# A STABLE CHANNEL DESIGN APPROACH FOR THE RIO SALADO, SALT RIVER, ARIZONA

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## ABSTRACT

Planned environmental restoration of the Rio Salado (also known as the Salt River) involves the design and construction of a stable soft-bottom low flow channel through a 8-kilometer (5-mile) project reach in Phoenix, Arizona. The low flow channel will have a minimal footprint, thereby maximizing the area available for restoration in the overbank areas, yet convey the low-flow design discharge of 340 cubic meters per second (cms), or 12,200 cubic feet per second (cfs) (a 4-year peak discharge), without significant scour and/or deposition. This paper presents the low flow channel design approach. The channel was initially designed using channel stability methods and then refined using a sediment transport model. The initial channel slope, channel geometry and grade control locations were determined during the stable channel analysis. The stable channel slope was estimated using several analysis methods: evaluation of existing stable channel conditions; erodible channel design guidelines from the U.S. Army Corps of Engineers (Corps); stable channel slope estimate equations from the Albuquerque Metropolitan Arroyo and Flood Control Authority (AMAFCA); and the Corps' Hydraulic Design Package for Channels (SAM). The channel cross section geometry was determined using velocity constraints and normal depth methods. Sediment transport modeling was then used to refine the channel geometry until scour and deposition were minimized, determine the optimum grade control elevation and placement, and find the overexcavation depth in depositional zones that resulted in minimal maintenance. Guide dike structures were designed and strategically located to maintain the alignment of the low flow channel, protect the main channel bank, and minimize formation of secondary channels in the overbank areas.

# INTRODUCTION

As part of planned environmental restoration on the Rio Salado, the goal of this project was to design a low flow channel having “soft” sides and bottom along a 8-kilometer (5-mile) reach of the river (also known as the Salt River) in Phoenix, Arizona (see location map, Figure 1). The term “soft” implies an earthen channel, possibly vegetated, as opposed to a channel constructed with concrete or soil cement. The channel would have a minimal footprint, thereby maximizing the area available for overbank park and recreation and habitat development, yet convey the low flow design discharge of 340 cms (12,000 cfs) without significant scour or deposition.

This paper presents a design approach for a stable low flow channel on the Rio Salado. The channel was initially designed using channel stability methods. Several methods were used to estimate an appropriate stable slope for the low flow channel. The initial channel design was based upon the results of the stable channel analysis, velocity constraints, and the normal depth method. The U.S. Army Corps of Engineers’ River Analysis System (HEC-RAS) (Corps, 1998) computer program was used to confirm the channel capacity. The initial design was then refined using a sediment transport model. In addition, a low flow channel alignment was proposed and grade control structures were located to minimize scour. Guide dikes were proposed to help preserve the alignment of the low flow channel during flood events that exceed the design capacity of the low flow channel.

