Bendway weir design – Rio Grande physical model

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April 2012
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Introduction

Bendway weirs are transverse instream structures designed to pass flow over the weir crest at the annual mean flow level, disrupt secondary currents, improve navigation, and redirect flow from the outer bank of a bend toward the center of the channel. They have been identified by the United States Bureau of Reclamation (Reclamation) as potential erosion mitigation measures in the reach of the Rio Grande River downstream of the Cochiti Dam in New Mexico. To quantify hydraulic effects of bendway weir structure installation in a channel bend, Colorado State University (CSU) was contracted by Reclamation to design and test four structure configurations installed in a previously existing scaled physical model representing two prototype Rio Grande bends. Previously completed physical modeling conducted by CSU entailed evaluation of hydraulics in an empty, baseline condition model and quantification of conditions with modeled spur-dike instream structures. Comparisons between hydraulics due to bendway weirs with both baseline and previously modeled spur dikes were emphasized.

Weir design guidance primarily focuses on state parameters consisting of crest elevation, width, length, profile angle, plan form angle, and spacing ratio. Design recommendations for parameters from the literature draw from field, laboratory, and numerical data, experience, and observations. This document details the selection of design criteria for the modeled bendway weirs and the final design of the four structure configurations.

Bendway weir geometric parameters

Instream structures such as bendway weirs are placed in series in a channel bend, typically are angled upstream, and have a crest elevation coinciding with the intended purpose of the structure. Plan and profile schematics of a bendway weir configuration are provided in Figure 1. Past physical modeling conducted by Colorado State University investigated hydraulics associated with spur dikes and vanes. Spur dikes have a structure height set at the bankfull or peak design flow elevation with a horizontal crest. Vanes have a bankline crest elevation at the bankfull or peak design flow elevation, then slope downwards into the channel. Spur dikes are usually oriented downstream while vanes are oriented upstream. Part of the bendway weir test program focused on providing the most direct comparison of resulting hydraulics and those observed during the spur dike testing program. Therefore, bendway weir structure designs were made as close as possible to the design of the vane-spur dikes, primarily altering crest length and elevation to conform to recommendations found in the literature

