necessary for hydraulic and sediment transport modeling.

Watershed hydrology and design flows were developed in part based on an existing HEC-1 model (Loomis, 1994), with modifications and additions, including preparation of an HEC-HMS model, to meet the specific needs of our evaluation. Hydraulic and sediment transport modeling utilized a HEC-6 model to simulate the response of the sediment wedge behind the dam to hydrologic events and flows of interest for the management scenarios, identified above, involving partial or full dam removal.

Our field investigations and results, analysis, modeling, and interpretation of simulation results are discussed below.

This study was completed with Charlie Schlinger as Principal Investigator and project manager with critical contributions from Sean Welch, Paul Trotta, Justin Ramsey, Jim Janecek and Bill Auberle of Northern Arizona University (NAU). . Greg Gentsch of NAU provided invaluable help in surveying at Fossil Springs. Also, we would like to acknowledge the contributions of NAU College of Engineering & Technology students: Kara Brand, Clayton Ten Eyck, Robin Birnbaum, Seth Teora, Jaikrishna Nair and Cory Helton. Alex Baer, extraordinaire, of NAU supported the effort throughout the entire project.

2. DATA COLLECTION

We initiated our work with a data collection effort focusing on previous investigations. Scientific and engineering studies, including other information pertinent to dam and reservoir sediment mitigation strategies were collected and reviewed.

For an up-to-date review of Fossil Springs area literature, maps, reports and other information, please refer to Monroe (2002) or verde.nau.edu/Research/fossilcreek/index.htm for an online bibliography assembled by Stephen Monroe and Bruce Hooper.

We made use of available existing topographic data, which includes both an unpublished high-resolution topographic survey recently completed by APS in the area of the Fossil Springs dam, and available lower-resolution USGS topographic data, both digital and in print form, for other areas. Additionally, we made use of an old drawing from the time of facility construction that illustrates the dam site topography prior to construction of the Fossil Springs diversion dam.

3. GEOMORPHOLOGY

Certain aspects of the geo- and fluvial morphology of the Fossil Creek area have been addressed in reports and studies by APS (1992), Loomis (1994), Monroe (2000), and most recently by Monroe (2002), and as a result of travertine investigations, e.g., by Matthews (1995), Overby and Neary (1996) and Malusa (1997).

A topographic survey of the reach immediately below the Fossil Springs diversion dam was performed during November 11, and 12th of 2002. The survey extended approximately 350 feet downstream of the dam to define channel morphology and conditions in the immediate vicinity of the project area. The survey data was gathered using electronic distance measurement-capable total station survey equipment. Our topographic survey data were merged with digital topographic data provided by APS (survey completed in August, 2002). These digital data were used to prepare a Triangular Irregular Network (TIN), from which we prepared our composite topographic contour map of the diversion dam site vicinity (Figure 1).

Sediment behind the dam was estimated as part of this project, by APS, using the 1914 and 2002 topographic surveys; the volume was estimated at nearly 25,000 cu. yd. This agrees well with Monroe's (2002) estimate.

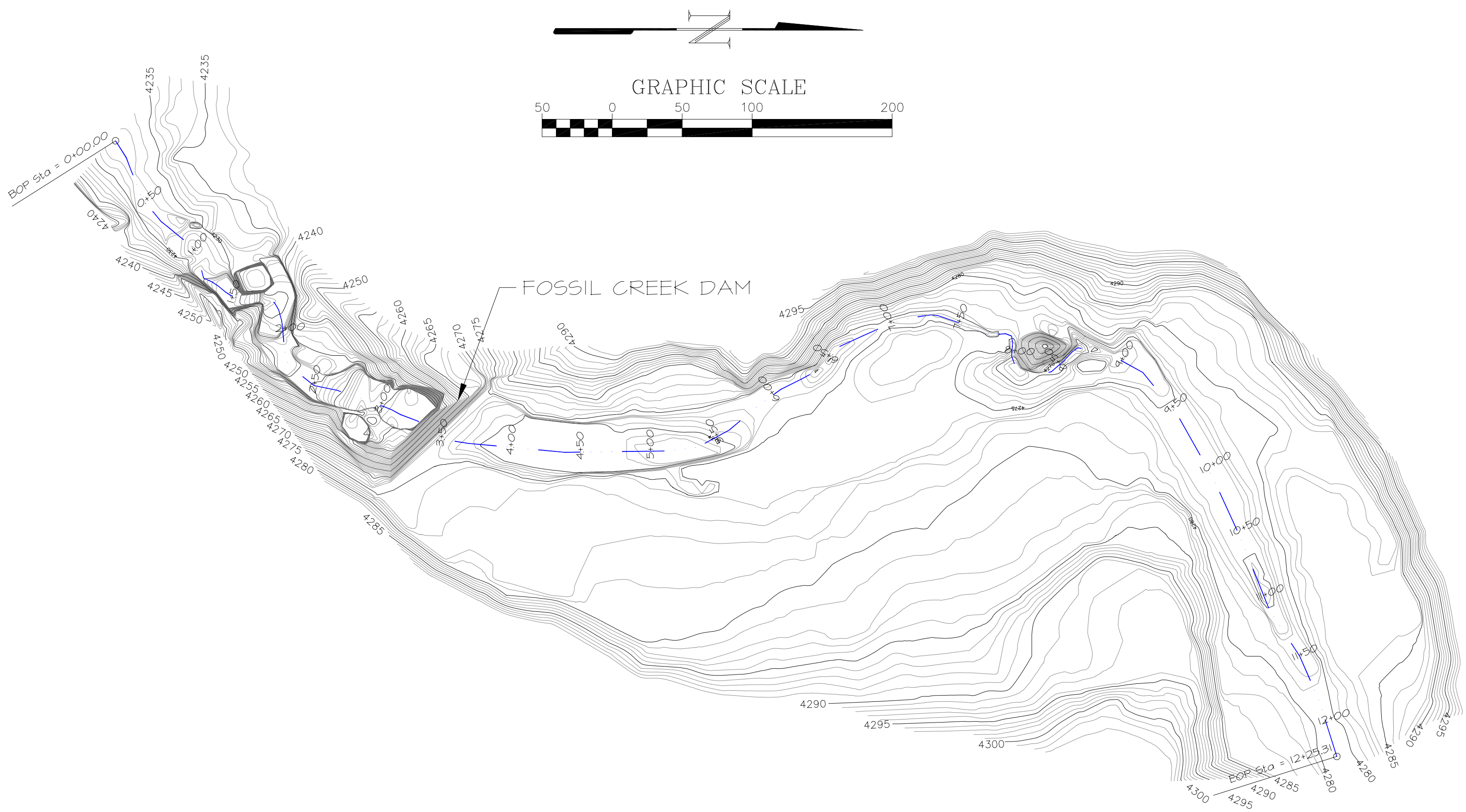

FIGURE 1: FOSSIL SPRINGS DAM SITE COMPOSITE TOPOGRAPHIC MAP

We completed a geomorphic characterization of the project reach discussed above – from nearly 1,100 ft upstream to 400 ft downstream of the dam site – see Figure 1, to identify dominant watershed and channel fluvial processes. This included measurement and evaluation of the reach parameters needed for the hydraulics and sedimentation model (including roughness coefficients and bed and floodplain material gradations). Pebble counts for determining bed and flood plain material gradation were completed for cross-sections indicated on Figure 1 following the procedure of Wolman (1954), with amendment following Kondolf (1997). The gradation data obtained are presented as grain-size distributions in Appendix A (note: cross-sections XS-1A and XS-2A are in the Fossil Springs reach of the channel, upstream of the project reach). Manning's roughness coefficients (*n*) were estimated for these same cross-sections following guidance and methods provided by Chow (1959) and Cowan (1956). Photographs of areas of cross-sections (Figure 1), together with estimated *n* values are provided in Appendix B.