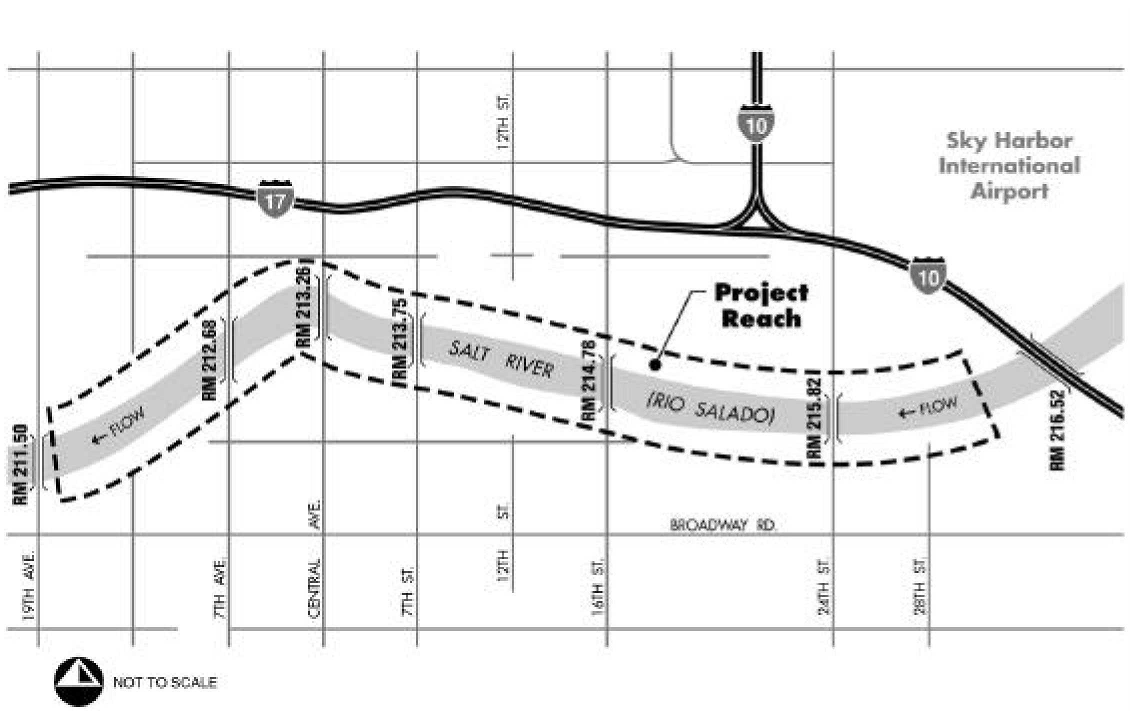


**Figure 1.** Location map of project reach in Phoenix, Arizona.

## EXISTING CONDITION AND CHANNEL STABILITY METHODS

Several methods were used to establish an appropriate stable slope for the low flow channel. The existing channel slope was examined first, and then several slope stability methods were used to "bracket" a stable design slope for the low flow channel.

### Existing Condition

Existing channel slopes within the project reach ranged from 0.0012 to 0.0028. The overall slope along the project reach was 0.0027. The existing low flow channel had a width to depth ratio between 20 and 25.

If a stream is in a quasi-equilibrium state, existing channel geometry is often a good indication of stable channel conditions. However, there were several reasons to suspect that the existing condition on the Rio Salado did not represent a system in equilibrium. Activity along the Salt River in recent years had likely disrupted the equilibrium of the system. This activity included levee work and channelization both upstream and downstream of the project reach, as well as sand and gravel mining throughout the system.

In addition, a project to raise the elevation of Roosevelt Dam upstream has reduced peak flows and flow duration. Because stable slope is inversely proportional to channel-forming discharge, if the channel-forming discharge (usually on the order of a 5-year to 10-year event for ephemeral streams like the Salt River) is decreased, the equilibrium slope will tend to become steeper. On this basis, the slope of the existing condition is probably lower than the ultimate stable slope.

### Stable Slope Methods

*Corps EM-1418*

The U.S. Army Corps of Engineers Engineering Manual No. 1110-2-1418 (Corps, 1994) offers a tentative design guide for erodible channels. Using the nomographs from this manual, stable channel dimensions can be bracketed. The Salt River analysis assumed very coarse granular banks with a median grain size diameter of approximately 30 mm. The width to depth ratio for "bank full" design discharge and resulting channel geometry was approximately 18. The predicted "stable" channel slope was approximately 0.0010.

The Corps developed the curves in EM 1110-2-1418 assuming a low bed-material transport rate. The manual warns that if the bed-material transport rate is high, the nomographs will underestimate the stable slope and depth. This is especially true of sand-bed channels and ephemeral channels, where flash floods carry a great deal of sediment. Since the Salt River is a flashy system, one would expect that the results of this analysis to underestimate the ultimate stable slope. This expectation is corroborated by the fact that the stable slope estimate from EM 1110-2-1418 is slightly lower than that found in the existing condition on the project reach.