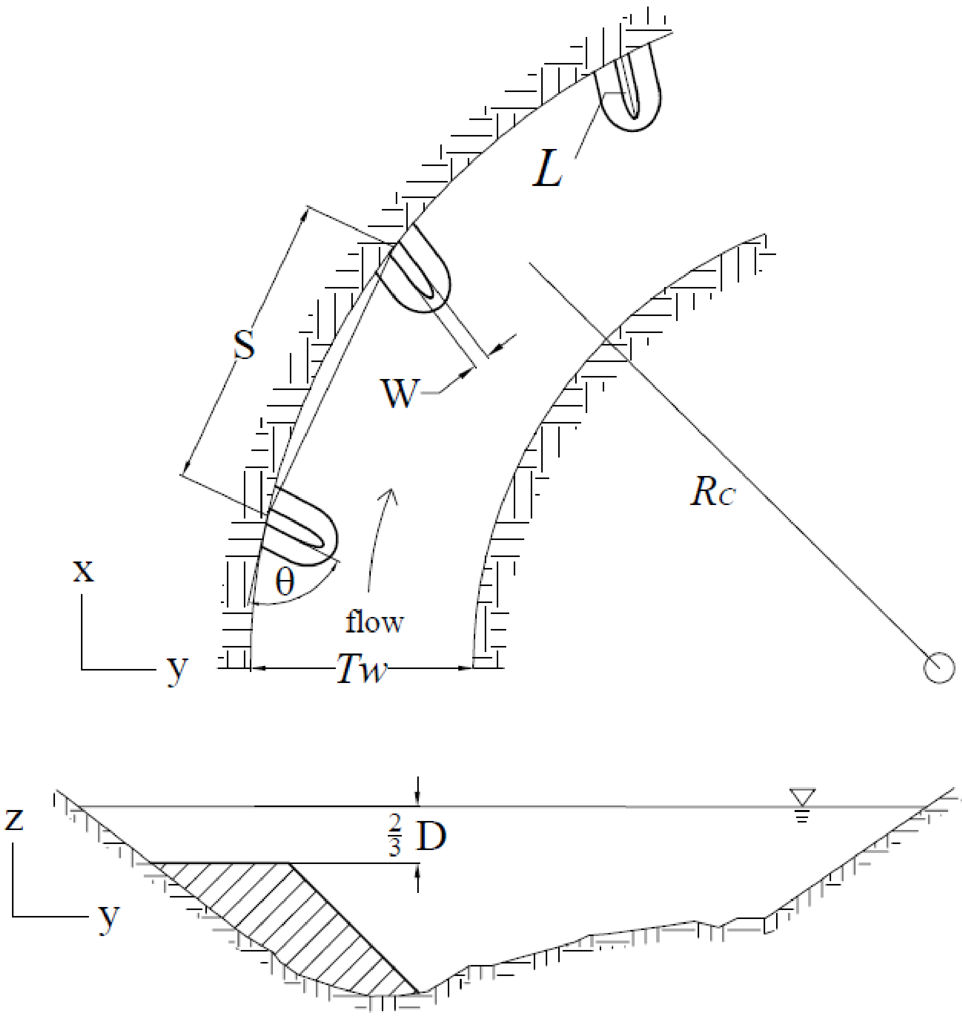

Figure 1. Bendway weir geometric parameter definitions

Three primary sources for the documentation and interpretation of bendway weir guidance were identified. Recommendations as summarized from the sources are detailed in Table 1.

Table 1. Design guidelines for bendway weirs from literature (variables defined in Figure 1)

	Length		Height		Top width		Spacing		θ		Transverse slope	
Source	min	max	min	max	min	max	min	max	min	max	crest slope	transition
NCHRP Report 554, 2005	Tw/3	Tw/2	W/2	W	$2D_{100}$	$3D_{100}$	1.5L	1.5L	80	70	flat	flat
HEC-23, Design Guideline 1, 2009*	Tw/10*	Tw/3*	0.3 BF**	0.5 BF**	$2D_{100}$	$3D_{100}$	4L	5L	60	85	flat	1V:5H
Julien and Duncan, 2003	longer is better		max permitting navigation		none	none	2L	3L	60	60	none	none

**HEC-23 further recommends structure length to cross the stream thalweg

**HEC-23 further recommends structure height to fall between annual mean flow and annual low flow water surface elevations

Bend-averaged calculations

Hydraulic parameters such as the channel top width and design flow depth are integral parts of bendway weir design; however, they vary along the longitudinal distance of a migrating channel bend. It was assumed for the purposes of the model design that such parameters are bend-averaged at a bankfull, or approximately 2-yr return interval, scaled prototype discharge of 6000 cfs (12 cfs model scale). Model cross sections, the channel thalweg, 12-cfs waterline, top of bank, and flume walls are presented in Figure 2. The native bed topography constructed physical model contains a contraction in the approach to the upstream bend (model cross-sections 1-2) and an expansion at the outflow of the downstream bend (model cross-sections 17-18). Since this contraction and expansion are not representative of flow throughout the bend they were excluded in the calculation of the bend-averaged parameters. The upstream parameters were calculated from the average of model cross-sections 3-10 and the downstream parameters from model cross-sections 11-16.

