RIVER RESTORATION CHANNEL DESIGN: BACK TO THE BASICS OF DOMINANT DISCHARGE

Martin W. Doyle[1], Karin Fischer Boyd[2] and Peter B. Skidmore[2]

ABSTRACT

Channel design in river restoration is often based on matching channel capacity to the dominant discharge (Q_{dom}). Various working definitions of Q_{dom} have led to the use of measures such as Q_{ri} (return interval), Q_{bf} (bank-full) and Q_{eff} (effective) to estimate Q_{dom}, with Q_{bf} and Q_{ri} being the most commonly used values due to their ease of determination. Past research is inconclusive as to the reliability using Q_{ri}, Q_{bf} and Q_{eff} as measures of Q_{dom} within various channel types or geographic regions. This study examines various calculated values of dominant discharge for three rivers: Lincoln Creek (Wisconsin), the East Fork Carson River (Nevada), and the Teton River (Montana). For these rivers, Q_{ri}, Q_{bf} and Q_{eff} are not at all similar for unstable channels and channels which have 'poorly-sorted' flows (a term introduced in this paper). For these study sites, Q_{eff} was suggested for use in channel design to ensure that channel configuration would remain stable in time as well as to determine optimal channel configuration to compensate for altered watershed characteristics (e.g. dam removal). Such predictions were not possible using Q_{ri} or Q_{bf}. Based on this study, Q_{eff} is suggested to be used in preference to Q_{ri} or Q_{bf} for channel design.

INTRODUCTION

In designing a channel during restoration efforts, the application of an appropriate design discharge for channel conveyance is critical to long-term channel stability. A channel which is sized and shaped appropriately should remain stable through time given consistent watershed conditions. Channel stability is ultimately dependent on the ability of the channel to convey a proper amount of sediment, that is, significant changes in channel morphology indicate an imbalance in the sediment budget. A stable stream, with appropriate channel characteristics, should provide just the velocity required for transportation of all of the sediment supplied from above (Mackin, 1948). In channel restoration, it is the condition of sediment continuity that is critical in channel design.

River restoration to this point has considered dominant discharge (Q_{dom}) as that discharge which a channel should be designed to convey. Q_{dom} is the flow that is equivalent to the effects of all the varying flows experienced over a period of time, and hence, that flow which is dominant in controlling channel form. This serves as an excellent concept, however, quantifying a value for Q_{dom} is problematic. The following

---

[1] Dept of Earth and Atmos. Sciences, Purdue Univ., W. Lafayette IN 47907, mdoyle@purdue.edu

[2] Inter-Fluve, Inc. 25 N. Willson Ave Suite 5, Bozeman MT 59715, dmfluve@aol.com

are attempts to generate quantitative expressions for discharge values that are believed to approximate Q_{dom}, and hence provide a practical approach for channel design:

1) the effective discharge or that discharge which over time, transports the most bed load (Q_{eff}).
2) the natural bankfull discharge (Q_{bf}), and
3) a discharge based on statistical return intervals (Q_{ri}) such as the 2-yr flow,

Q_{eff} for Channel Design

In regards to channel stability, any change in the morphology of a river is the result of an imbalance in the sediment budget. Q_{eff} allows for the *quantification* of the sediment budget of a channel for a given hydrologic regime. In addition, in the event of a future alteration to the watershed conditions, knowledge of the channel sediment budget can help design a channel which will react to these changes appropriately. Ironically, most discussion in the realm of applied channel restoration in recent years has focussed on the validity of the relationship of Q_{ri} to Q_{bf} (discussed below); consequently, little attention has been given to Q_{eff}, which is the most critical geomorphic and hydraulic parameter in channel design. Possible reasons for the limited use of Q_{eff} are the relatively large amount of data that are required (historical hydrology for flow duration, channel surveys for hydraulic analysis, sediment data for sediment transport analysis) and the relative inexperience of many restoration designers with sediment transport. However, due to the size and cost of many restoration projects, as well as their possible implications for public safety (e.g. flooding), data collection to allow for hydraulic and sediment transport modeling should be given adequate priority. Further, the development of numerical models for both channel hydraulics (e.g. HEC-2, HEC-RAS) and sediment transport (e.g. HEC-6, SAM) makes calculation relatively easy as well as rapid. Finally, the lack of knowledge and/or experience in sediment transport may indicate that the restoration team has an inadequate basis of expertise from which to attempt a river restoration project.