There is unavoidable uncertainty concerning the depth variation of the channel and flood-plain area grain-size distributions, as well as the variation of *n* with channel changes due to erosion or deposition. However, for the purposes of this preliminary evaluation, these uncertainties are not felt to be significant. At a location adjacent to and upstream of the Fossil Springs diversion dam, APS obtained sieve analyses for 5 samples at depths from the surface to 7 ft, with an average of approximately 62% and a range of 13% to 97% passing the #200 (75 micron, or 0.075 mm, opening) sieve. At this location, there was no clear trend in grain size variation with depth.

For the purposes of this study, we have assumed that the approximate grain-size distributions determined for surficial materials are valid for the subsurface.

Qualitative field based analysis allowed the project team to better define the existing conditions of the project reach and identify the channel characteristics within the depositional area immediately above the dam as well farther up the system above the dam's hydraulic influence. The channel morphology is markedly different above the springs, through the springs reach and down to the depositional area. The most pronounced changes in channel morphology result from the gradient of the system and the presence of a lateral floodplain feature.

Starting well above the springs the channel assumes step-pool to riffle-pool type channel morphology. The bed material in this reach is much larger than that evidenced downstream and consists of large cobble, boulders, and bedrock within the active channel. Energy dissipation within this reach is achieved through the form roughness of the large diameter bed material and the step-pool type bed forms. Little deposition of fine-grained material was found in this reach except at locations well out of the active channel where flood stage velocities decrease and fine sediments fall out of suspension.

The intermediate reach through the springs down to the area of deposition influenced from the dam is characterized by a lowering of valley gradient and a commensurate reduction in the slope of the natural grade control. This is evidenced by the step-pool morphology transitioning into riffle-pool type bed features. This reach exhibits well-developed pools in a consistent interval, separated by the riffle features. The floodplain increases laterally in this reach with a general widening of the valley. The floodplain in this area appears to be flooded more frequently by flows of bankfull and above and there is a greater accumulation of fine sediments deposited across the floodplain feature.

The dam influences sediment deposition for approximately 680 feet upstream at an average stream gradient of approximately 0.14%. As gradient decreases sinuosity increases, and although the channel runs closely along the toe of slope on valley right, increased sinuosity is observed. The floodplain through this reach consists of a broad, reasonably level feature that is inundated frequently by above bankfull flows.

4. HYDROLOGY

Hydrological input for the sediment transport analysis was required in the form of discretized stream flow hydrographs. Because of time constraints and the availability of an existing hydrological model, we decided to build on this existing model.

4.1 EXISTING HEC-1 MODEL

The U.S. Forest Service (USFS), in 1994, completed a hydrologic study of the portion of the Fossil Creek watershed tributary to Fossil Springs (Loomis, 1994). That study was completed as part of the U.S. Forest Service response to APS' (1992) application to FERC for re-licensing. The USFS study used the U.S. Army Corp of Engineers (USACE) Hydrologic Engineering Centers (HEC) Flood Hydrograph package HEC-1 (U.S. Army Corps of Engineers, 1998a). The application of HEC-1 follows an established engineering standard practice and uses methods accepted by regional and state agencies. HEC-1 is designed to simulate the surface runoff response of a river basin to precipitation by representing the basin as an interconnected system of hydrologic and hydraulic components (U.S. Army Corps of Engineers, 1998a). The model is a deterministic event-based model that transforms excess precipitation into a runoff hydrograph. This transformation is achieved by using either historical or design rainfall and transforming it to a runoff hydrograph by unit hydrograph techniques (Chow et al., 1988).

Loomis' (1994) model was developed as follows. A rainfall runoff model was applied to calculate differences in peak flow. Peak flows were computed for Fossil Creek at Fossil Springs following a method described in the Arizona Department of Transportation (ADOT), Highway Drainage Design Manual (ADOT, 1993). This method employs a hypothetical rainfall distribution based on depth-duration-frequency statistics derived from the NOAA Atlas 2, Volume VIII and less than 1-hour storm durations from ADOT (1993). Rainfall losses were estimated by combining initial abstraction with the Green and Amp infiltration equation. The Clark unit hydrograph procedure in the HEC-1 model was used to convert excess rainfall into sub-basin outflow. The normal depth method was used to route the flood flows from the sub-basins within the watershed. The contributing watershed for Fossil Springs was divided into six sub-basins. The sub-basins were delineated by separating areas at major junctions in stream order, land-use, vegetation, hydrologic soil group and topographic relief.

A hard copy of the HEC-1 study (USFS, Loomis, 1992) was obtained for use in this analysis. The USFS study modeled the 2-, 5-, 10-, 25-, 50- and 100-yr 24-hr events for 3 different conditions of the watershed identified as degraded, current and natural. The variation of watershed condition, as modeled, was limited to a change in the saturated hydraulic conductivity (K_{sat}) used within the Green and Ampt model of infiltrative losses. The variation of modeling parameters for the differing return periods was confined to the use of the matching depth-duration-frequency precipitation data and an adjustment to the time of concentration (T_c) for each basin within the model. The USFS study derived T_c values from an ADOT-recommended empirical equation developed for desert/mountain conditions (ADOT, 1993). These T_c values were then ascribed to the 100-yr events.

Subsequent to their estimation of T_c, a T_c adjustment recommended in the ADOT highway drainage design manual was implemented. This increases the T_c for events more frequent than the 100-yr event. A justification for this is the slower channel velocities associated with lower flows, which result from smaller more-frequent storm events. A new HEC-1 model was built using the input parameters provided in the USFS model for the 2-yr event in the current hydrologic condition. The 2-year event is often associated with a bank-full condition that is generally considered the most significant channel-forming event over extended periods. The new HEC-1 model faithfully reproduced the USFS model flows for this event and watershed condition. Our new HEC-1 model input data was subsequently imported into HEC-HMS (U.S. Army Corp of Engineers, 2001a) and this new HEC-HMS model became the basis for hydrologic investigations conducted in this study.

4.2 HEC-HMS MODEL

After the HEC-1 model was completed and verified, the HEC-1 input file was imported into the USACE HEC Flood Hydrograph package HEC-HMS and the input data were appropriately modified.

The HEC-HMS software package supersedes the HEC-1 Flood Hydrograph Package. The HEC-HMS program contains most of the watershed runoff and routing capabilities of HEC-1. With equivalent input data, there can be some variation in output between software versions. Therefore, some differences in output between the USFS model and our HEC-HMS model were expected.

After careful consideration of the goals of this study, we concluded that the modified T_c values for the 2-year event as developed in the USFS study would be used consistently for the development of all the hydrographs needed in the sediment studies. These increased T_c values for the more frequent events likely results in lower flows than would be obtained by using smaller values of T_c. Realistic channel velocities were essential to the sediment transport studies. Using the T_c associated with the bank-full condition, it was expected to provide the most appropriate flows and consequently the most appropriate velocities in the sediment analysis. This study showed lower peak flows for the 50 and 100-year events than were reported in the USFS study. The differences noted approached a factor of two for the 50- and 100-yr events but considering the high variability in hydrologic predictions for un-calibrated models this is reasonable.

Six hydrologic conditions, incorporating the 43 cfs base flow condition, were analyzed: 2-yr 3–hr; 2-yr 12-hr; 10-, 50- and 100-yr 24-hr storms, and, the base flow alone. The point of concentration for all precipitation events was at the Fossil Springs dam, cross-section 3+50 (Figure 1).