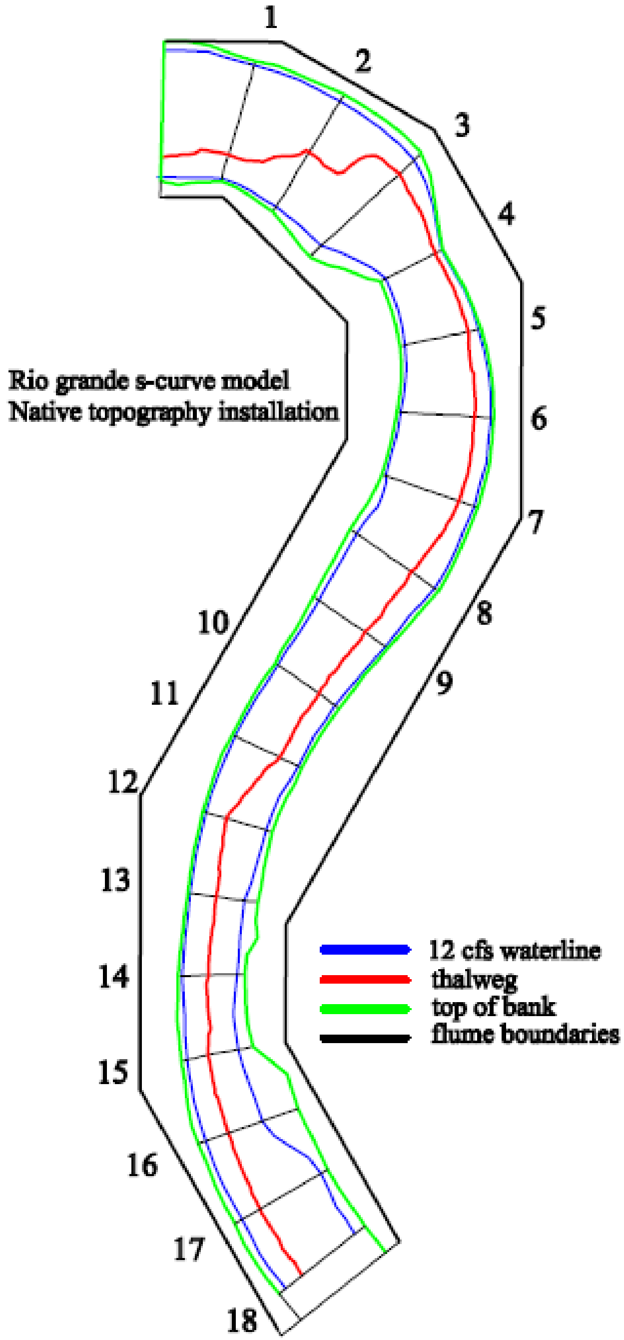

Figure 2. Flume plan view schematic

Top-width (T_W) for the model was found by averaging survey data collected at the bankfull discharge, throughout the channel bends. The upstream bend T_W was found to be 11.76 ft and the downstream bend was 7.86 ft. Bankfull flow depth was computed as the hydraulic depth using surveyed bathymetry and the calculated T_W at a given cross section. Hydraulic depth values were then averaged across the upstream and downstream bends, giving values of 0.55 ft and 0.59 ft, respectively.

Weir crest length

The length, *L*, is defined as the distance along the crest axis from the intersection of the weir crest and the channel bank to the weir tip; i.e. not including the transition slope from the crest to the channel bottom. Length measurement is calculated from the intersection of the bankfull water-surface elevation and outer bank as opposed to the intersection of the weir crest and channel bed. As noted in the summary of Table 1, the range of weir crest lengths spans one-tenth to one-half of the channel top-width. Additional guidelines include that the weir should be long enough to cross the stream thalweg (FHWA, 2009). Setting the crest length in the upstream bend to $T_W/4$ and $T_W/2$ in the downstream bend resulted in structures which adhered to ranges of *L* from the literature and also crossed the stream thalweg along the outer channel. Upstream weir lengths were set at 2.94 ft and downstream weir lengths at 3.93 ft.

Weir crest height

Structure crest elevation was set at one-third of the bend-averaged bankfull hydraulic flow depth, or two-thirds of the hydraulic flow depth down from the water-surface elevation. Additional guidelines stipulate that the weir crest elevation be set below the mean annual water-surface elevation and above the mean annual low-flow water-surface elevation (FWHA, 2009). Flow data from the prototype reach at USGS Gage 8317400 were collected over the period of record since the Cochiti Dam construction and are detailed in Figure 3. The mean annual discharge was calculated as the average over the period of record as 1344.93 cfs (model 2.69 cfs) and the mean annual low-flow was found from the average of the dry months of July – September to be 1054.98 cfs (model 2.11 cfs). Scaled model discharges were inputted to a HEC-RAS model of the constructed physical model, tailwater was set as normal depth ($S = 0.000865$, $n = 0.018$), and model water-surface elevations were obtained for design comparisons. As detailed in Figure 4, the weir crest elevation of one-third bankfull hydraulic flow depth corresponds well to the narrow elevation band bracketed by the specified water-surface elevations in the case illustrated. Many cross sections corresponded to Figure 4. At some cross sections the weir crest elevation did not fall within this small elevation window, in which cases the crest elevation usually fell below the low flow water level. The annual mean and low flow water surface elevations were computed only as a check on the guidelines provided by FWHA (2009) and it was concluded that designing the structures to one-third of the bend-averaged bankfull hydraulic flow depth