Q_{bf} for Channel Design

Studies have documented significant relationships between Q_{bf} and Q_{eff} (Andrews, 1980; Pickup and Warner, 1976). Q_{bf} has been strongly advocated in channel design, primarily through the idea of using a 'template' or 'reference' reach' (Rosgen, 1994; 1998). However, before accepting Q_{bf} as a valid design discharge, one should consider the following:

1. An unstable channel is a result and/or indicator of an unstable watershed (Shields et al., 1995);
2. Channel restoration is most often (if not always) practiced in unstable channels, and hence, unstable watersheds (the instability of a channel is the reason the channel is needs restoration);
3. Q_{bf} assumes *complete adjustment* of the channel/watershed to hydrologic and geomorphic conditions. This assumption, especially in areas affected anthroprogenically, is most likely invalid, and further is impossible to verify;
4. Q_{bf} assumes an unconfined channel and an unconfined floodplain. This is rarely the condition in contemporary channel design initiatives.

Thus, assuming Q_{bf} as an indicator of a stable channel regime within an altered watershed characteristics is doubtful at best. In addition, using Q_{bf} as a 'reference reach' from which to design a channel elsewhere (either in the same or different watershed) inherently requires *extrapolation* of conditions and dimensions (Rosgen, 1994; 1998). Such extrapolation and corresponding uncertainty can be greatly reduced if one uses one of many physical models which are currently available (e.g. Millar and MacVicar, 1998; Hey et al., 1998). In most cases, these physical models consider Q_{eff} (or similar sediment transport concept) as the discharge which should be considered for design, rather than Q_{bf}.

Q_{ri} for Channel Design

Early studies identified statistical relationships between channel capacity and flood recurrence intervals. In general, these studies found that Q_{bf} was somewhat related to a flood recurrence of approximately 1 to 2.5 years, although intervals of greater time were also documented (Table 1). However, there have also been studies documenting little, if any relation between Q_{bf} or Q_{eff} to any Q_{ri}. For instance, while Williams (1978) found a modal bankfull discharge of approximately 1.5 years, Andrews (1980) documented 50% of sites having Q_{bf} recurrence intervals greater than 1.75 years or less than 1.25 years. Such discrepancy in previous research suggests that assuming *a priori* that there is a significant relation between Q_{ri} and Q_{eff} or Q_{bf} for a given channel should be avoided in channel design.

Table 1. Studies relating Q_{eff} and Q_{bf} to Q_{ri} (adapted from Gregory and Madew, 1982).

Channel Feature Related to Flow	*Recurrence Interval Used*	*Geographic Region*	*Study*
Q_{bf} and Q_{eff}	$Q_{1.2} - Q_{1.4}$	Western USA	Andrews (1980)
Q_{bf}	$Q_{1.58}$	Eastern Australia	Riley (1976)
Q_{bf}	$Q_{1.58}$	USA	Dury (1976)
Q_{bf}	$Q_{2.0}$	Western Canada	Bray (1975)
Q_{eff}	$Q_{1.15}$ to $Q_{1.4}$	Australia	Pickup and Warner (1976)
Q_{bf}	Q_4 to Q_{10}	Australia	Pickup and Warner (1976)
Q_{bf}	$Q_{1.5}$	UK	Hey (1975)
Meander wavelength	$Q_{2.33}$	USA	Dury (1964)

To illustrate the problems with various measures of dominant discharge in stream restoration, we will investigate the relationship between Q_{ri}, Q_{bf} and Q_{eff} at four study sites which are being considered for channel restoration. These sites were selected based on their representation of a wide range of geomorphic and hydrologic settings. In each case, the choice of an appropriate channel design discharge will be discussed. The implications of sediment transport for long term river restoration within each study site will also be discussed.

RESTORATION SITES

Four sites from 3 watersheds were investigated: Lincoln Creek, having an incised reach and an upstream stable reach, the East Fork Carson River, and the Teton River (Table 2 and Figure 1). Each site is under design for channel restoration.

Table 2. Study sites descriptions

Study site	*Location*	*Watershed/Channel Description*	*Mean Daily Flow (cfs)*	*Max Daily Flow of Record (cfs)*
Lincoln Creek – Stable	WI	Urban/Stable	1.9	200
Lincoln Creek – Incised	WI	Urban/Incised	3.3	311
East Fork Carson River	NV	Agricultural, winter snow-pack/Incised	365	12,200
Teton River	MT	Undeveloped, winter snow-pack/Stable	145	20,000