*AMAFCA*

The AMAFCA Sediment and Erosion Design Guide (Resource Consultants and Engineers, 1994) offers an estimate of stable channel geometry that does not involve sediment particle size distribution. For U.S. Customary units, the stable slope ($S_s$) is estimated as:

$$S_s = 18.28 n^2 F^{0.133} Fr^{2.133} Q^{-0.133}$$

where:

| | | |
|---|---|---|
| $n$ | = | Manning roughness coefficient |
| $F$ | = | width to depth ratio of water flowing full in arroyo |
| $Fr$ | = | maximum Froude number |
| $Q$ | = | bank-full or channel-forming discharge, in cfs |

In U.S. Customary Units, the width (in feet) of the resulting channel can be estimated as:

$$W = 0.5 F^{0.60} Fr^{-0.40} Q^{0.40}$$

The width to depth ratio ($F$) is usually on the order of 40, but the results from the existing condition and the Corps method suggest that the ratio could be around 20, perhaps as low as 10 to 15. Using a width to depth ratio of 20, a channel-forming discharge of 340 cms (12,200 cfs), a Froude number of 0.70 (estimated from HEC-RAS modeling of the system), and a Manning roughness coefficient $n$ of 0.030, the AMAFCA method yielded a stable channel slope of 0.0033. This is close to the overall existing condition channel slope on the study reach.

The AMACA method yielded channel width estimates that were smaller than those obtained by the Corps method. To check the sensitivity of the AMAFCA method, post-Roosevelt Dam modification 5-year (572 cms, or 20,200 cfs) and 10-year (1501 cms, or 53,000 cfs) discharges were substituted into the equation. Using these discharges, the AMAFCA method yielded slopes of 0.0031 and 0.0027, respectively. These slopes were still slightly steeper than the current over-all slope of the study reach.

*SAM*

The Corps of Engineers Hydraulic Design Package for Channels, or SAM (Thomas et al., 1996), allows the user to calculate a “family” of stable channels based upon hydraulic and sediment data for the channel. The SAM Hydraulic design package utilizes an analytical procedure for calculating stable channel dimensions developed by Copeland (1994). This procedure determines dependent design variables of width, slope and depth from the independent variables of discharge, sediment inflow, and bed material composition. Copeland’s method uses sediment transport and resistance equations developed by Brownlie (1981). Williams (1995) reports that the Brownlie relations work well for low flow velocities and depths with medium sands, but not so well for larger streams with large flow velocities and depths with sediment sizes up to coarse sands.

To estimate a value for the concentration of bed-load sediment inflow, the full gradation from a composite bed sample taken downstream of 19th Avenue ($d_{50}$ = 30 mm) was used with the Ackers-White bed transport function (Ackers and White, 1973). The Ackers-White relation can theoretically be used for sediment ranging from 0.04 mm to 4.94 mm, though Williams (1995) recommends that the range be limited to 0.125 mm to 0.50 mm. In spite of these limitations, it was felt that the SAM analysis would be a useful tool to evaluate the reasonableness of the design.

The resulting family of channel geometries from SAM showed a "minimum stream power" solution at a bottom width of 22 m (72 feet) and a slope of 0.0087, with a corresponding depth of 2.68 m (8.8 feet). The width to depth ratio of this minimum stream-power stable channel was nine.

In the bank-full sense, 340 cms (12,200 cfs) is a channel-forming discharge. However, in a frequency sense, its recurrence interval is a little too low, only about four years. For flashy streams in the arid west like the Salt River, the channel-forming discharge is often less frequent, with a recurrence interval of five to ten years. It is reasonable to assume that the true stable slope might be associated with a channel-forming discharge above 340 cms (12,200 cfs). Therefore, the SAM results could be seen as the upper bound for the stable channel design, that is to say on the steep side of the best estimate.