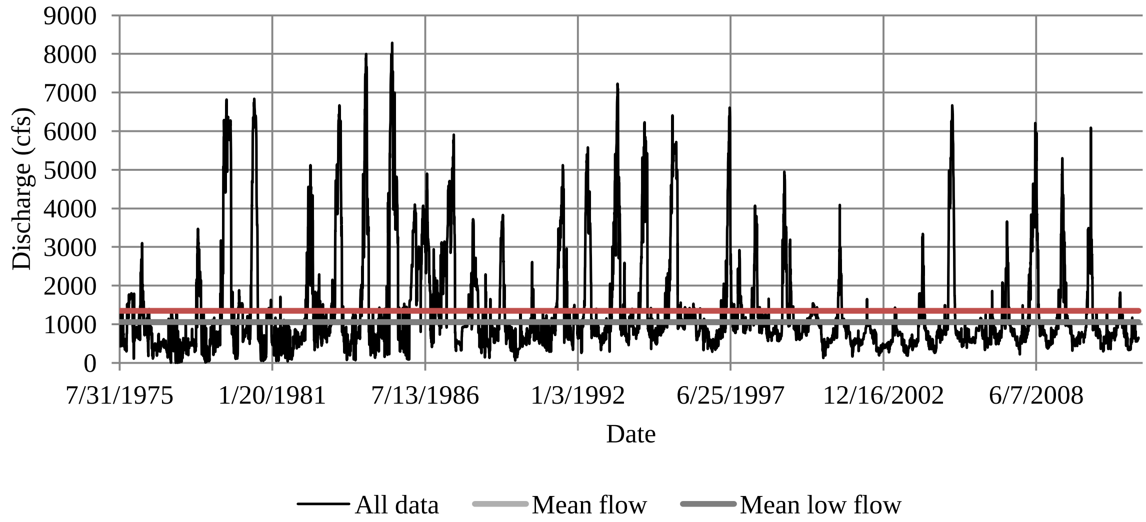

Figure 3. Prototype discharge record (USGS Cochiti Gage 8317400)

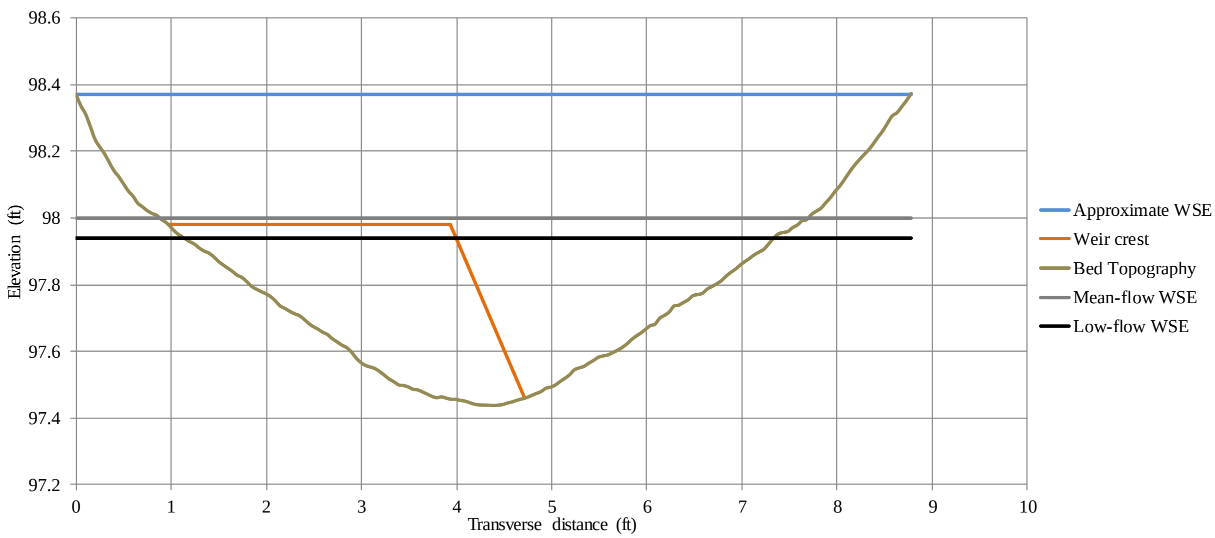

Figure 4. Weir crest elevation with mean annual and low flow water surface elevations identified (BW01, weir 2)