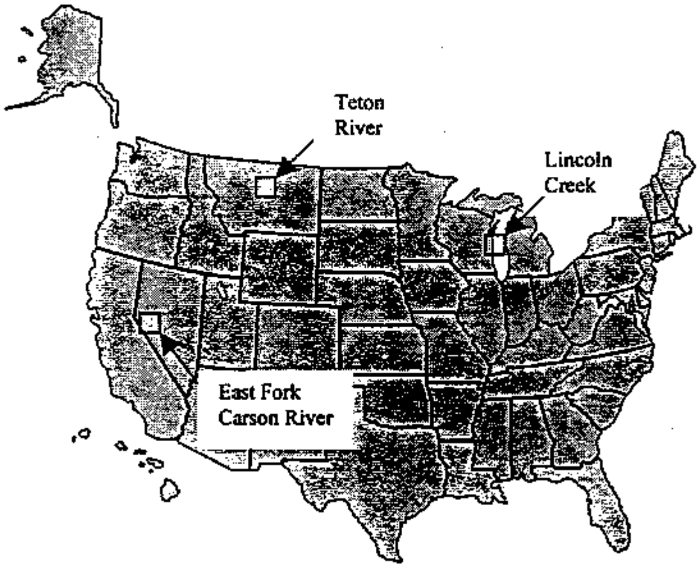

Figure 1. Study site locations

Lincoln Creek, Wisconsin

The Lincoln Creek watershed is located in Milwaukee, Wisconsin (Table 2). Historic maps indicate that Lincoln Creek is the result of channelization of wetlands in the 1930's. Lincoln Creek has been further altered to increase drainage and accommodate railroads and urbanization. Straightening of the main channel as well as increased drainage from tributaries has resulted in channel incision (downcutting and widening) into underlying sediments through the lower reaches of the study area. Two reaches are considered in this study: an incised reach and an upstream reach which is stable (upstream of the extent of channel incision).

East Fork Carson River, Nevada
The East Fork of the Carson River is located in the Upper Carson River Basin, south of Carson City, Nevada. In the 1960's, the East Fork was extensively channelized through the Carson Valley by the for the purpose of flood control. The channelization resulted in incision of the East Fork into underlying alluvial deposits. Immediately following the flood of record (20,300 cfs) in early January of 1997, the channel was excavated into a trapezoid at the project site to increase flow conveyance. Nine months later, a concrete power dam located approximately 1 mile upstream of the project site was lowered to stabilize the structure that had been damaged by the flood. The impoundment had an extensive sediment wedge which was graded upon dam lowering and left to erode naturally. By the end of the 1998 spring runoff, several thousand cubic yards of sediment had been eroded and transported downstream of the structure, jeopardizing earlier channel enlargement efforts.

Teton River, Montana
The Teton River originates on the eastern flank of the northern Rocky Mountains and flows eastward into the Marias River which joins the Missouri River near Great Falls, Montana. On the plains east of the Rocky Mountain Front, the river hydrology is dominated by spring snowmelt runoff, and summer flow limitations due to agricultural diversions. The project reach evaluated for this study is located near Fort Benton, Montana. The Teton River restoration project is primarily intended to stabilize a bridge site using natural bank protection (i.e. bio-engineered).

METHODS

For each of the three channels, Q_2 (2-yr flood event), Q_{bf} and Q_{eff} were calculated. It is difficult to independently select a return interval for Q_{ri} based on the large range of flows compared to Q_{bf} and Q_{eff} in previous studies (e.g. Table 1). Q_2 has been used in previous work (Bray, 1975) and is approximately a mid-value for the range of flows used in the other studies, so was used here. Q_2 was calculated using historic gage data for Teton River and East Fork Carson River and generated numerically for Lincoln Creek (calibrated XPSWMM model) using daily precipitation data available throughout the Lincoln Creek watershed. A log-Pearson Type 3 Distribution was used for flood-frequency analysis, as is the general recommendation by Maidment (1993). Flow duration curves were generated for each set of hydrologic data (discharge vs. percent time of exceedence). Also, the ratio of $Q_{75\%}$ to $Q_{25\%}$ (where $Q_{75\%}$ and $Q_{25\%}$ are the flows which are exceeded 75% and 25% of the time respectively) was calculated for each set of hydrologic data in order to compare the relative differences in the distribution of flows in the channels. The 75th and 25th percentiles were used rather than the 84th and 16th percentiles (commonly used in sediment distribution analysis) so as not to imply that the flow duration curve is a probability curve. The flow duration curve is not a probability curve due to the fact that daily discharge is correlated between successive days (a given day's discharge is dependent on the previous day's discharge) and discharge characteristics are dependent on season of the year (Maidment, 1993).