Table 1 offers a comparison of USFS HEC-1 model output (Loomis, 1994) with our HEC-HMS model output for peak flows on Fossil Creek. Note that our model output data were developed using a 50% hydrograph peak advancement (discussed below), felt to be appropriate for spring cyclonic storms in the Mogollon Rim area.

TABLE 1: FOSSIL SPRINGS DAM SITE PEAK FLOWS

	USFS HEC-1 Model	NAU HEC-HMS Model
Recurrence Interval (yr)	Current (cfs)	Spring Cyclonic (cfs)
2	1026	1077
5	2257	2317
10	3737	3235
25	6034	4539
50	8998	5609
100	13531	6743

The watershed is divided into six sub-basins with a total combined area of 54.8 square miles. The last sub-basin, Fossil Springs, contains the springs. The springs discharge a constant 43 cfs. The 43 cfs base flow was added to the Fossil Springs sub-basin using the constant monthly base flow method, available in HEC-HMS.

The reaches between the Tin Can Draw sub-basin and Mud Tanks Draw sub-basin and the Fossil Springs sub-basin were modeled using the Muskingum-Cunge 8 Point routing method (Chow et al., 1988).

Three National Climatic Data Center (NCDC) precipitation gages were reviewed to identify the average periods within a given year where precipitation peaks would likely contribute discharge. This information showed that the average yearly precipitation peaks occurred in March and August; this is consistent with information provided by the Coconino National Forest's Terrestrial Ecosystem Survey (TES).

The March storms are represented by longer-duration frontal type events and the August storms are short duration and high intensity local summer thunderstorms. These represent the two types of storm events that likely contribute to high seasonal storm flows.

Seasonal variations in storms are an important component to the hydrology of the system. To distinguish the characteristics of seasonal storm events, the peak center function in HEC-HMS was utilized to shift the storm peak to different times within the storm duration. The 2-yr 1-, 2-, 3- and 6-hr events were modeled as the summer (August) monsoon events with a peak advancement coefficient of 0.25 (25%). This shifted the peak intensity of the storm events towards the start of the event with a longer trailing, or receding limb. This technique was used to attain a "flashier" type storm that is of high intensity with a shorter duration. The general or winter/spring cyclonic storms were modeled with the 6-, 12-, and 24-hr duration storms. An advancement coefficient of 0.5 (50%) was used for these storms to affect a more centralized storm peak within the given duration. For comparison of the summer event with the winter/spring cyclonic event, the 6-hr storm was used with a consistent storm total depth but with a change in storm advancement coefficient (Welch, 2000). Tables 2 and 3 provide a summary of peak flows for these events.

TABLE 2: SUMMER MONSOON EVENTS

Duration (hr)	Return Period (yr)					
	2	5	10	25	20	100
1	93.38	604.49	1164.40	1978.20	3262.50	3357.90
2	215.99	882.29	1523.30	2475.60	3262.50	4110.10
3	290.98	1073.70	1724.70	2713.60	3554.50	4446.70
6	448.12	1367.30	2104.20	3201.70	4068.40	4999.00

TABLE 3: WINTER /SPRING EVENTS

Duration (hr)	Return Period (yr)					
	2	5	10	25	20	100
6	655.17	1644.10	2499.60	3656.40	4587.40	5579.60
12	899.55	2026.30	2925.60	4143.50	5154.50	6224.00
24	1077.40	2317.30	3235.40	4538.90	5609.30	6742.60

The HEC-HMS simulations utilized a time step of five minutes and a total duration of 48 hours. The 48-hr period provided for a hydrograph with a descending member that encountered the 43 cfs base flow condition.

For the purposes of this preliminary evaluation of sediment transport, we elected to use the 2-yr 3-hr storm to simulate summer monsoon events that give rise to a bank-full condition (above the dam site) and the 2-yr 12-hr storm to simulate late winter to early spring precipitation event, with flow that exceeds the bank-full condition. Additionally, we used the 10-, 50- and 100-yr 24-hr storms to simulate the effects of low-frequency high-magnitude flows. Continuous and discretized hydrograph records, incorporating the 43 cfs base flow condition, for the 2-yr 3-hr; 2-yr 12-hr; 10-, 50- and 100-yr 24-hr storms appear in Figures 2 through 6.