Weir plan-form angle

Previous native topography physical modeling of spur dike instream structures utilized plan-form angles (θ) of 90^0 and 60^0. To keep the bendway weirs as close as possible to the spur dikes for comparison purposes while conforming to the parameter ranges indicated in Table 1, angles of 60^0 and 85^0 were selected. An angle of 90^0 would not redirect the flow towards the channel center, but rather towards the outer bank downstream of the bendway weir structure, violating both the design recommendations and functional purpose of a bendway weir. Altering θ by 5^0 is a minimal change to the spur dike plan-form design which allows for near direct comparison with the bendway weir structures behaving as intended.

Weir crest top-width and angle

Typical construction practices for instream structures include driving heavy machinery over the crest of the structure during the build in order to drop material into the stream. Physical modeling of vane-spur dike instream structures accounted for this fact, estimating that a required 12 ft (model 1 ft) of crest-top width would be needed for construction equipment. The crest width was translated directly to bendway weir design and all model structure widths were set at 1 ft. Structure material is approximately 0.3 ft to 0.5 ft angular rock, corroborating with design guidelines of a crest width of $2D_{100} - 3D_{100}$. Similar to the previously installed native topography spur dike structures, and adhering to design guidelines, the crest of the bendway weirs extends at a constant elevation into the channel, and then drops at 1V:1.5H down to the channel bottom at the end of the weir length. Bendway weirs encounter the channel bed below the water surface.

Bendway weir design guidelines call for weir key which is typically riprap placed in an excavated trench into the bankline to protect against flanking. Weir keys are placed to the bank height and usually angled 1V:1.5H from the top of the bank. Depending upon the vertical bank angle, riprap can extend into the flow between the top of the bank and the bendway weir crest. In this case the vertical bank angle is flatter than 1V:1.5V, thus no riprap was installed between the top of the physical model bank and the bendway weir crest. A benefit of not including bendway weir roots is that only the effects of the bendway weirs exist in the physical model and resulting design equations. There will also be a better understanding of the vertical flow contraction effects on the flow field without placing additional riprap or weir material to the bank.

Weir spacing

Spacing ratios translated directly from the spur dike physical modeling process with the structure start points located at the same locations along the bankfull waterline. Spacing distance was calculated as the chord running between points defined by the intersection of the centerline of the weir crest with the bankfull waterline. Resulting values ranged between $2.69L$ and $4.17L$ which fall within the ranges of bendway weir design recommendations.

Final structure designs

Given the economic and temporal constraints of the physical modeling process, four configurations were designed for hydraulic evaluation. Configurations correspond to previously tested spur dike structure layouts when possible, which represented maximum and minimum velocity reduction design conditions observed during trapezoidal model testing. Previous tests were given the nomenclature NW01 and NW04 for the downstream and upstream bend minimum design, respectively. Maximum velocity reduction designs were designated NW03 and NW02 for the downstream and upstream bends, respectively. Concordantly, bendway weir configurations are named BW01 through BW04 and represent the same location, spacing, and plan view angle (except as noted above) as the NW counterparts. The maximum and minimum velocity reducing location, spacing and plan view angle for the bendway weirs will likely be different than spur dikes since their respective hydraulic effect are different. Table 2 details the design parameters and calculated values for the modeled bendway weir configurations. Figure 5 presents the designs of BW01 through BW04 with the 12 cfs waterline shown.

Table 2. Model bendway weir configurations and parameters

Maximum design

Location	*Length*	*Height*	*Top width*	*Spacing*	θ	*Transverse slope*
Upstream BW02	TW/4	0.333 BF hydr. depth	$2D_{100}$	3.37L	60	0
Downstream BW03	TW/2	0.333 BF hydr. depth	$2D_{100}$	2.36L	60	0

Maximum values

Location	*Length (ft)*	*Height (ft)*	*Top width (ft)*	*Spacing (ft)*	θ	*Transverse slope*
Upstream BW02	2.940	0.182	1	9.90	60	0
Downstream BW03	3.934	0.195	1	9.30	60	0