Survey data were collected along the project reaches and used for the development of a HEC-RAS hydraulic model. These models were used to calculate Q_{bf} as well as the hydraulic characteristics for the sediment transport relations for the determination of Q_{eff}. Because hydraulic characteristics varied between sites, various sediment transport relations were used to establish sediment budgets. The hydraulic package SAM was used for sediment transport calculations as it provides recommendations for appropriate sediment transport relations to use as well as rapid calculation of sediment transport quantities (Thomas et al., 1993). A summary of the models used is given in Table 3. Finally, a sediment-discharge rating curve (sediment discharge vs. discharge) was generated using the flow-duration results and the sediment transport results.

Table 3. Sediment transport relations used for each channel

Channel	*Sediment Transport Relation Used*
Lincoln Ck – Stable	Laursen-Copeland
Lincoln Ck – Incised	Laursen-Copeland
E. Fork Carson Riv	Meyer-Peter-Muller
Teton Riv	Brownlie

RESULTS AND DISCUSSION

There were large discrepancies between the values of Q_2, Q_{bf} and Q_{eff} for the study sites (Table 4). These discrepancies relate to differences in the morphology and hydrology of the channels.

Table 4. Calculated values for Q_2, Q_{bf} and Q_{eff} for the study sites. Numbers in parentheses indicate the percent difference from Q_{eff}.

	Lincoln Creek - Stable	*Lincoln Creek - Incised*	*East Fork Carson River*	*Teton River*
Q_2 (cfs)	39 (86%)	70 (40%)	2500 (79%)	1000 (25%)
Q_{bf} (cfs)	18 (-14%)	200 (300%)	6800 (386%)	900 (13%)
Q_{eff} (cfs)	21	50	1400	800

Effects of Channel Morphology

With respect to channel morphology, the channels can be grouped into two categories: stable and incised. Stable refers to channels exhibiting primarily local erosion rather than overall degradation or aggradation. Incision of Lincoln Creek-Incised and the East Fork Carson River has led to high values of Q_{bf} in comparison to Q_{eff} and Q_2. This is not surprising in light of the fact that deepened and widened channels will contain greater than normal flows. In contrast, the stable channels (Lincoln Creek – Stable and Teton River) have relatively good agreement between Q_{eff} and Q_{bf}, indicating the adjustment of the channel to the range of discharges that transport the bulk of the sediment load (Andrews, 1980).

It is also important to note that the sediment-discharge rating curves for Lincoln Creek-Incised and the East Fork Carson River are much 'broader' than the curves for Lincoln Creek-Stable and Teton River (Figure 2). This broader curve indicates that sediment transport is distributed over a large range of flows in contrast to the narrow range of flows for Lincoln Creek-Stable and Teton River. It is suggested that this broad distribution of sediment moving flows is a result of the increased capacity of incised channels. The increased channel conveyance confines larger-than-normal flows, and reduces dissipation of erosive energy onto the floodplain. Thus, larger flows in incised channels, though infrequent, convey inordinately large quantities of sediment because they are confined to the enlarged channel. In contrast, in stable channels with a lower floodplain, large flows will convey less sediment because they are spread out on the floodplain.