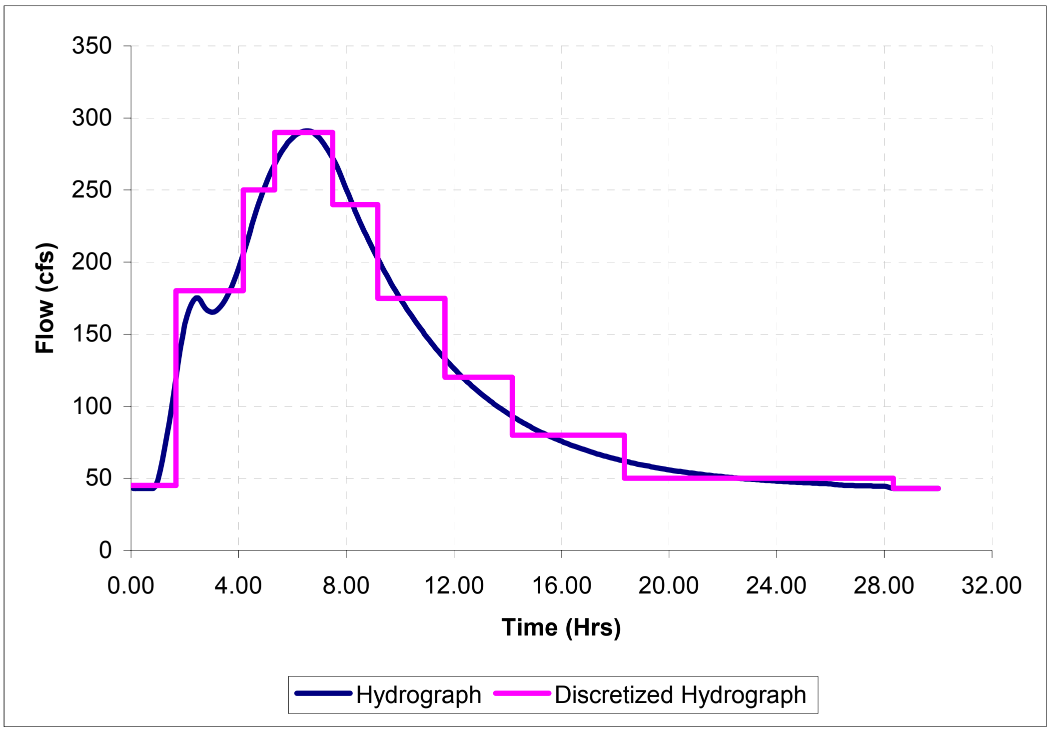

FIGURE 2: 2-YEAR 3-HOUR HYDROGRAPH

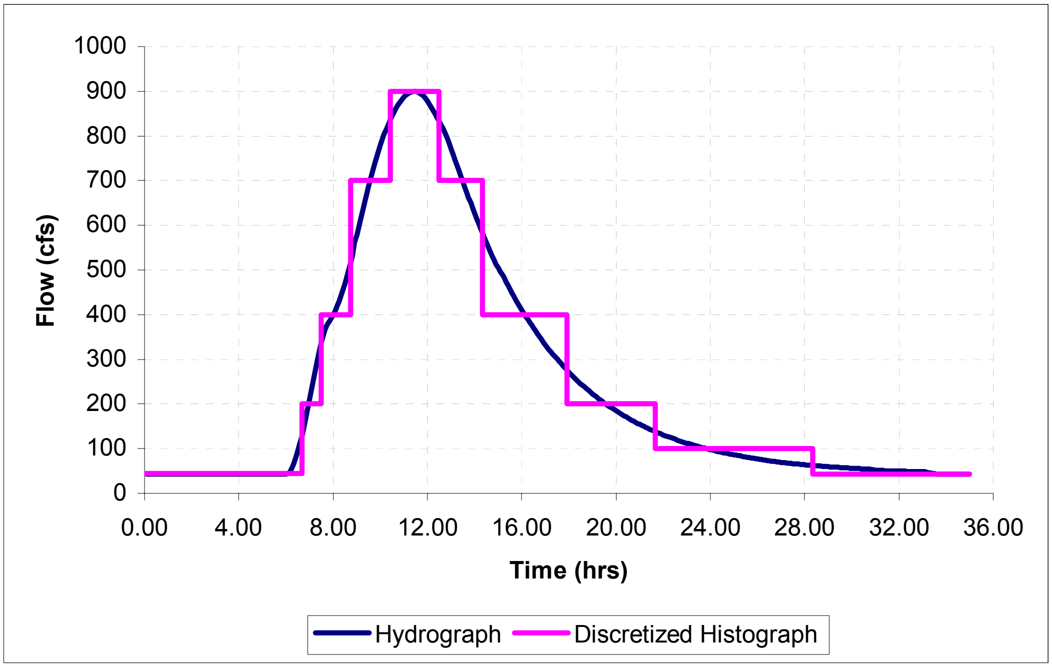

FIGURE 3: 2-YEAR 12-HOUR HYDROGRAPH

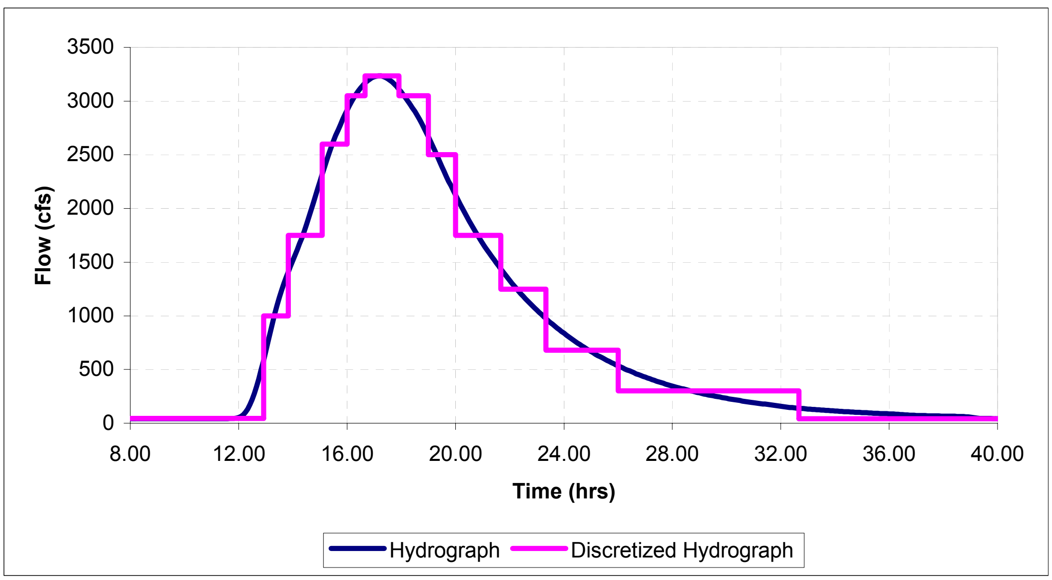

FIGURE 4: 10-YEAR 24-HOUR HYDROGRAPH

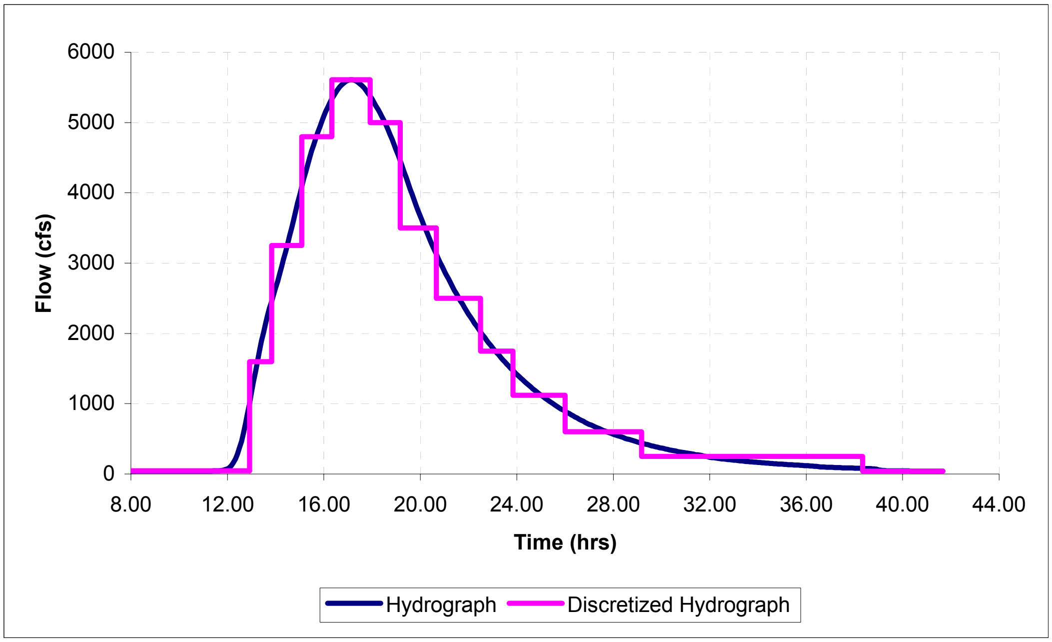

FIGURE 5: 50-YEAR 24-HOUR HYDROGRAPH

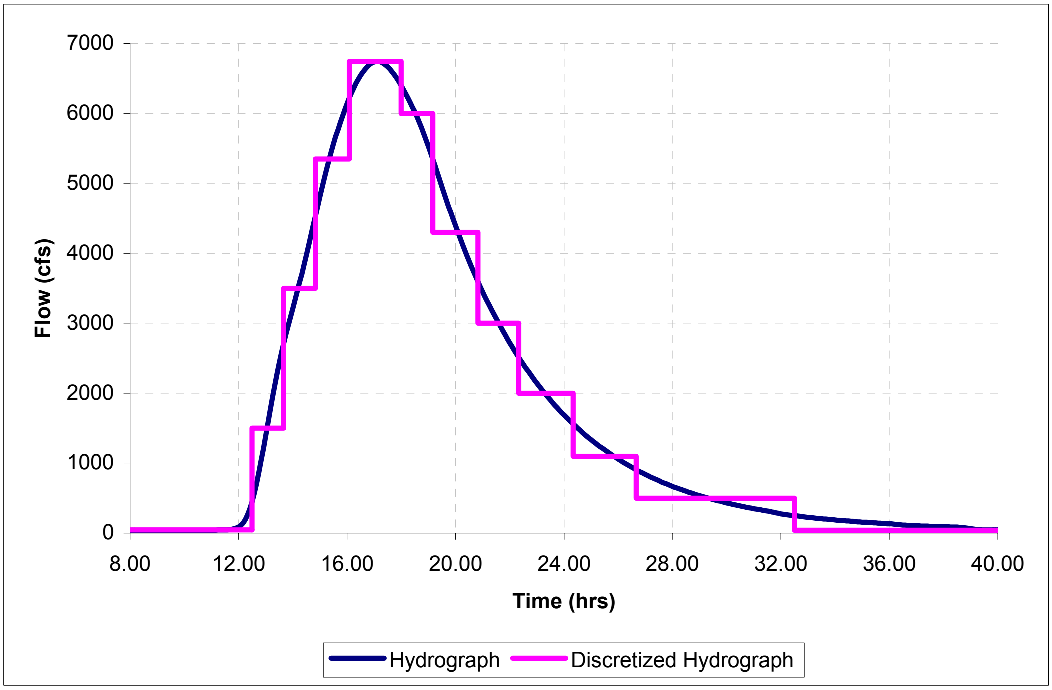

FIGURE 6: 100-YEAR 24-HOUR HYDROGRAPH

5. <u>HYDRAULICS AND SEDIMENT TRANSPORT</u>

5.1 INTRODUCTION

The U.S. Army Corps of Engineers Scour and Deposition in Rivers and Reservoirs model HEC-6 was chosen for this project. HEC-6 (HEC, 1990, 1998b) is a one-dimensional movable boundary open-channel flow and sediment transport model designed to simulate changes in river profiles due to scour and deposition over fairly long time periods (typically years, although applications to single flood events are permissible).