Minimum design

Location	*Length*	*Height*	*Top width*	*Spacing*	θ	*Transverse slope*
Upstream BW04	TW/4	0.333 BF hydr. depth	$2D_{100}$	4.17L	85	0
Downstream BW01	TW/2	0.333 BF hydr. depth	$2D_{100}$	2.69L	85	0

Minimum values

Location	*Length (ft)*	*Height (ft)*	*Top width (ft)*	*Spacing (ft)*	θ	*Transverse slope*
Upstream BW04	2.940	0.182	1	12.25	85	0
Downstream BW01	3.934	0.195	1	10.60	85	0

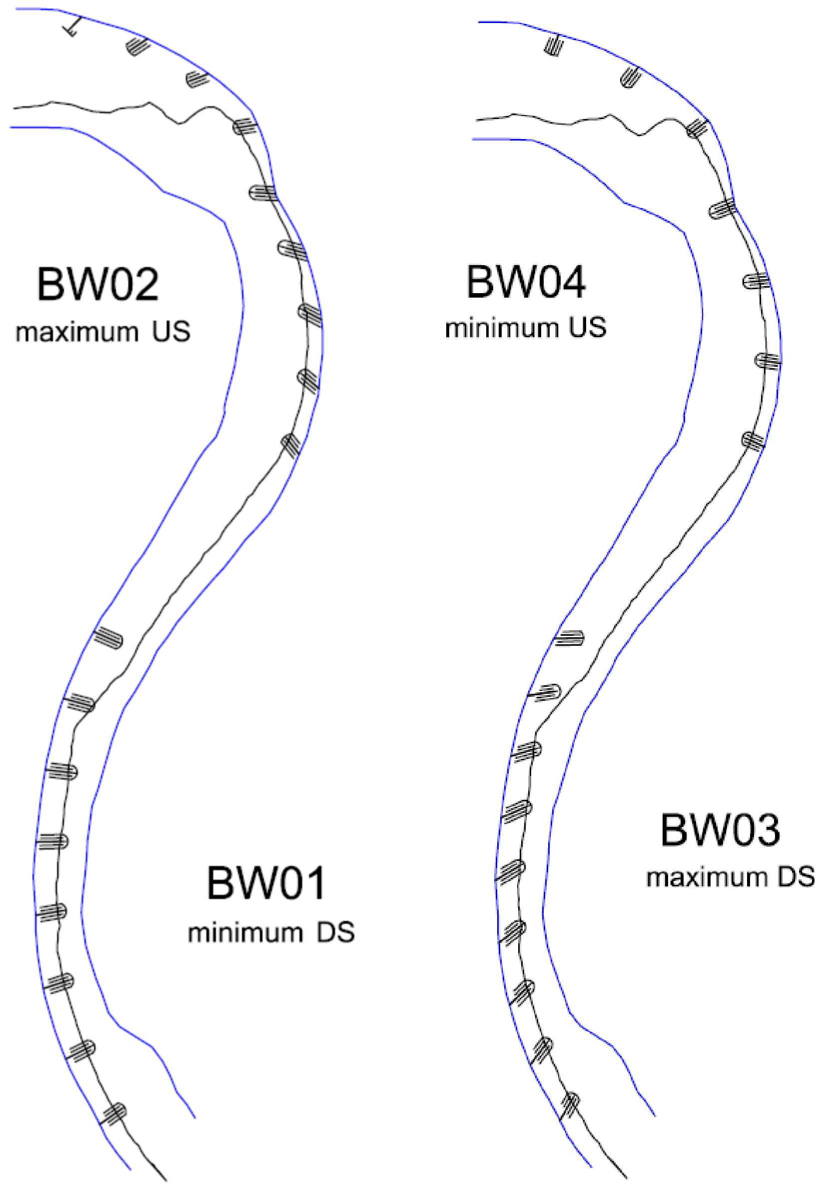

Figure 5. Bendway weir configurations

Summary and conclusions

In conjunction with the Bureau of Reclamation, Colorado State University developed a physical model and testing scheme for the evaluation of four configurations of bendway weir fields installed in channel bends. The design of the bendway weir fields was based upon recommendations from the literature, and the ability to compare results with previous spur dike modeling. Four bendway weir field configurations were developed which adhere to both literature design guidelines and spur-dike comparison needs.

References

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