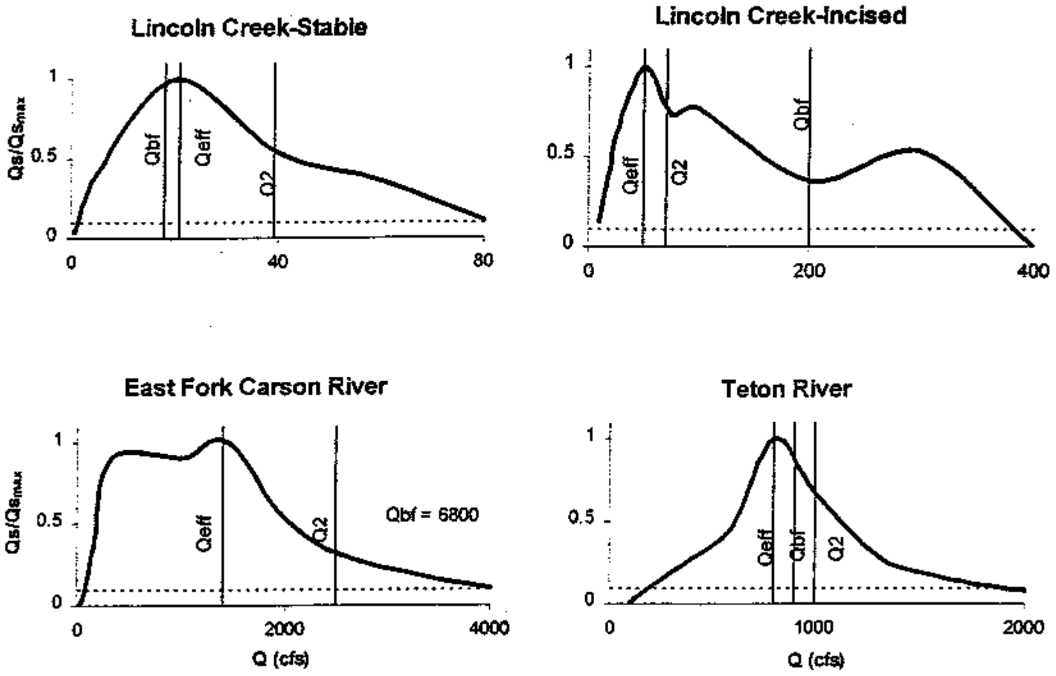

Figure 2. Sediment-discharge rating curves the study sites. Dotted line indicates Qs/Qsmax of 0.1 so as to plot curves on relatively scaled horizontal axes.

To the knowledge of the authors as well as others researching incised channels (A. Simon, personal communication), relationships between Q_{eff}, Q_{bf} and Q_{ri} have received little, if any, attention in incised channels. However, based on current knowledge of how channels evolve during incision (Schumm et al., 1984; Simon, 1989), it is expected that Q_{eff} and Q_{bf} will constantly change as the channel adjusts until the channel reaches a state of 'quasi-equilibrium' (Simon, 1989). At the point of quasi-equilibrium, Q_{bf} and Q_{eff} will continue to adjust, but by smaller amounts as the channel continues to stabilize. Although speculative, it is expected that, after the channel has continued to equilibrate for a large period of time with the new channel/watershed conditions, the sediment-discharge

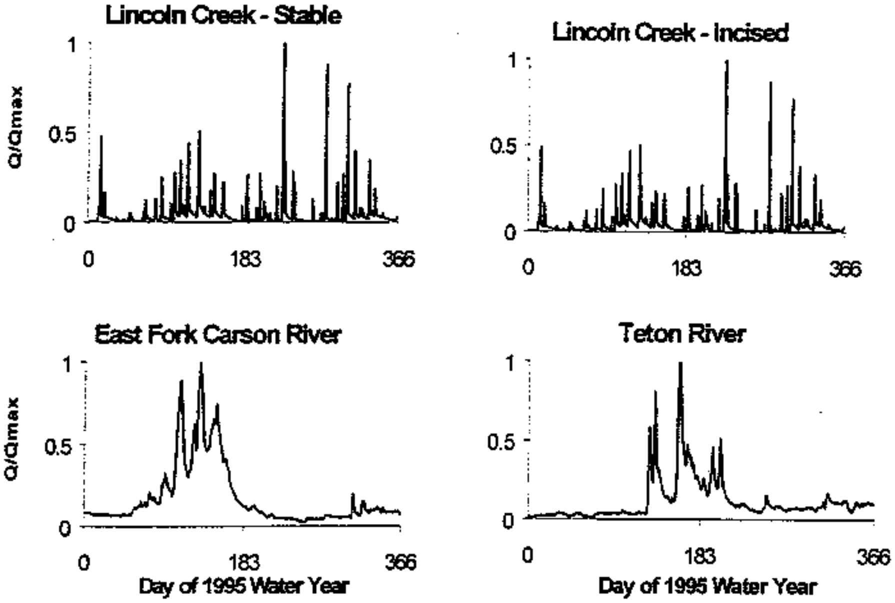

Figure 3. Example hydrographs for the study sites during 1995

rating curve will become more defined (i.e. more similar to the shape of the Teton River curve) through the development of an inset low-flow channel (Simon, 1989) Note that Q_{ri} remains constant through the adjustments.

Effects of Hydrology

Discrepancies between Q_{bf}, Q_{eff} and Q_2 in the channels should also be considered in light of the differences in watershed hydrology. As mentioned earlier, Lincoln Creek lies within a relatively small, urbanized watershed while the East Fork Carson River and Teton River have little or no urbanization in their relatively large watersheds. In addition, while the Lincoln Creek hydrology is affected by short duration storm events, the East Fork Carson and Teton Rivers are products of snow-melt driven, long duration flow events. Figure 3 shows the effect that these differences have on daily discharges. Lincoln Creek shows 'flashy' hydrographs which are in contrast to the well-defined and long-duration hydrographs of Teton River and East Fork Carson River. These differences are also noticeable in their effects on the flow duration curves of the study channels (Figure 4).