In HEC-6, the continuous flow record is broken into a sequence of steady flows of variable discharge and duration. For each flow, a water surface profile is calculated, thereby providing energy slope, velocity, depth, etc. at each cross section. Potential sediment transport rates are then computed at each section. These rates, combined with the duration of the flow allow for a volumetric accounting of sediment for each reach. The amount of scour or deposition at each section is then computed and the cross section shape adjusted accordingly. The computations then proceed to the next flow in the sequence and the cycle is repeated beginning with the updated geometry. The sediment calculations are performed by grain size fraction thereby allowing for the simulation of hydraulic sorting and armoring.

Data input parameters required for the application of the HEC-6 movable bed simulation includes geometric, sediment, hydraulic and hydrologic data (U.S. Army Corps of Engineers, 1990, 1998b). These data are input as ‘records’, the names and parameters of which are discussed below.

5.2 STREAM GEOMETRY INPUT

5.2.1 CHANNEL GEOMETRY: GR RECORD

The format of the HEC-6 input GR record is similar to that of HEC-2 and the hydraulics computations utilize the same step-backwater computational scheme. We first created a model based on the composite reach geometry. The composite topography allowed us to develop the cross-sections and reach lengths necessary for the geometric definition of the model. Cross-section locations were selected based on changes in channel morphology, expansion and contraction, and at areas where more-detailed descriptions of channel and floodplain features were required. Please refer to Figure 7.

Overbank and channel lengths were also prescribed to account for meandering and areas of increased sinuosity. This included prescribing increased channel length on the outside of meanders to better represent the path of the center of mass of the discharge during overbank flooding events. Model cross-section locations are shown in Figure 7.

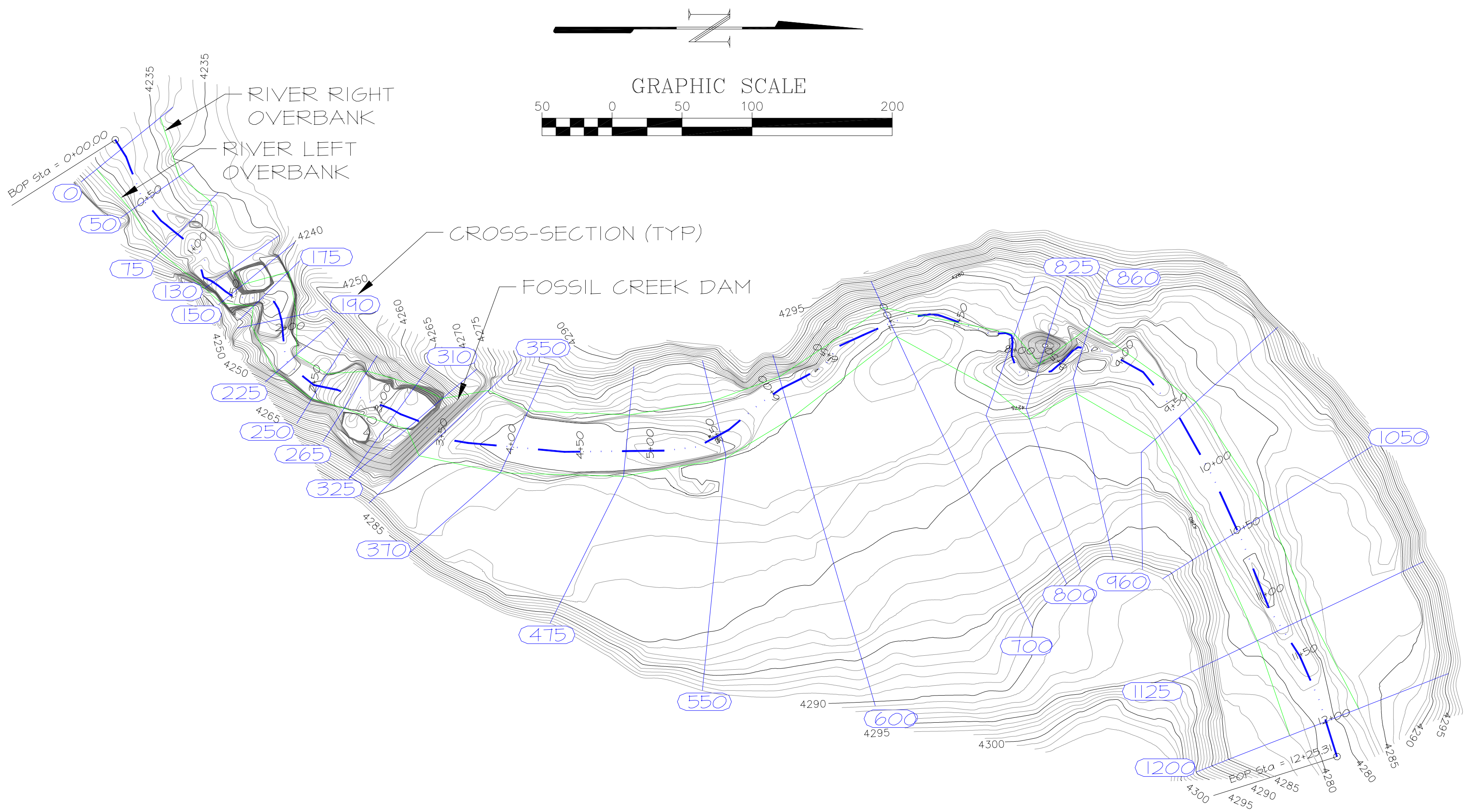

FIGURE 7: HEC-6 CROSS-SECTION LOCATIONS

5.2.2 ROUGHNESS COEFFICIENTS: NC RECORD

Manning's roughness coefficients for each cross-section were developed in the field using the method developed by Cowan (1959) which accounts for variations in channel features including degree of meandering, bed roughness, influence of vegetation, and obstruction to flow. This information is then utilized to modify a base "*n*" value to more accurately develop the friction parameter. The field derived roughness coefficient was reviewed and adjusted by comparing against reference values (e.g., Barnes, (1967); Phillips and Ingersoll, 1998; Chow, 1959). Photos of the channel and field notes were compared to information provided in these manuals and reference tables. Roughness coefficients varied from $n = 0.06$ in the upper stream reaches, up to $n = 0.11$ in the heavily vegetated and boulder covered floodplain, with $n = 0.05$ in the scoured bedrock-controlled reaches below the dam. Reference photographs used for estimation of roughness coefficients are in Appendix B.

