APPLICATION OF THE FLOWSED AND POWERSED MODELS IN RIVER STABILITY, BRIDGE DESIGN AND RIVER RESTORATION

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Abstract: FLOWSED and POWERSED are models that predict total annual sediment yield and transport capacity. The predicted outputs of total annual bedload, suspended sand, and total suspended sediment using the models, as programmed in RIVERMorph^{TM}, along with other applications are used to assess river stability and bridge design. This paper assesses the ability of FLOWSED and POWERSED to predict river stability using Douglas Creek in Montana as a case study. The results show that the stability predictions from POWERSED (stable, aggrading or degrading) agreed with the actual channel stability observations. This paper also evaluates the model prediction of sediment transport capacity for a three-cell bridge design in Maryland. The models accurately depicted the observed depositional patterns and demonstrated the value to predict channel and culvert response for a particular design. Overall, the results of this study provide confidence of the applications FLOWSED and POWERSED can have for appropriate stability predictions, better bridge and culvert designs, and for realistic sediment consequence prediction for river restoration.

INTRODUCTION

Stream restoration designers need to assess not only sediment competency but also sediment transport capacity. Streams must be able to transport the sediment supplied by their watersheds without aggrading or degrading (Rosgen, 1996, 2001, 2006a, 2006b). As such, designers need tools to evaluate the efficacy of restoration designs to transport sediment, particularly in an effort to minimize risk and promote long-term dynamic stability (NRCS, 2007). The FLOWSED and POWERSED models (Rosgen, 2006a, 2006b), which are programmed into the software program RIVERMorph^{TM}, provide users with such tools whereby total annual sediment yield (FLOWSED) and aggradation or degradation potential (POWERSED) are predicted.

FLOWSED is based on the use of both dimensionless flow-duration and sediment rating curves and requires bankfull discharge and bankfull sediment (suspended and bedload) as the normalization parameters to convert dimensionless relations to reach-specific dimensional values; thus field-collected bankfull or near-bankfull measurements of the study site are required to transform dimensionless relations into actual values (Rosgen, 2006a, 2006b). The total annual sediment yield in FLOWSED is determined by first developing a dimensionless flow-duration curve from gage site data that represents a similar hydro-physiographic province as the study site. This curve is established by obtaining a flow duration curve at the gage site and making the curve dimensionless by dividing all flow values by the mean daily bankfull discharge at the gage site. Second, dimensionless sediment rating curves are required for use in the FLOWSED model. Existing dimensionless sediment relations have been developed based on stream stability ratings (Pfankuch, 1975) as modified by stream types (Rosgen, 1996, 2001). The field-measured bankfull discharge and sediment values are used to convert the dimensionless flow-duration and sediment curves to site-specific dimensional curves. The combination of the dimensional flow-duration and sediment rating curves are then used to calculate total annual bedload and suspended sediment yield.

POWERSED uses the output from FLOWSED to determine channel stability (stable, aggrading or degrading). The model compares the sediment transport capacity from an upstream, adjacent sediment supply reach by predicting transport rate change due to channel hydraulics, which reflect potential changes in morphological variables (e.g., width, depth and slope). The corresponding changes in flow resistance are used to predict velocity, shear stress and unit stream power for a wide range of flow stages. POWERSED develops reference bedload and suspended sediment curves by converting the FLOWSED output sediment rating curves from discharge to unit stream power for a wide range of flows. Revised values of annual sediment transport can then be compared to the upstream sediment supply from the subsequent change in the hydraulic geometry of the stream channel and corresponding response in sediment transport. Additional details regarding the FLOWSED and POWERSED models are available in Rosgen (2006a, 2006b) and the establishment, application and validation of dimensionless sediment rating curves in Troendle *et al*. (2001) and Rosgen (2010).

Objectives: 1) Assess the ability of the FLOWSED and POWERSED models to predict river stability using Douglas Creek in Montana as a case study; 2) Evaluate the FLOWSED and POWERSED prediction of sediment transport capacity for a three-cell bridge design in Maryland; and 3) Discuss application of the models for river restoration.

METHODS

River Stability – Douglas Creek, Montana: Douglas Creek is located near Helmville, Montana and has a drainage area of 75 square miles. The upstream section of Douglas Creek is a relatively stable, moderately entrenched, gravel-bed stream (B4c stream type, Rosgen 1994, 1996). The reach downstream of the B4c stream type is a more unstable, entrenched, high width/depth ratio, gravel-bed stream (F4 stream type) and transitions downstream into a meandering, gravel-bed stream with a floodplain (C4 stream type). The stream has a bankfull discharge on the order of 71 cfs and flows into Nevada Creek in the upper Blackfoot River basin. In general, the watershed consists predominantly of forested and agriculture lands.