The Teton River and East Fork Carson River have what may be considered 'well-sorted' flows, while Lincoln Creek flows may be considered 'poorly-sorted.' These relative variations in sorting are reflected in the ratios of $Q_{75\%}$ to $Q_{25\%}$. (Table 5). These ratios show that the Teton River and the East Fork Carson River have clearer distinction between flood flows and normal flows (Table 5 and Figure 4), hence their characterization as well-sorted. In addition, ratios of $Q_{75\%}/Q_{25\%}$ were calculated for three channels in southwest Montana which are driven by snow-melt hydrology for further comparison. In contrast to well-sorted snow-melt driven hydrology, the flashy nature of the Lincoln Creek Watershed leads to poorer distinction between flood flows and normal flows and hence the poorer sorting (Table 5) as reflected by the relatively low values of

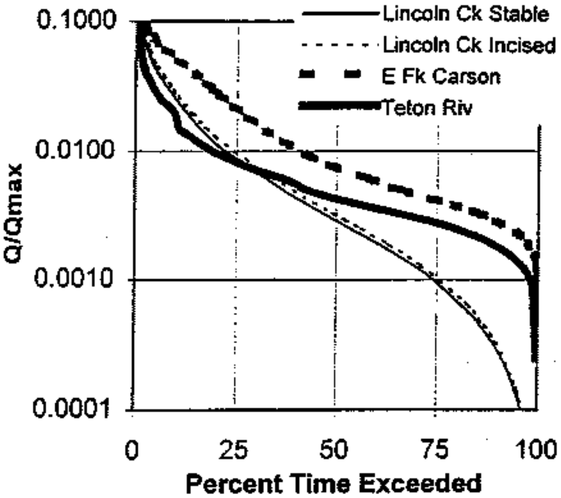

Figure 4. Flow duration curves relative to Qmax (see Table 2)

Table 5. Ratios of $Q_{75\%}$ to $Q_{25\%}$ for mean daily flows. High values of $Q_{75\%}/Q_{25\%}$ indicate well-sorted flows, low values indicate poorly sorted flows.

Channel	*$Q_{75\%}$ (cfs)*	*$Q_{25\%}$ (cfs)*	*$Q_{75\%}/Q_{25\%}$*
Lincoln Ck – Stable	0.2	1.8	0.11
Lincoln Ck – Incised	0.3	3.2	0.09
E Fork Carson Riv	83	420	0.19
Teton Riv	55	160	0.34
Nevada Riv[a]	9	30	0.30
Rock Ck[a]	34	100	0.34
Ruby Riv[a]	100	165	0.61

[a] These channels are not a part of the study, but are shown for comparison

$Q_{75\%}/Q_{25\%}$. The authors are unaware of any similar analysis of hydrologic data or other attempts to quantify 'flashy' hydrology. However, we wish to emphasize that no relations between $Q_{75\%}/Q_{25\%}$ and physical (morphologic) features have been investigated, and that no conclusions should be drawn from our simple analysis. Rather, we are introducing a term distinguish hydrology which may drive channel morphology. Further data sets would need to be collected and analyzed to determine proper delineation of 'well-sorted' and 'poorly sorted' flows, as well as their physical implications on stream dynamics.

The two stable channels provide the most insight into the effects of watershed hydrology on channel configuration because of the overwhelming influence of morphologic adjustment on the two incised channels (as discussed earlier). The Teton River showed the greatest agreement between Q_{eff}, Q_{bf} and Q_2 (Table 4) while Lincoln Creek – Stable showed good agreement between Q_{bf} and Q_{eff}, but poor agreement between Q_{eff} and Q_2. Just as the incised channels had broader sediment-discharge rating curves, so Lincoln Creek – Stable has a broader curve than the Teton River. While Q_{eff} lies at the center of a narrow curve for Teton River, on Lincoln Creek – Stable, Q_{eff} and Q_{bf} lie within a broader range of flows capable of moving similar quantities of sediment. Because both channels are considered stable, the relative difference in shape of the two curves can be attributed to their differences in hydrology. We suggest that a channel with well-sorted flows will experience significant flows (i.e. flows capable of producing bed and bank adjustments) for a large period of time. This period of time allows the channel to adjust its bed and banks to an optimal channel configuration for water and sediment conveyance, and thus a narrow sediment-discharge rating curve. In contrast, if a channel experiences a variety of large, channel forming flows for only short periods of time (poorly sorted), the channel may never attain an optimal configuration. This inability to reach an optimal configuration is reflected by a large range of flows capable of moving similar amounts of sediment (i.e. a broad sediment-discharge rating curve).