## INITIAL CHANNEL DESIGN

A design slope of 0.0025 was selected for the Rio Salado low flow channel. The selected design slope was the best estimate taken from the many estimates of stable slope explained previously. A slope of 0.0025 resides on the upper range of the current slopes of the project reach, which is probably striving for a steeper slope due to changes in the hydrologic regime. The selected slope is also above the stable slope predicted by EM 1110-2-1418, which is likely underestimating the stable slope of a flashy, sediment-laden system like the Salt River. The selected slope is also much flatter than those suggested by the SAM package, which was considered an upper bound for the stable channel design. The selected slope is much closer to that predicted by the AMAFCA methodology, which was designed for use in the arid west. Additionally, the AMAFCA estimate was based on the existing width to depth ratios of the system.

### Normal Depth and HEC-RAS Analysis

The geometry of the low flow channel was first determined using velocity constraints and normal depth methods, and the design capacity of the low flow channel was confirmed by using the U.S. Army Corps of Engineers' River Analysis System (HEC-RAS) program (Corps, 1998). In order to maintain the stable design slope, several grade control structures were proposed. The elevation drop at each grade control structure was limited to 0.91 m (3 feet) in order to prevent the formation of dangerous hydraulic rollers.

### Channel Dimensions

At the upstream part of the reach, the channel bottom is 50.3 m (165 feet) wide, with a sideslope cotangent of three (3H:1V) and a depth of at least 2.44 m (8 feet) depending on the existing channel ground. On the downstream part of the project, the channel bottom is 62.5 m (205 feet) wide, maintaining a sideslope cotangent of three (3H:1V). Here, the channel slope is reduced to 0.00125 to complete the transition to the existing channel. In addition, there is planned over-excavation at the downstream end of the project to help minimize future channel maintenance.

The alignment for the low flow channel closely follows the existing channel thalweg. The alignment maintains a reasonable distance from the banks of the main channel or levees, Arizona Public Service (APS) transmission towers and other major features identified by local stakeholders. At bridges, the low flow channel location and alignment considered the number of bridge piers within the low flow channel and aligned flow with the bridge piers. The proposed low flow channel also maintains a similar sinuosity to the existing low flow channel. Total sinuosity is 1.06 for the existing condition and 1.07 for the low flow channel design.

## SEDIMENT MODELING

Twenty-two long-term sediment transport simulations were completed for the low flow channel analysis. The results were used to evaluate grade control locations, determine over-excavation depths, determine annual maintenance requirements, and estimate the effects of 25-year, 50-year and 100-year discharge events.

The proposed channel design was refined using the sediment transport HEC-6T Sedimentation in Stream Networks computer program, Version 5.13.05 (Mobile Boundary Hydraulics, 1999). HEC-6T is an enhanced version of HEC-6 Scour and Deposition in Rivers and Reservoirs (Corps, 1993) written by William A. (Tony) Thomas, who developed the original HEC-6 code. HEC-6T is a one-dimensional movable boundary open channel flow numerical code designed to simulate and predict changes in river profiles resulting from scour and/or deposition over long time periods.

### HEC-6T Model Inputs

Inputs for an HEC-6T model include geometric data, sediment data and hydrologic data. The geometric data include cross section geometry, Manning roughness coefficients, deposition and erosion limits, and depth of the bed sediment reservoir. Most geometric data were taken from the HEC-RAS model of the proposed low-flow channel, and reasonable assumptions were made for sediment reservoir depth and deposition and erosion limits. The number of cross sections from HEC-RAS model was reduced in order to decrease the computation time for the HEC-6T model and improve computational stability related to sediment continuity.

The bed gradations, sediment transport method and inflowing sediment load are part of the sediment data. Composite bed gradations for cross sections within the low flow channel were developed from Corps' sediment samples taken between 0 to 1.83 m (6 feet) below the proposed low flow channel invert. In general, the sediment bed is composed of sand (20 percent), gravel (60 percent) and cobbles (20 percent). Since sand transport is the main transport size and there is a high percentage of gravel in the bed, the Toffaleti, Meyer-Peter and Muller combination transport method is used in the HEC-6T sediment transport simulations because the method suitably transports gravel as well as sand. A lack of detailed historical bed elevation data and man-made changes to the Salt River (including sand/gravel mining and channelization) precluded direct calibration of the model. Therefore, an equilibrium bed material load curve far upstream of the project was calculated for the Toffaleti, Meyer-Peter and Muller combination transport method and used as a basis for the inflowing sediment load for the model.