Four river reaches of Douglas Creek (Figure 1 through Figure 4) were compared to an upstream sediment supply/transport reach to determine the potential of the stream to accommodate the delivered sediment. Predicted bed stability using FLOWSED, POWERSED and stability indices (Rosgen, 2001, 2006b) was compared to observed resurvey data following one year of flows at the site. A typical view of the stable B4c stream of Reach 1 and corresponding cross section are shown in Figure 1. The unstable Reach 2 and cross section of the F4 stream type transitioning from the B4c are shown in Figure 2. A C4 stream type has developed from an F4 and is depicted in Figure 3 and Figure 4, which represent Reach 3 and Reach 4 respectively. Livestock grazing use had been curtailed for five years previous to this study.

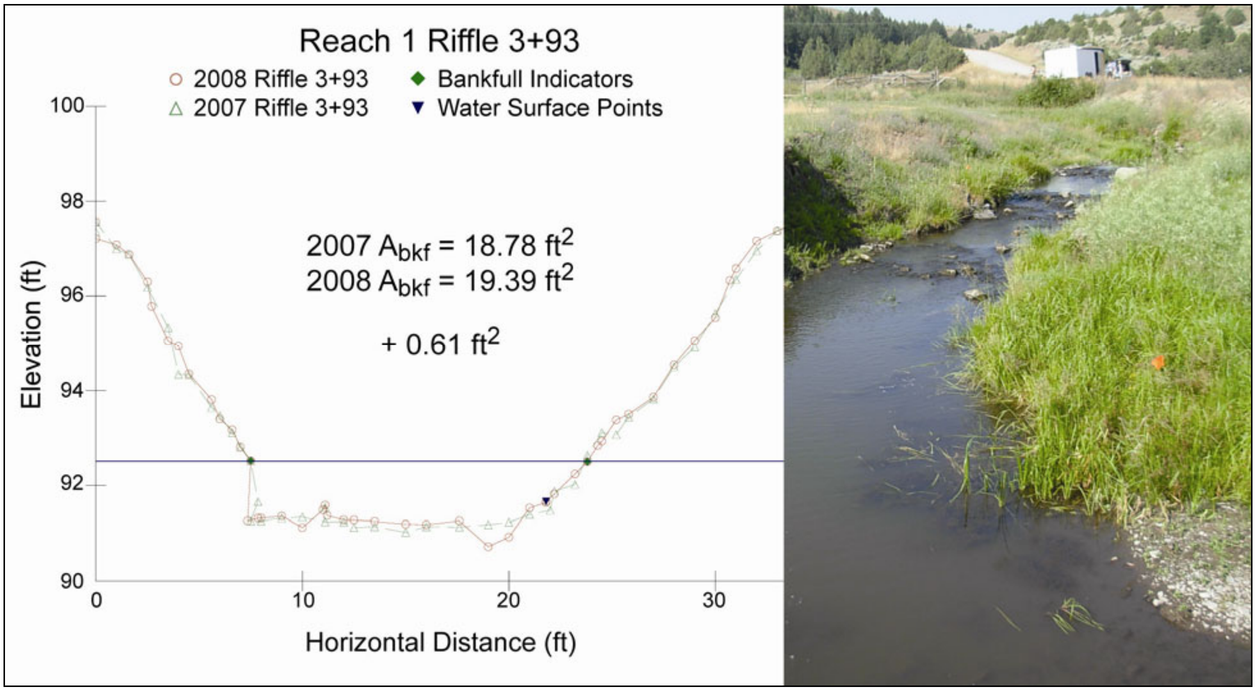

Figure 1 Photograph of Reach 1 (B4c stream type) and cross section surveys for 2007 and 2008.