Interactions between Morphology and Hydrology

The discussions above have attempted to separate morphology and hydrology as independent driving factors of sediment transport, in order to identify causes of variation in Q_{eff}, Q_2 and Q_{bf}. In reality, and as would be expected, the two are inter-related. For instance, Doyle and Shields (1998) showed that channel incision resulted in decreasing the time a given flood event passed through a channel. That is, incision promoted flashy hydrology. Similarly, Simon and Curini (1998) suggested that the duration of storm events can be of greater consequence in morphologic adjustment (specifically bank failure) than the size of the flood event.

IMPLICATIONS FOR CHANNEL DESIGN

Each of the study sites is a channel under design for restoration. The incorporation of sediment transport into channel restoration design, and specifically the value of the knowledge of Q_{eff} rather than Q_{bf} or Q_2 for each of the cases is discussed below.

Lincoln Creek – Stable and Lincoln Creek – Incised

There have been an increasing number of attempts to restore incised channels, many of which include extremely costly measures such as raising the channel bed to pre-incision conditions or lowering the floodplain to match the new, incised conditions. In many cases, it has been suggested that a template reach from upstream or from an adjacent watershed be used for sizing the channel (Rosgen, 1998; 1994). However, template reaches offer little knowledge on how a channel is passing sediment (i.e. which flows are conveying the majority of sediment or how much sediment is being conveyed). It must be assumed that the template reach is stable (has reached full equilibrium) and that its conditions are applicable to the reach to be restored. In reality, a stable template reach may not have begun adjusting to the altered watershed conditions which caused the instability of the project reach. In the case of Lincoln Creek, sediment mobility was calculated for the stable reach (located upstream of the extent of incision), as well as other reaches along the channel which were either incising or recovering from incision (i.e. aggrading their beds). In this manner, an envelope of conditions could be developed which allowed for optimization of channel characteristics in order to assure that the restored channel would mobilize the same quantity of sediment that was being delivered to it.

East Fork Carson River

In addition to the East Fork Carson River channel recovering from incision, approximately one mile upstream of the restoration project site, a dam was lowered due to public safety concerns. The concerns at the restoration project site were: 1) to ensure that the historic incision was complete, and 2) to ensure that the sediment transported from the dam site would not fill the channel and thus increase the frequency of flooding of local farm land and an adjacent fish hatchery. Sediment transport and geomorphic analysis revealed that the incised channel had begun to aggrade (recover) and form an inset low-flow channel in a small portion of the project reach. Geomorphic and sediment transport analysis also revealed that in the area where the channel had been excavated and no low-flow channel had formed, the channel would most-likely not be able to pass the vast amount of sediment stored upstream of the dam. Hence, in the reaches where a well-defined low-flow channel had not formed or had been excavated out, one was designed to convey the calculated Q_{eff}. This configuration should maintain maximum transport of the sediment stored upstream of the dam.

Teton River

The Teton River restoration project is intended to stabilize a bridge site using natural bank protection (i.e. bio-engineered). Calculations of Q_{bf} and Q_{eff} were intended to assure that the channel would not be prone to large morphologic changes in the future. By assuring that Q_{eff} and Q_{bf} were closely related (as demonstrated in Figure 2 and Table 4), it can be reasoned that the channel is in its most stable configuration. Thus, bio-engineering techniques may be used to address present concerns only (i.e. local scour and deposition) and not concerns of morphologic changes brought on by sediment imbalances (i.e. reach-scale degradation or aggradation).

CONCLUSIONS

Previous studies have attempted to relate Q_{eff}, Q_{bf} and Q_{ri}. However, discrepancies in these studies are numerous and thus making the use of assumed relations between Q_{eff}, Q_{bf} and Q_2 a poor tactic for channel design. It is suggested that in sizing a channel, preference should be given to Q_{eff} over Q_{bf} or Q_2. This study found marked variations between Q_{eff}, Q_{bf} and Q_2 for two incised channels. Agreement increased for a stable, urbanized channel and was the greatest for a stable channel driven by a well-sorted, snow-melt hydrology.