5.2.3 EXPANSION AND CONTRACTION COEFFICIENTS: NC RECORD

The expansion and contraction coefficients used in this study were varied for different locations along the modeled reach, respectively. These coefficients were evaluated based on channel morphology, photographs taken from the site, and comparison with values provided in the HEC-2 reference manual. All cross-sections within the model except those located in the bedrock-controlled area downstream of the dam were modeled with an expansion coefficient of 0.3 and contraction of 0.1. These values are indicative of very gradual cross-sectional transitions within the stream channel. The reach below the dam was modeled with an expansion coefficient of 0.4 and contraction of 0.2 to better account for the abrupt narrowing and widening of the channel due to the bedrock control in this area.

5.3 SEDIMENT DATA

5.3.1 BED MATERIAL GRADATION DATA: PF RECORD

Bed material sampling using the method proposed by Wolman (1954) was utilized to develop representative gradation curves for both the active channel and floodplain features throughout the project reach. Thirteen transects were identified as areas that provided reach representative channel conditions and bed material samples. All cross-sections included at least 100 discrete measurements in the active channel with an additional 100 counts performed at the sections that were identified for an additional floodplain count. The field data was plotted for both cumulative and incremental distributions (Appendix A) with percentage finer for several classes identified for input on the HEC-6 PF Record. The model sections that include floodplain counts were entered as cumulative gradations incorporating both the floodplain and active channel data.

5.3.2 DEPTH OF SEDIMENT: HD AND H RECORDS

HEC-6 requires that the sediment control volume be established through the model at each cross-section location. This information is input on the H & HD records to specify the depth or a base elevation of sediment at a given station. The model then utilizes this input to vertically constrain the scour computations. The 1914 pre-dam channel condition was provided by APS in digital format along with the 2002 APS survey above the Dam. The file with this information was originally utilized for end area computations to identify sediment volumes behind the dam. This file provided the base data for the generation of a digital terrain model for both the 1914 topography and the 2002 APS Survey. We utilized these models to develop thalweg profiles for both the historical condition in 1914 and the current condition 2002. The profiles were compared and the vertical separation was determined at each of the model cross-sections. This method provided us with estimates of the vertical accumulation of sediment, by station, upstream of the dam. The dam and the bedrock-controlled reach downstream were modeled with HD set to zero to constrain the simulations to deposition only at these locations.

5.3.3 UPSTREAM BOUNDARY CONDITION: LQ, LT, LF RECORDS

Several bed-sampling transects were performed above the area of deposition behind the dam, where the channel transitions into riffle-pool type channel morphology. HEC-6 requires the determination of a "supply reach" rating curve.

Sediment discharge measurements are not available for Fossil Creek, which necessitated the development of an upstream boundary condition utilizing sediment transport theory. The HEC-6 User's Manual (U.S. Army Corps of Engineers, 1998b) suggests a supply reach upstream of the study reach, with slope, velocity, width, and depth typical of the reach that is transporting the sediment into the study area and that is in approximate equilibrium. The model cross-section located at section 12+00 (Figure 7) was utilized for this purpose.

The rating curve was synthesized for a full range of discharges up to and including the 100-yr peak of 6743 cfs. The Meyer-Peter and Mueller (MPM) sediment transport relation (Meyer-Peter and Mueller, 1948) as implemented by HEC-6 was utilized to synthesize the rating due to its applicability and calibration to coarse-grained materials. We used the U.S. Army Corps of Engineers SAM program (U.S. Army Corps of Engineers, 2001) to develop the necessary input for the HEC-6 LF record. The input requirements include the percentage of total sediment discharge per flow subdivided by fraction in each sediment grain size class. The HEC-6 model then utilizes this sediment-discharge rating curve to compute inflowing sediment loads per variable discharge conditions. The rating values generated with SAM are provided below in Table 4.

TABLE 4: UPSTREAM BOUNDARY SEDIMENT RATING CURVE

	Peak Discharge cfs	MPM(1948) HEC-6 tons/day
Base Flow	43	1185.05
2 Year 3 Hour	291	5578.46
2 Year 6 Hour	655	16990.01
2 Year 12 Hour	1077	34055.49
5 Year 24 Hour	2317	80413.37
10 Year 24 Hour	3235	114486.1
25 Year 24 Hour	4539	167901.02
50 Year 24 Hour	5609	213338.8
100 Year 24 Hour	6743	253045.58

Field observations at the project site indicate that very little, if any, sediment transport was occurring at the 43 cfs base flow condition. For the objectives of our simulations, the sediment discharge rating for 43 cfs was set to 0.0, to approximate observed conditions and compensate for the fact that base flow originates in the project reach, rather than above.

5.3.4 THE EXNER EQUATION: I1 RECORD

The sediment continuity equation iteration scheme must be defined by the user for mobile boundary simulations. The model results are sensitive to the choice of this variable and multiple sensitivity runs were conducted to isolate the appropriate value. Ultimately this value was set to allow HEC-6 to determine the appropriate number of computational iterations.

5.3.5 TRANSPORT EQUATION I4 RECORD

HEC-6 provides the user with a number of different sediment transport equations. Selection of the appropriate equation for modeling the disposition of the impounded sediment was facilitated with the use of the U.S. Army Corps of Engineers SAM (U.S. Army Corps of Engineers, 2001b) package. This program accepts the input of hydraulic and sediment parameters representative of the projects reach and screens transport equations for the appropriate match. The equation identified for the lower gradient reach of depositional influence was the Ackers-White relation as implemented by HEC-6. This function is derived from the concept of stream power, which incorporates a dimensional analysis technique that expresses mobility and transport in terms of dimensionless parameters.

5.3.6 HYDRAULIC WEIGHTING FACTORS: I5 RECORD

HEC-6 provides two schemes for the definition of hydraulic weighting factors. Scheme 1 was utilized during the base flow simulation due to its stability at large values of time discretization. This was appropriate for the 43 cfs simulation over a 9-month period for the 6-foot and 20-foot removal management scenarios. This 9-month period for low flow simulations was chosen as the period most likely to represent the longest time between the summer and the winter-spring runoff events. Scheme 2 was applied for runoff events modeled using the hydrograph data as input. This option, while unstable at large time intervals, is more sensitive to bed changes. Time discretization for each portion of the discretized hydrographs was subdivided 100 times to enhance Scheme 2 computational stability.

5.4 HYDROLOGIC INPUTS

Hydrologic information obtained from the HEC-HMS simulations (Section 3) was utilized to provide the discharge inputs into the HEC-6 model. The hydrographs were discretized into a histogram of variable time steps to facilitate input into HEC-6. See Figures 2 thru 6. Each hydrograph was reduced to between 10 and 13 variable time intervals, each with an associated discharge value.

5.4.1 DOWNSTREAM BOUNDARY CONDITION: $ RATING

A downstream boundary condition must be established for the computation of subcritical step-backwater computations. A rating curve of stage vs. discharge can be utilized for this purpose. Normal depth computations were used to develop the stage-discharge relationship at station 0+00 (see Figure 7) for the HEC-6 downstream boundary condition. The rating table for Station 0+00 is provided in Figure 8.