The hydrologic data are composed of the discharge-elevation rating curve and hydrographs. The 25-year long-term hydrograph was taken from a portion of a simulated hydrograph based on hind-cast flows at Granite Reef Diversion Dam with the Modified Roosevelt Dam in place (Corps, 1996). The rating curve for the downstream boundary condition in HEC-6T was obtained from the HEC-RAS model results.

The sediment models were analyzed for sensitivity to inflowing sediment load, sediment transport method, and the occurrence of peak flows.

**Optimum Number of Grade Controls**

Sediment transport simulations with equilibrium inflowing bed material load were used to evaluate five grade control scenarios. The first scenario included only the existing grade control structures at the upstream and downstream end of the project reach. Each subsequent scenario added a grade control structure at locations in the study reach.

The analysis demonstrated the need for and the locations of the four grade control structures. The specific functions of the recommended structures are listed below:

1. The proposed grade control located at Cross Section 216.23 limits the degradation below the existing grade control at Cross Section 216.40, which is 0.16 km (0.10 mile) downstream of I-10 (Cross Section 216.52).

2. The proposed grade control located at Cross Section 215.65 reduces degradation in the upstream low flow channel reach.

3. The proposed grade control located at Cross Section 214.65 was added to protect the 16th Street Bridge (Cross Section 214.79) and the 0.91-m (36-inch) water line at Cross Section 214.80 from excessive scour.

4. The proposed grade control structure located at Central Avenue (Cross Section 213.26) protects the bridge from pier scour.

**Over-Excavation Depths and Maintenance Requirements**

With the equilibrium inflowing sediment load, the HEC-6T models indicate that deposition occurs in the downstream reach of the low flow channel. This deposition decreases the low flow channel capacity, which in turn increases flooding and damage in the overbanks. Therefore, channel excavation is needed periodically to maintain the low flow channel capacity.

Four over-excavation scenarios (0.31-m (1-foot), 0.61-m (2-foot), 0.91-m (3-foot), and 1.22-m (4-foot) over-excavation depths) were evaluated and the resulting volume and frequency of channel maintenance (i.e., channel excavation) examined. The 0.61-m (2-foot) over-excavation scenario was recommended because it results in the least amount of scour above the grade control located at Cross Section 214.65 (i.e., at the 0.91 m (36-inch) water line). For the 0.61-m (2-foot) over-excavation scenario, the scour depth at the 0.91-m (36-inch) water line is 0.15 m (0.5 foot) less than that for the 0.91-m (3-foot) and 1.22-m (4-foot) excavation scenarios.

## GUIDE DIKES

One of the interesting features of the low flow channel design is that guide dikes were located at strategic locations between the grade control structures. These multi-purpose guide dikes (see Figure 2) will help to maintain the alignment of the low flow channel, protect the main channel bank from erosion, and reduce damage in the overbank areas. The dikes will also help prevent the development of secondary low flow channels in the overbanks. This is accomplished by directing flow toward the low flow channel during the period of receding flood flows, which will help preserve the location of the original meander geometry and location of the low flow channel. Like the grade control structures, the guide dikes were designed to withstand a 100-year flood event.