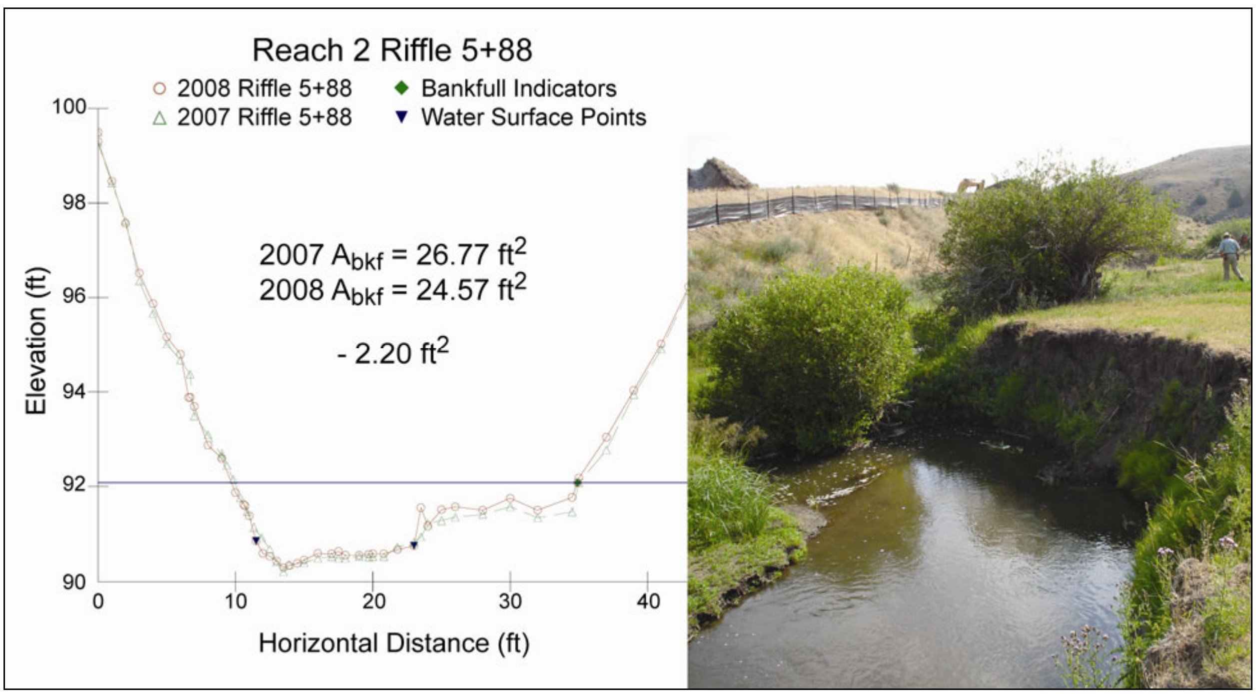

Figure 2 Photograph of Reach 2 (F4 stream type) and cross section surveys for 2007 and 2008.

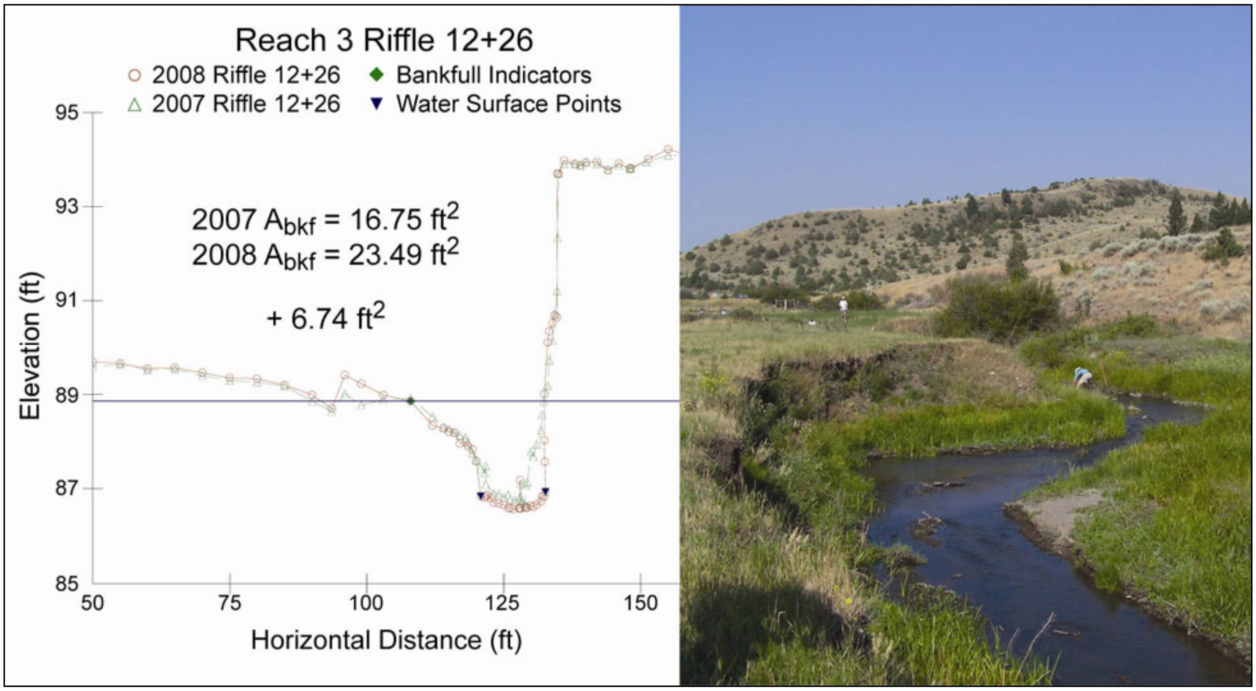

Figure 3 Photograph of Reach 3 (C4 stream type) and cross section surveys for 2007 and 2008.