In regards to channel design and the determination of a design discharge, the following conclusions are suggested from this study:

1. Strong agreements between Q_{eff}, Q_{bf} and Q_2 are rare and were not supported by this study for 3 out of 4 cases. Assuming that any one of these adequately predicts the others is likely to lead to an incorrectly sized channel.
2. Incised channels have a large range of flows capable of conveying large quantities of sediment. Q_{bf} and Q_{eff} will most likely be temporally dynamic in incised channels until the channel has regained stability.
3. Channels which have 'well-sorted' flows will be more likely to have a narrow range of sediment-moving discharges in comparison to those with 'poorly-sorted' flows. This is a reflection of the channel adjustment to large duration channel-forming flows.
4. Q_{eff}, although more difficult to calculate than Q_{bf} or Q_2, offers the most information about channel dynamics and the interaction of the channel to watershed hydrology. In addition, its calculation allows for the optimization of channel size for specific sediment transport concerns.

ACKNOWLEDGEMENTS

Support for this study while the first author was at Inter-Fluve, Inc. is greatly appreciated. Mike Rotar and Dewitt Domminick provided data for the East Fork Carson River and Teton River, respectively. This study benefited greatly by discussion and reviews of an earlier version by Jon Harbor and Derek Fabel.

REFERENCES

Andrews, E.D. (1980). Effective and Bankfull Discharges of Streams in the Yampa River Basin, Colorado and Wyoming. Journal of Hydrology, 46: 311-330.

Bray, D.I. (1975). Representative Discharges for Gravel-Bed Rivers in Alberta, Canada. Journal of Hydrology 27: 143-153.

Doyle, M.D. and F.D. Shields (1998). Perturbations of Stage Hydrographs Cause by Channelization and Incision. ASCE Water Resources Engineering, Memphis.

Dury, G.H. (1964). Principles of Underfit Streams. USGS Professional Paper 452A.

Dury, G.H. (1977). Peak Flows, Low Flows and Aspects of Geomorphic Dominance. In Gregory, K.J. (ed.), River Channel Changes. John Wiley and Sons Ltd.

Gregory, K.J. and J.R. Madew (1982). Land Use Change and Flood Frequency and Channel Adjustments. In Hey, R.D., J.C. Bathurst and C.R. Thorne (eds), Gravel-bed Rivers. John Wiley and Sons Ltd.

Hey, R.D. (1975). Design Discharge in Alluvial Channels. In Hey, R.D. and T.D. Davies (eds.), Science, Technology and Environmental Management: pp. 73-88. Saxon House.

Hey, R.D., B.R. Hall and R.R. Copeland (1998). Determining the Design Discharge for Channel Restoration Projects. ASCE Wetlands Engineering and River Restoration Conference, Denver.

Mackin, J. H. (1948). Concept of a Graded River. Bulletin of the Geological Society of America Vol. 89: 463-512.

Maidment, D.R. (1993). Handbook of Hydrology. McGraw Hill, Inc.

Millar, R.G. and B.J. MacVicar (1998). An Analytical Method for Natural Channel Design. ASCE Wetlands Engineering and River Restoration Conference, Denver.

Pickup, G. (1976). Adjustment of Stream Channel Shape to Hydrologic Regime. Journal of Hydrology 30: 365-373.

Pickup, G. and R.F. Warner (1976). Effects of Hydrologic Regime on Magnitude and Frequency of Dominant Discharge. Journal of Hydrology 29: 51-75.

Riley, S.J. (1976). Aspects of Bankfull Geometry in a Distributary System of Eastern Australia. Hydrological Sciences Journal 21: 545-560.

Rosgen, D. (1994). Applied River Morphology. Wildland Hydrology Publications.

Rosgen, D. (1998). The Reference Reach – A Blueprint for Natural Channel Design. ASCE Wetlands Engineering and River Restoration Conference, Denver.

Schumm, S.A., M.D. Harvey and C.C. Watson (1986). Incised Channels: Morphology, Dynamics and Control. Water Resources Publications.

Shields, F.D., C.M. Cooper and S.S. Knight (1995). Experiment in Stream Restoration. Journal of Hydraulic Engineering 121(6): 494-502.

Simon, A (1989). The Discharge of Sediment in Channelized Alluvial Streams. Water Resources Bulletin 26(6): 1177-1188.

Simon, A. and A. Curini (1998). Pore Pressure and Bank Stability: The Influence of Matric Suction. In ASCE Water Resources Engineering, Memphis.

Thomas, W.A., Copeland, R.R., Raphelt, N.K. and McComas, D.N. (1993). Users Manual for the Hydraulic Design Package for Channels (SAM). Draft Report, US Army Engineers Waterways Experiment Station, Vicksburg, Miss.

Williams, G.P. (1978). Bankfull Discharge of Rivers. Water Resources Research 14(6): 1141-1154.