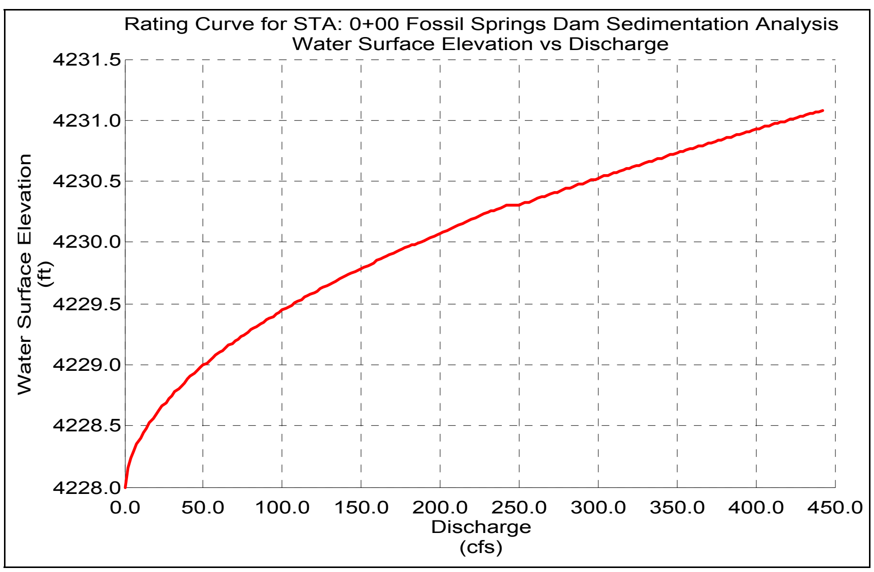

FIGURE 8: RATING CURVE AT DOWNSTREAM BOUNDARY

5.4.2 FLOW SIMULATION INPUT: X RECORD

HEC-6 requires that the time step for the hydrologic data be represented as a fraction of a day for day-or-less simulations or as the number of days for extended period simulations. The total duration in days must also be specified to define the total time frame for computation. Steady flow analysis was performed for the base flow condition by utilizing the X Record to identify the length of the simulation (270 days – 9 months) and the interval time step utilized for the computations. This technique was also used for simulating the hydrograph time steps with the flow duration for a given discharge increment specified as a fraction of day with the fraction being further subdivided to add computational iterations.

As stated above, the sediment discharge and model stability are dependent on time step selection. Each of the simulations for each of the management scenarios followed a process of time step interval adjustment to identify stability in the HEC-6 simulation results. For the variable-flow storm event hydrographs, stability in the computational process was achieved by subdividing each hydrograph time step into 100 subdivisions (Scheme 2). The time step for the simulation of the constant 43 cfs base flow was 54 days (Scheme 1).

5.5 MODEL IMPLEMENTATION

Implementation of the model included several procedural steps to verify the accuracy and stability of the sediment transport computations.

5.5.1 HYDRAULICS EVALUATION

The first step in the HEC-6 simulation process was to perform a fixed-bed analysis of the system to evaluate the performance of the base hydraulics model. This process was performed by running the input file as a HEC-2 simulation. Model results were evaluated for errors and warnings then the input file was imported in the U.S. Army Corps of Engineers River Analysis System HEC-RAS Version 3.0.1 (U.S. Army Corps of Engineers, 2002). Figure 9 shows the profile results of a HEC-RAS simulation for the 2-yr 3-hr discharge of 291 cfs. The hydraulic and energy grade lines are plotted on the profile as well as inundation areas. EG is energy grade line, LOB is left overbank, ROB is right overbank, CRIT is water surface profile at critical depth, WS is water surface profile, and GROUND is the elevation along the thalweg.

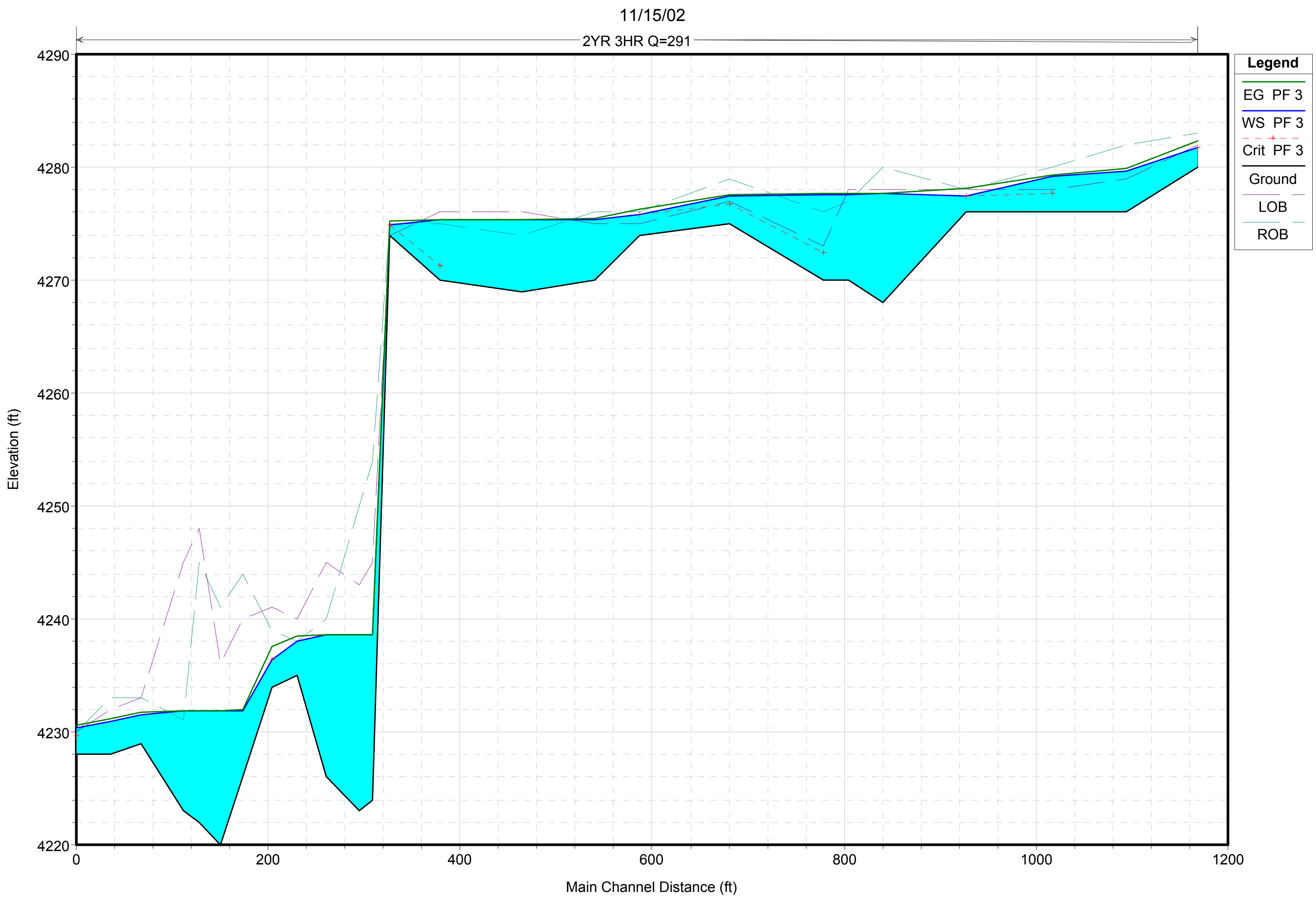

FIGURE 9: HEC-RAS PRESENTATION OF HEC-6 FIXED-BED RESULTS

5.5.2 SEDIMENT TRANSPORT SIMULATIONS

The three management scenarios identified for the Fossil Springs dam:

1) dam remains in place;
2) top 6 ft of dam is removed;
3) dam is completely removed.

Scenario 1 utilized ground geometries representing the existing condition at Station 3+50, located at the dam crest. The model for this no-action scenario was evaluated under the 43 cfs base flow condition to aid in the selection of the appropriate sediment transport equation for the depositional area upstream of the dam and to verify hydraulic effects within the existing channel. Scenarios 2 and 3 served as the basis for the HEC-6 sediment transport simulations. Subsequent simulations of scenario 2 utilized modified geometry at Station 3+50. This was accomplished by modifying the GR Record to account for a six-foot decrease in the maximum section of the structure. For scenario 3, the complete removal of the dam was simulated by reducing the GR-Record by 20 feet. These methods provided a more realistic representation of the ground geometries at the dam and accounted for a tapering of the sediments immediately upstream to Station 3+70.

Seasonal variability and fluctuations of sediment discharge were modeled by utilizing the different two-year hydrographs developed with HEC-HMS (Section 3). The 2yr 3-hr storm was modeled two capture sediment transport effects typical of a summer, convective type thunderstorm event. The 2-yr 12-hr hydrograph simulated a longer duration and more centrally located peak representative of late winter-early spring cyclonic type storm cells. Modeling these hydrographs provided a process to more accurately capture the two predominate periods of precipitation occurring in March and August, respectively. Figure 10, below, shows the months of highest average precipitation as measured by gages near the project site.

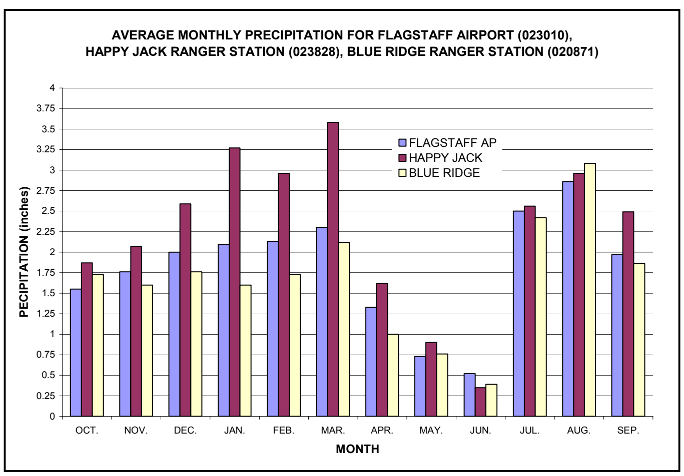

FIGURE 10: MONTHLY PRECIPITATION PEAKS FOR NEARBY GAUGES

Larger events with a lower probability of occurrence where also simulated with the 10, 50 and 100 year events. Although the hydrographs representing these storms are less likely to occur for a given year, the effects these events under management scenarios two and three had the most pronounced effect on the depositional area above the dam.

Summary tables and profiles for results from our HEC-6 simulation are contained in the following appendices. Appendix C – HEC-6 Model Results, contains water surface and bed profiles at the conclusion of each simulation. Appendix D – Bed Profiles from HEC-6 Simulations, contains the 1914, 2002, 6-ft removal and complete dam removal thalweg profiles. Appendix E – Sediment Volumes at Sections, contains sediment eroded or deposited at each cross section. Data in Appendix E were developed during the HEC-6 simulations with a default unit weight of 93 pcf for conversion between tons and cubic yards.

6. DISCUSSION AND CONCLUSIONS

In this section, we consider management scenarios 2 (removal of 6-ft off top) and 3 (total removal) for the dam. Refer to tabular HEC-6 output data on bed adjustments provided in Appendix C, profiles, based on the Appendix C data, which appear in Appendix D, and HEC-6 sediment transport volume data provided in Appendix E.

Our interpretation of the geomorphology, hydrology and the results of our hydraulic and sediment transport simulations follows.

- For all scenarios considered, at base flow, the water surface profiles (Appendix C), with the exception of pool areas, will be little different from the thalweg profiles. Since HEC-6 is a one-dimensional model, and the existing surface of the sediment wedge is relatively flat, we anticipate a potential for greater reduction in thalweg profile above the dam than indicated by HEC-6. This is because intermediate- magnitude and frequency flows have the potential for downcutting in a more limited channel area, rather than in the full width of the sediment wedge.

- Based on our sensitivity analysis using the HEC-6 model, the depth of erosion in the sediment wedge area upstream of the dam is not that dependent on the sediment-rating curve at the upstream boundary of the model. That is, sediment-free water flowing into the system at the top end deposits little but this 'hungry' water is very effective in eroding in the sediment wedge reach. During high-magnitude infrequent storms, sediment-laden waters flowing into the system will deposit material in the upstream springs portion of the investigated reach. (This was evident from our field reconnaissance observations of early November 2002, when we noted recent deposition in the springs area – probably from early September 2002, storm events.) However, the sediment-laden water will have less capacity than sediment-hungry waters to erode the sediment wedge.

- Regardless of flow magnitude and duration, the 6-foot removal option will maximize stability of the upstream sediment wedge and minimize sediment transport. A drop in the water table (phreatic surface) of nearly 6 ft at the dam and in much of the wedge area can be forecast.

- The 43 cfs Fossil Springs base flow has minimal impact on the sediment wedge presently behind the dam, regardless of dam removal scenario. In the long term, simulations greater than 3 to 9 months need to consider storm flows in additional to base flow.

- Seasonal flows corresponding to the 2-yr 3-hr event (summer) and the 2-yr 12-hr event (winter/spring) have the potential to move significant quantities of sediment for the total removal option. Sediment volume eroded from the wedge area during the 2-yr 3-hr event is estimated to be in the ballpark of several hundred cubic yards for 6-ft removal, and, for full removal, perhaps 1,000 cu yd. We project sediment erosion during the 2-yr 12-hr event, of several hundred cubic yards, for 6-ft removal, and, perhaps 2,000 cu yd for full removal. These discharges occur over a period of less than 48 hours.

- Storm flows, regardless of peak flow magnitude, will establish a similar bed profile in the case of full removal. With increasing peak flow, the slope of the sediment wedge is laid back further and further upstream, but this upstream impact on the sediment wedge is nowhere as significant as the bed profile reduction near the dam. We project sediment wedge erosion, during the 10-yr 24-hr event, of as much as 500 cu yd, for the 6-ft removal scenario, and perhaps 3,500 cu yd for full removal of the dam. We estimate sediment wedge erosion, during the 100-yr 24-hr storm, of about 1,000 cu yd, for 6-ft removal, and for full removal, of nearly 5,000 cu yd. Again, these sediment discharges occur over a period of less than 48 hours.

- After full removal, the phreatic surface of the perched aquifer behind the dam will drop to the pre-existing bedrock surface, a reduction of 22 ft. Upstream of this location, in much of the sediment wedge area, the water table will drop by a similar amount.

- Based on the HEC-6 bed profiles, we estimate that the 100-yr 12-hr storm has the potential to remove upwards of 1/5th to 1/3rd of the total sediment wedge volume of approximately 25,000 cu. yd., or 5,000 to 8,000 cu yd.

- In the case of full removal, a high-magnitude infrequent flow, such as a 100-yr 12-hr storm, may, depending on when it occurs (*and this could be tomorrow*), have the potential to create a uniform gradient bed profile (see Appendix D, page D-6) that could allow non-native fish species to migrate upstream. This profile could develop due to the large volume of sediment eroded and transported from the existing sediment wedge and deposited below the section where the dam presently exists.

- We anticipate, with the dam completely removed, a return to the pre-dam site topography, due to high-magnitude infrequent storm flow events. A realistic forecast on the timing of this return will require implementation of a two-dimensional sediment transport model using a simulation based on probable long-term continuous precipitation data.

7. ACKNOWLEDGEMENTS

We would like to thank Phil Smithers, John Mitchell and Nick Svor of APS for their assistance on this effort. Also, we thank: Grant Loomis of the Tonto National Forest for providing us with a copy of his report on HEC-1 modeling of the Fossil Creek watershed; Tom Loomis of the Maricopa County Flood Control District for making available a copy of the Skunk Creek HEC-6 modeling report; and, Stephen Monroe of the U.S. Geological Survey for discussing this project with us and for sharing a copy of his Masters thesis on the Fossil Springs dam site.

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