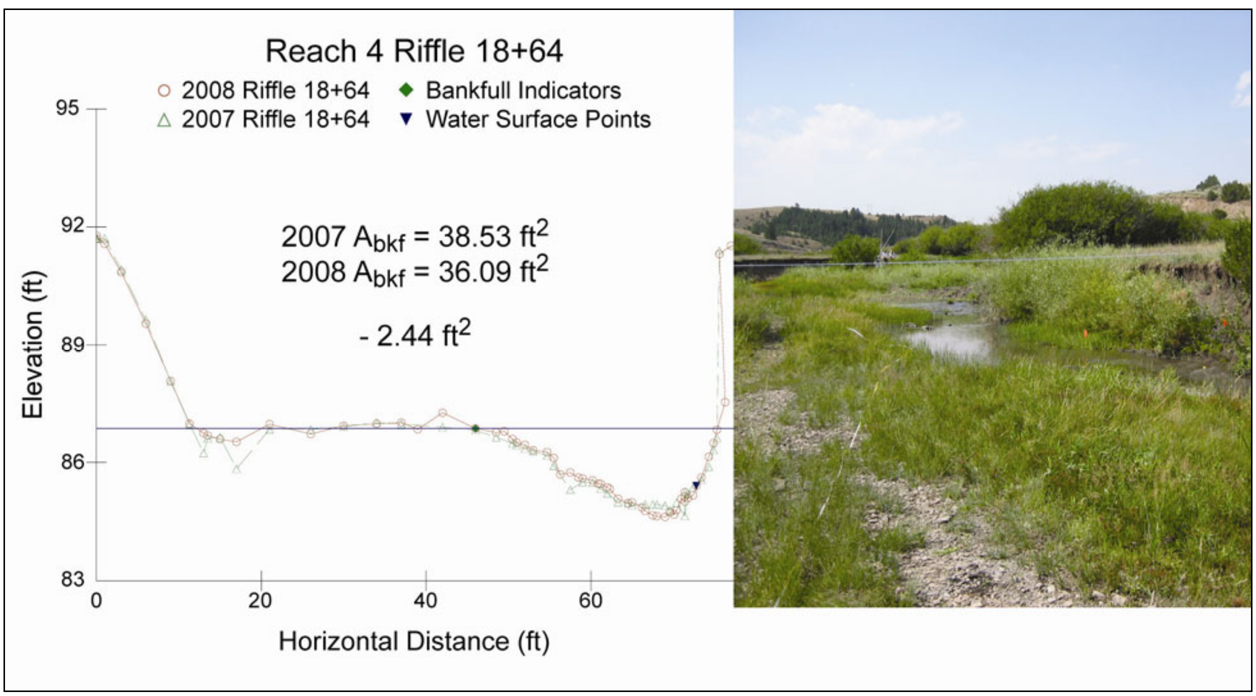

Figure 4 Photograph of Reach 4 (C4 stream type) and cross section surveys for 2007 and 2008.

The four reaches of Douglas Creek were assessed in the summer of 2007 for river stability using the procedures outlined in *Watershed Assessment for River Stability and Sediment Supply (WARSSS)* as described in Rosgen (2006b). Cross sections, longitudinal profile data, and

Pfankuch channel stability ratings were obtained for this portion of the study. The four reaches were established with permanent markers to facilitate future monitoring of the site over time. The permanent markers (rebar pins) consisted of establishing end pins at cross section locations, establishing the start and ending point of longitudinal profiles, and placing toe pins and erosion pins at locations of bank study profiles. A resurvey of the site was completed approximately one year later, which consisted of replicating the geomorphic measurements completed in 2007.

The data collected at the Douglas Creek site was then used to complete FLOWSED/ POWERSED runs to predict bed stability of the four individual reaches. The site-specific flow duration curve was developed utilizing mean daily flow data from Nevada Creek near Helmville, Montana (USGS Gage No 12335500), which is located approximately 10 miles from the site and has a bankfull discharge of 250 cfs. The Nevada Creek gage site has the same hydro-physiographic province as the Douglas Creek watershed. Bedload and suspended load bankfull data used in the analysis were based on regional sediment relationships by drainage area established in the Blackfoot River Basin from field-measured bedload and suspended sediment concentration data collected at six sites. The FLOWSED/POWERSED runs were completed using the RIVERMorph™ software.

Results: Based on the resurvey of the monumented cross sections at each of the four reaches along Douglas Creek, Reach 1 exhibited essentially no change in cross sectional area, Reaches 2 and 4 exhibited aggradation and Reach 3 exhibited degradation. Typical plots of the surveyed cross sections from 2007 and 2008 developed using the RIVERMorph™ software are illustrated in Figure 1 through Figure 4, and the results of the cross section resurveys are summarized in Table 1.

Table 1 Results of cross sectional surveys for Douglas Creek.

Reach	2007 Area (Sq. Ft.)	2008 Area (Sq. Ft.)	Difference in Area (Sq. Ft.)	Channel Response
1	18.78	19.39	0.61	Stable
2	26.77	24.57	-2.20	Aggrading
3	16.75	23.49	6.74	Degrading
4	38.53	36.09	-2.44	Aggrading

To run FLOWSED and POWERSED, it is necessary to establish a supply riffle to first calculate the total annual sediment yield expected for the river. For the supply riffle to be effective in the FLOWSED/POWERSED analysis, it should be able to pass the sediment delivered to the watershed without aggrading or degrading. The riffle at Station 3+93 (B4c stream type) within Reach 1 of Douglas Creek was monitored for one year and essentially showed minimal change in cross sectional area and validated the “stable” bed stability. Due to the stable bed of Reach 1, it was decided to utilize this cross section as the supply reach for the FLOWSED/POWERSED analyses.

Using the cross section from Reach 1, the FLOWSED model was used to predict the total annual sediment yield being supplied to the study area. The first step in this procedure is to predict the site-specific flow duration curve using the dimensionless flow duration curve developed from the nearby gage site. The flow duration curve developed for Douglas Creek is presented in Figure 5.

The predicted bedload rating curve from FLOWSED using the Pagosa dimensionless sediment rating curves from Southwestern Colorado (Rosgen 2006a, 2006b, 2010) is shown in Figure 6. Suspended sand concentration versus discharge relation is obtained in the same manner. The sand concentration was separated from the washload (silt/clay) for use in this analysis as it is hydraulically controlled. Using FLOWSED, which includes the developed flow duration curve (Figure 5) and the bedload and suspended sediment rating curves, the estimated annual sediment yield of the stable supply reach (Reach 1) was calculated to be 43 tons of bedload transport and 443 tons of suspended sediment transport for a total sediment yield of 486 tons (Table 2).

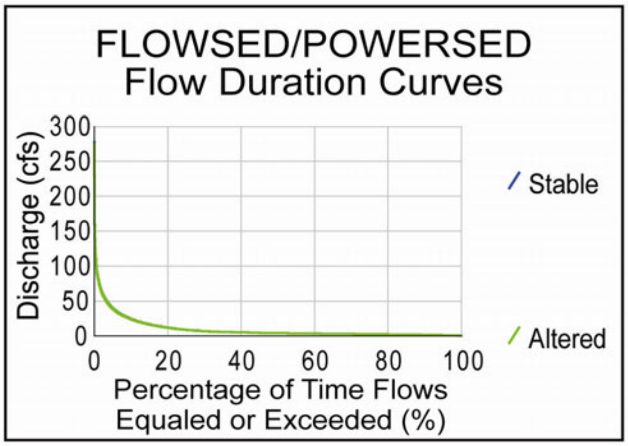

Figure 5 Flow duration curve developed for Douglas Creek.

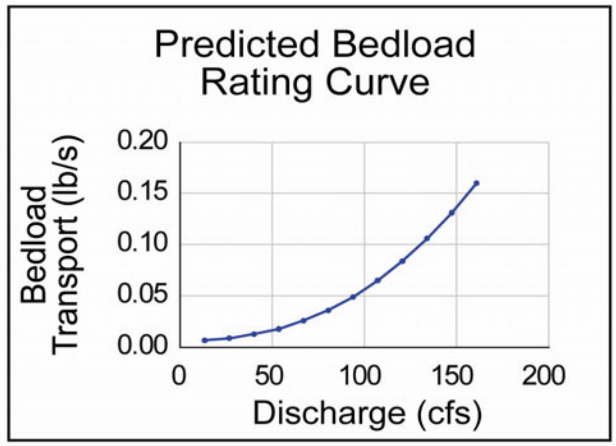

Figure 6 Predicted bedload sediment rating curve for Douglas Creek.

Table 2 FLOWSED/POWERSED results of annual sediment yield predictions for Douglas Ck.

Reach	Bedload (tons/year)	Suspended Sand Load (tons/year)	Total (tons/year)	Difference (tons/year)	Stability Prediction
1	46	443	486	N/A	Stable
2	8	198	206	-280	Aggradation
3	72	667	739	253	Degradation
4	0	142	142	-344	Aggradation

Using the POWERSED model, the change in bedload and suspended load was predicted between the supply cross section (Reach 1) and the remaining reaches. The POWERSED model utilizes changes in unit stream power between the supply and the study cross section to predict the change in sediment transport. A relationship between streamflow and unit stream power is established as shown for the supply reach and predicted Reach 2 cross-sections in Figure 7. The next step is to develop reference bedload and suspended sediment curves from the supply cross section by plotting bedload transport rate and suspended sand concentration separately as a function of unit stream power. The reference bedload rating curve in Figure 8 is established by plotting bedload transport versus unit stream power calculated for the supply cross section, which essentially consists of combining the relations in Figure 6 and Figure 7. The POWERSED model then uses hydraulic geometry by stage from the study cross section to calculate the unit stream power for a wide range of flows. Once the unit stream power is determined for the study cross section, the bedload transport in the supply cross section is then predicted from the reference bedload and suspended sand sediment curves adjusted for unit stream power. The resulting predictions for both annual bedload and suspended sand sediment yield for each reach are presented in Table 2.

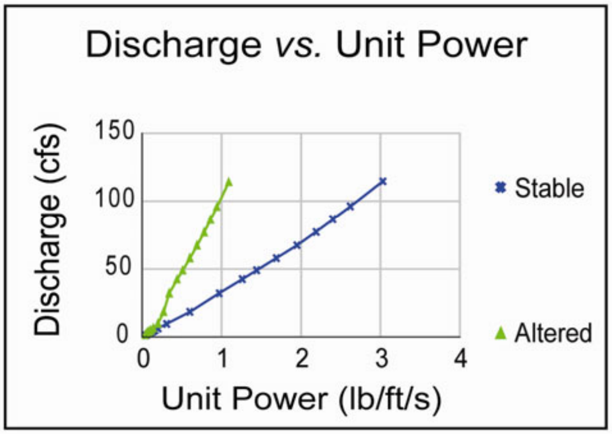

Figure 7 Conversion of streamflow *vs.* unit stream power for supply Reach 1 and predicted Reach 2.

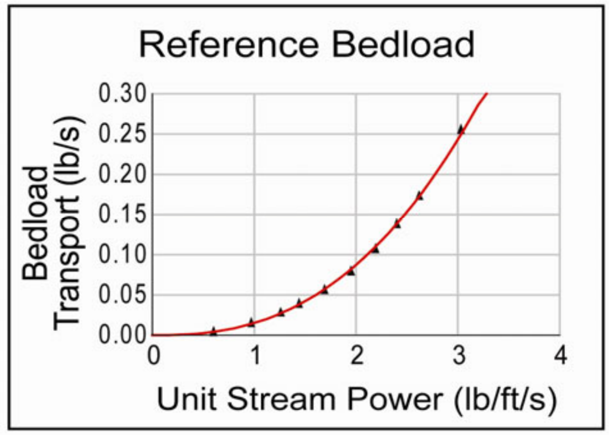

Figure 8 The reference bedload rating curve for supply Reach 1.

The predicted sediment yield values of Reach 2 show a major reduction in both bedload and suspended sand yield compared to the supply Reach 1 (Table 2). The potential reduction of 280 tons/year indicates streambed aggradation, which also agrees with the reduction of cross-sectional area from the measured cross sections for Reach 2 (Table 1). The sediment yield prediction from POWERSED for Reach 3, however, indicated degradation because the stream had excess energy to transport 26 additional tons of bedload and 224 tons of suspended sand beyond the supply, which would have to be made available from the channel. The cross-section for Reach 3 (Table 1) also indicates degradation, agreeing with the POWERSED model. Reach 4 POWERSED results indicate aggradation or insufficient energy to transport the available sediment (Table 2). The cross section data (Table 1) also agrees with the POWERSED prediction and indicates aggradation due to the loss of channel cross sectional area.

It is encouraging to have a sediment transport model predict streambed stability close to actual channel stability observations. The results of this study indicate that FLOWSED and POWERSED show great potential for future river stability applications.

<u>Culvert/Bridge Design – Unnamed Tributary to Little Bennett Creek, Maryland:</u> The placement of bridges and culverts along streams for roadways is often problematic resulting in high maintenance costs. Typically, stream crossings are over-widened relative to the stream channel upstream and downstream of the crossing in an effort to pass a designed flood through the culvert openings. Often the designs of these crossings do not adequately consider the effects of the structure on the sediment transport of the stream. The consequences of such designs are partial filling in of the structure, redirection of stream flows resulting in the potential for bank erosion, and reduced conveyance. Significant annual maintenance is often required to maintain the conveyance through the structure. Multiple cell box culverts are particularly problematic as they typically increase the width/depth ratio of the stream channel as all invert positions share the same elevation.

A study was undertaken to investigate if FLOWSED and POWERSED could adequately predict the sediment transport response through an existing multiple cell box culvert. An unnamed tributary to Little Bennett Creek located in Montgomery County, Maryland, was used as the study site. The stream is a slightly entrenched, meandering gravel-bed stream (C4 stream type, Rosgen, 1994, 1996) with a width/depth ratio of 17. A three-cell bridge (culvert) was constructed at the site that consisted of three, ten-foot wide cells. The amount of sediment in two of the three cells was measured to average approximately 0.9 feet. Pictures of the three-cell box culvert are shown in Figure 9 and Figure 10 indicating the typical deposition problem found in other similar designs.

Figure 9 Typical view of the three-cell box culvert across an unnamed tributary to Little Bennett Creek, Maryland.

Figure 10 Extensive deposition of sediment within one of the cells of the culvert.

Methods: FLOWSED/POWERSED, as programmed in RIVERMorph™, was implemented using the original design configuration of the three-cell box culvert. The model simulation was conducted using three separate cells for the computation. Bankfull bedload and suspended sand sediment values were obtained from regional sediment curves from the Maryland Piedmont region. An additional model simulation was conducted to determine a potential threshold design for sediment transport capacity (i.e., where sediment would not be deposited in any of the cells). The first iteration was to use the highest depositional elevation in the existing cells as the designed invert of the two “flood discharge” cells; the third cell would provide capacity to accommodate the bankfull discharge.

FLOWSED and POWERSED, as was done for Douglas Creek, first requires a supply riffle to calculate the total annual sediment yield expected for the river. The selected supply riffle cross section for the study was located along Macgruder Branch (Figure 11), which is located near the site and exhibits a stable bed without significant aggradation or degradation. This supply cross section has a width/depth ratio of 11.3 and classifies as a B4c stream type (Rosgen, 1994). The gage used to develop the site specific sediment rating curve is the Patuxent River near Unity, Maryland (USGS Gage No. 01591000).

The FLOWSED/POWERSED runs with the altered design of the simulated sediment transport capacity threshold using the existing 0.9 depth of the sediment deposition in the two cells is depicted in Figure 12. For the analysis, the cross section was divided into three cells.

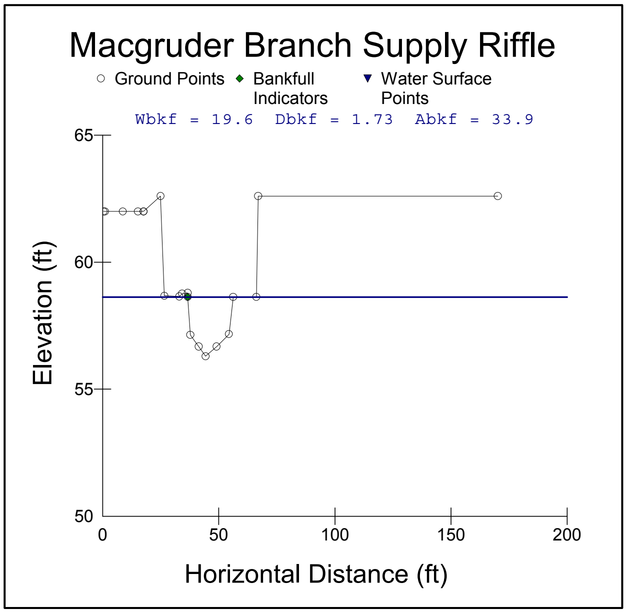

Figure 11 Macgruder Branch supply riffle cross section.

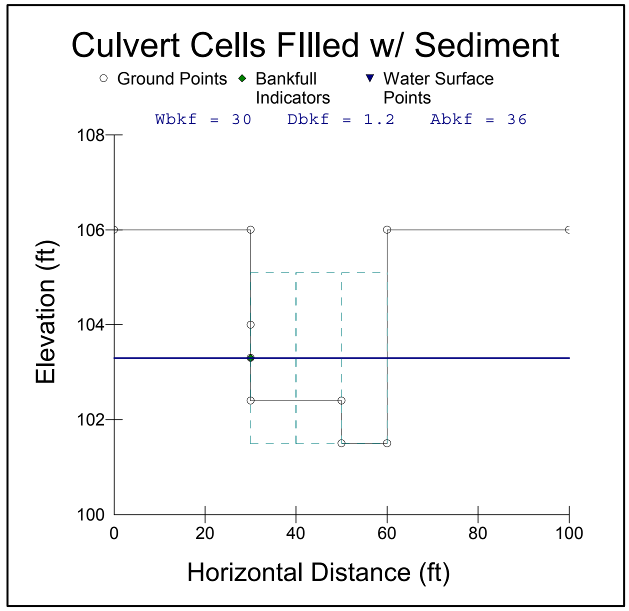

Figure 12 Cross section used to simulate the sediment transport capacity of the three cell box culvert with two of the cell inverts at the deposition height of the existing boxes.

Results: The triple-cell box culvert was simulated in RIVERMorph™ using FLOWSED and POWERSED that mimicked the original design of the three-cell box culvert. FLOWSED and POWERSED were run using similar procedures as previously described for Douglas Creek. Using the FLOWSED model, the supply for flows up to and including bankfull flow was calculated to be 102 tons per year for bedload and 99 tons per year for suspended sand sediment for a total annual sediment yield of 201 tons (Table 3). The POWERSED model calculated that with the original design, the three-cell bridge would only have the capacity to transport 45 tons of bedload and 51 tons of suspended load for a total annual sediment of 96 tons. This is roughly 45% of the sediment supply being delivered to the system, which indicates that the empty culvert would be subject to aggradation. The amount of excess sediment was calculated at 105 tons. Converted back to square feet of area for this structure resulted in an estimate of 72.7 square feet. The amount of deposition existing in the two cells was 54 square feet. This represents a 26% difference in predicted deposition.

A model run was then completed for the cross section design as shown in Figure 12 with two of the three cells raised to the level of the deposition. Results of this run indicated that this design would now be able to transport 123 tons per year of bedload and 81 tons per year of suspended sediment for a total annual transport of 204 tons, which compares closely to the supply sediment of 201 tons. This indicates that the culvert had reached an approximate equilibrium with 0.9 feet of sediment deposited in two of the three cells, as any additional sediment for subsequent years was routed through the culvert. Unfortunately, the deposition in the two cells reduced the flood capacity for the larger events, requiring frequent cleaning. The result of this analysis is summarized in Table 3.

Table 3 Summary of FLOWSED/POWERSED results.

Run	Bedload (tons/year)	Suspended Load (tons/year)	Total (tons/year)	Difference (tons/year)	Stability Prediction
Supply	102	99	201	N/A	N/A
Original design	45	51	96	105	Aggradation
Culvert with two raised cells to deposition level	81	123	204	3	Stable

The results of the FLOWSED/POWERSED runs indicate that the models can accurately predict channel and culvert response relative to observed depositional patterns. Accordingly, the models can be valuable tools in the future engineering design of culverts and bridges.

An alternative method of constructing multiple cell box culverts and multiple cell bridges is to construct one of the cells at close to the thalweg elevation of the channel with a designed capacity to accommodate the bankfull discharge with the appropriate width/depth ratio. The remaining cell inverts are located at the bankfull elevation such that the additional storage capacity of the bridge is accessed at flood flows above bankfull. This approach was utilized by the Maryland Department of Highways (See Figure 13 and Figure 14) and has resulted in significant reduction in maintenance costs, has maintained the channel stability, and has improved fish habitat. This approach sustains culvert conveyance over time without the need for maintenance.

Figure 13 Multiple-cell culvert constructed with two cell inverts at bankfull elevation.

Figure 14 The multiple-cell culvert in Figure 13 performing at high flow.

River Restoration – Applications of FLOWSED and POWERSED: River restoration using natural channel design involves proposed channel dimensions, pattern and profile associated with discharges that range from baseflow, bankfull and the flood stage. To determine the success of such a proposed channel design, one must predict the sediment competence and capacity as part of the assessment (Phase III) and design (Phase V and VI) (Rosgen, 2007). FLOWSED and POWERSED are used to predict sediment transport capacity to evaluate the stable "reference reach," the existing condition as well as the proposed design reach. Prior to finalization and implementation of the design, it is imperative to complete the sediment transport capacity calculations. For example, if the proposed channel depth indicates either aggradation or degradation, then a revised cross-section would be simulated to obtain a sediment balance. The wrong slope from a pattern problem would also be accurately depicted in the models to enable the designer to modify the pattern necessary to reflect a stable slope.

In a previous study involving two separate locations on Weminuche Creek in Southwestern Colorado, FLOWSED/POWERSED predicted within 3.5% of the accuracy of the total annual sediment yield for the meandering, gravel-bed (C4) stream reach and within 6% of the braided, gravel-bed (D4) stream reach (Rosgen, 2006a). FLOWSED and POWERSED can justify confidence in the predicted sediment yield output due to its consistency of prediction.

FLOWSED and POWERSED have been successfully applied on over 16 major restoration projects using natural channel design procedures between these authors. The models are also used for cumulative watershed impact assessments dealing with impaired streams as part of *WARSSS* (Rosgen, 2006b).

SUMMARY

As greater demands are placed on river systems and even greater expectations of success from those working to improve the health and function of river systems, it is essential that our predictive tools are reliable, accessible, practical and reasonable. The reality of the inherent complexity and uncertainty of sediment transport capacity predictions will not diminish;

however, with continued validation of such models, our applications and testing may provide better answers for the future. The results of this study provide renewed confidence of the applications FLOWSED and POWERSED can have for appropriate stability predictions, better bridge and culvert designs, and for realistic sediment consequence predictions for river restoration.

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