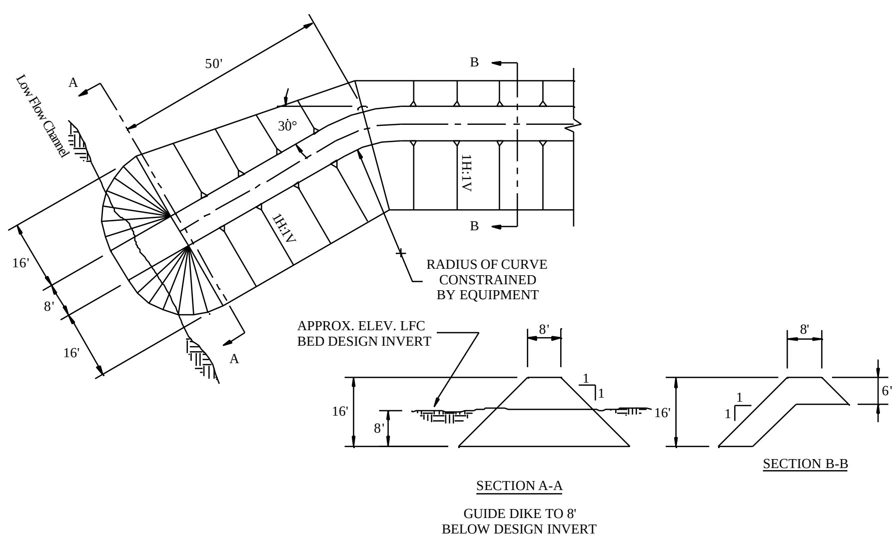


**Figure 2.** Detail of guide dike near low flow channel.

## CONCLUSION

This paper presented a stable channel design approach for the Rio Salado (also known as the Salt River) in Phoenix, Arizona. The design approach consisted of the following general steps:

1. Analyze the existing condition of the system and use channel stability methods to determine a design slope that will minimize scour and deposition on the project reach.

2. Develop an initial channel design using the normal depth method and confirm channel capacity using an HEC-RAS model.

3. Refine the sediment transport model HEC-6T, optimizing the number and location of grade control structures and determining the over-excavation depths that will minimize annual maintenance requirements.

4. Include guide dikes in the design to preserve the alignment of the low flow channel during flood events that exceed the design capacity of the low flow channel.

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## REFERENCES

Ackers, P. and W. R. White. (1973). "Sediment Transport: New Approach and Analysis." Journal of the Hydraulics Division, American Society of Civil Engineers. **99**(HY11):2041-2060.

Brownlie, William R. (1981). "Prediction of Flow Depth and Sediment Discharge In Open Channels." Report No. KH-R-43A. California Institute of Technology. Pasedena, CA.

Copeland, R. (1994). "Application of Channel Stability Methods – Case Studies." Report No. TR-HL-94-11. U.S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.

Mobile Boundary Hydraulics. (1999). HEC-6T Sedimentation in Stream Networks User's Manual, Version 5.13.05 (June 29, 1999). Clinton, Mississippi.

Resource Consultants and Engineers, Inc. (1994). AMAFCA Sediment and Erosion Design Guide. RCE Ref. No. 90-5560.

Thomas, W. A., R. R. Copeland, N.K. Raphelt, and D.N. McComas. (1995). Hydraulic Design Package for Channels (SAM), DRAFT User's Manual. U.S. Army Corps of Engineers, Waterways Experiment Station. Vicksburg, MS.

U.S. Army Corps of Engineers, Hydrologic Engineering Center. (1993). HEC-6 Scour and Deposition in Rivers and Reservoirs User's Manual (August 1993). Davis, CA.

U.S. Army Corps of Engineers, Hydrologic Engineering Center. (1998). HEC-RAS River Analysis System User's Manual, Version 2.2 (August 1998). Davis, CA.

U.S. Army Corps of Engineers, Los Angeles District. (1996). Hydrologic Evaluation of Water Control Plans, Salt River Project to Gila River at Gillespie Dam. Section 7: Study for Modified Roosevelt Dam, Arizona (Theodore Roosevelt Dam). March, 1996.

U.S. Army Corps of Engineers. (1994). Channel Stability Assessment for Flood Control Projects. EM-1110-2-1418. Washington, D.C.

Williams, D.T. (1995). "Selection and Predictability of Sand Transport Relations Based Upon a Numerical Index." Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado.