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“Effective Discharge” as an aid to river rehabilitation

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SUMMARY: The size of a natural alluvial channel is highly variable depending, amongst other things, on the characteristics of its flow regime. The size of a river channel may alter in response to changes in the magnitude, duration or hydraulic characteristics of the flows. Such geomorphic change can be a major contributor to degradation of riverine environments. Examples include channel changes downstream of dams or retarding basins, channel changes downstream of urban areas, or channel changes as a result of physical changes to floodplains.

Successful river rehabilitation in these situations relies on understanding the direction and magnitude of geomorphic response to hydrologic or hydraulic change.

This paper presents two examples of channel change associated with river regulation downstream of dams and diversions: one case of channel enlargement and one case of channel contraction.

In its original form, the *effective discharge* concept proposes that an alluvial channel will adjust its size and shape such that its bankfull capacity corresponds to that discharge which, through time, is responsible for moving the most sediment. Thus, the *effective discharge* concept provides a relationship between the hydrologic characteristics of the channel, the hydraulic characteristics of the channel and the geomorphic characteristics of the channel. By providing a link between hydrology and geomorphology, it has the potential to allow predictions of the direction and magnitude of channel response to hydrologic change.

This paper explores a modification to the *effective discharge* concept based on stream power. The modified *effective discharge* approach is applied to the two examples of channel change to see if the concept could have predicted the direction and magnitude of the channel response that has been observed since river regulation.

The examples indicate that a stream power based *effective discharge* approach has potential to contribute to prediction of river channel change and hence to consideration of river rehabilitation options.

1. INTRODUCTION

Human activities can change the natural magnitude and sequences of river flows. Examples of such activities include construction of dams, diversions, or retarding basins, urban development, clearing of vegetation, remodelling of floodplains or land drainage.

If the natural sequence of flows that formed the channel is altered, changes in the size, shape and form can be expected in the river channel (Petts 1979).

Changes in the size, shape or form of a river channel can have significant adverse effects on environmental values. In some cases this can lead to broad based community demand for ameliorative action. For example, years of community and scientific concern over the downstream hydrologic and geomorphic impacts of the Snowy Mountains Scheme have lead governments in South Eastern Australia (Snowy Water Inquiry 1998) to consider options for improving river condition downstream of the Scheme’s dams and diversions.

Ameliorative actions can take different forms. The subject of this paper, r*iver rehabilitation* is taken to lie between the two extremes of *river restoration* (recreating an original river condition) and *habitat enhancement* (artificially improving habitat). *River rehabilitation* implies a less complete treatment than river restoration but one that is based more on recreating the natural attributes of the system than is necessarily the case in habitat restoration. *River rehabilitation* is “selective restoration”. It endeavours to rebuild the most environmentally important components of river character.

Successful *river rehabilitation* implies a managed interventionist approach. In general, for this to be successful, it requires an understanding of the direction and magnitude of the geomorphic changes occurring in the river channel.

2. TWO EXAMPLES OF CHANNEL CHANGES ASSOCIATED WITH CHANGES IN FLOW REGIME

This paper presents two examples of channel change associated with river regulation downstream of dams and diversions: one case of channel enlargement and one case of channel contraction.

2.1. Example One: Tumut River at Tumut

The Tumut River at Tumut is downstream of the Snowy Mountains Scheme: a water utilisation and hydro-electric project constructed mainly in the 1950s and 1960s in the Great Dividing Range of south eastern Australia (Snowy Mountains Hydro-Electric Authority

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1993). Water for irrigation is diverted inland via rivers including the Tumut River.

Hydrologic changes

Figure 1 shows an analysis of daily flow data from the Tumut River at Tumut for pre and post regulation periods. Flows here are affected by upstream regulation associated with the Snowy Scheme and irrigation releases from Blowering Dam. The total flow at Tumut is increased by about 50% over pre Scheme flows. Figure 1 shows that the distribution of flows across the flow range is significantly altered as well.

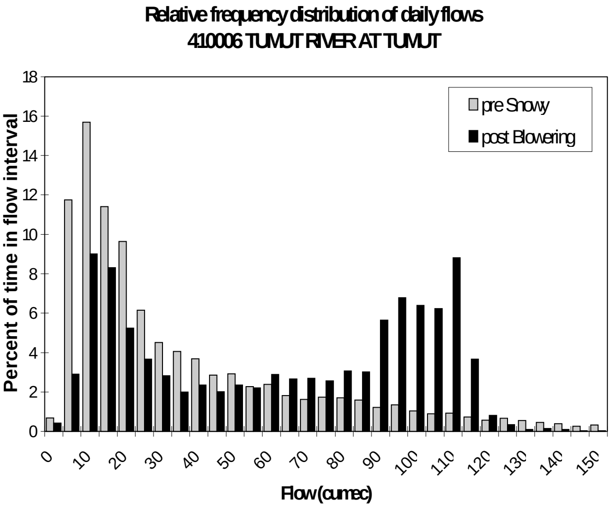


Figure 1. Example of the effect of river regulation on the amount of time that the flow spends in an interval of flow. Tumut River at Tumut.

In this case, river regulation has reduced the number of days that the river is flowing at low to moderate flows (60 m^3/s (5 200 Ml/d) or less) and increased the number of days that the river flows above this level. Regulated releases and pre-releases now mean that the river spends on average 116 days per year in the range of 90 to 120 m^3/s (7 800 to 10 400 Ml/d) compared to only 20 days/year on average in this range prior to the Scheme.

Geomorphic changes

Channel change near Tumut is shown by the change in surveyed channel cross section in Figure 2 and is illustrated in Figure 3. Gippel et al (1992) reports that stream gaugings at the Tumut gauge and cross-sectional surveys indicate that the river is generally wider and deeper than it was prior to the introduction of regulation and management.

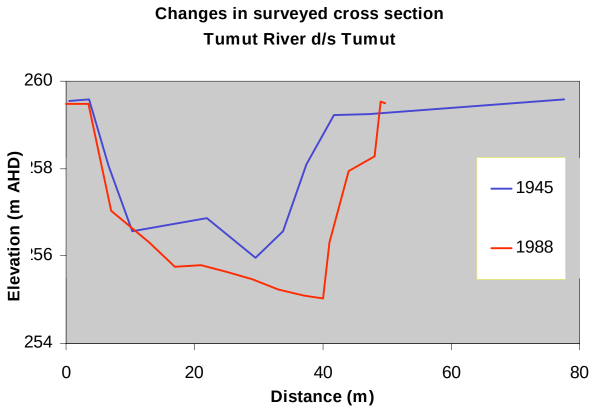


Figure 2. Cross section plot showing channel enlargement between 1945 and 1988. Tumut River downstream of Tumut.

Figure 3. Tumut River at Tumut looking downstream showing rock work on bank to control channel enlargement with active bank retreat even on the inside of a bend

2.2. Example Two: Snowy River at Dalgety

On the other side of the Great Dividing Range, flows in the Snowy River have been severely curtailed by the diversion of water inland as part of the Scheme.

Hydrologic changes

Figure 4 shows an analysis of actual flow data from the Snowy River at Dalgety, some 20km downstream of the Scheme. As indicated in the Figure, the impact of the diversions is extreme. Flow now occurs in the range of 0-5 m^3/s for 95% of the time whereas in the pre-regulation period, flows of up to 100 m^3/s occurred reasonably regularly.

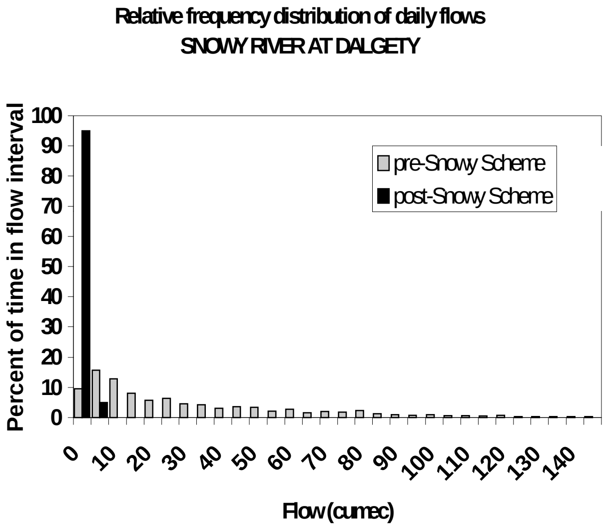


Figure 4. Example of the effect of river diversion on the amount of time that the flow spends in an interval of flow. Snowy River at Dalgety.

Geomorphic changes

Major channel contraction has occurred at this site associated with vegetative encroachment (Erskine, Terrazzolo et al. paper submitted). This is supported by comparative cross section surveys in 1949 and 1986 and illustrated by the comparative photographs in Figure 5 and by the aerial photograph in 6.

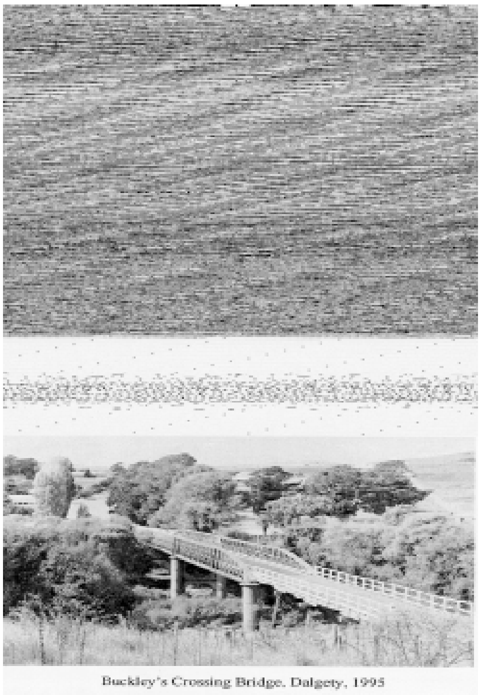


Figure 5. Photographic comparison showing vegetative encroachment and associated channel contraction. Snowy River at Dalgety. 1889 to 1995 (Snowy Genoa Catchment Management Committee 1996)

Figure 6. Aerial view of Snowy River near Dalgety 1998 showing channel contraction by formation and vegetative colonisation of in-channel bars

3. THE “EFFECTIVE DISCHARGE” CONCEPT

The “effective discharge” concept provides a possible means of explaining the above channel changes by linking geomorphic change to change in hydrologic regime.

3.1. Magnitude and frequency of forces

An alluvial channel carrying a sequence of flows will be subject to episodes of erosion and/or deposition that depend (amongst other things) on the relative magnitude of flows and the thresholds of motion of material in the bed, banks and in transport.

The largest flows have the highest energy and can do work on the channel boundaries at the greatest rate. But they occur only rarely. At the other extreme, low flows can have such low energy that they are incapable of altering the channel boundaries, regardless of how often they occur. More moderate flows, with moderate energy do work on the channel boundaries at a lower rate than the high flows, but if they persist for longer periods then these moderate flows can actually do more work over a period of time than the efficient but rare high flows. It follows that there is likely to be a discharge, at neither the high nor the low extreme, that is both sufficiently frequent and sufficiently effective to be *most important* in forming and maintaining the channel (Leopold 1994).

3.2. The “most effective” discharge

As early as 1922, an understanding of this concept had lead Schaffernak (1922) to propose that the size and shape of a river channel reflects the discharge at which most of the formative work is done. He further proposed that this discharge corresponds to that stage at which the bulk of the bed load is carried.

Wolman and Miller (1960) demonstrated that the largest proportion of total sediment load is carried by flows occurring on average once or twice each year rather than by more extreme but less frequent events. They also observed that the dimensions determining channel shape and planform are related to flows at or near the bankfull stage — flows that occur on average every year or two. This lead them to the conclusion that frequently recurring events of moderate intensity rather than rare floods of unusual magnitude are the *effective* events in forming significant alluvial landforms.

3.3. Effective discharge defined in terms of sediment transport

Building on these ideas, Pickup and Warner (1976) define the "*most" effective discharge* as:

> *…the midpoint of that range of flows, which, over a period of time transports a greater proportion of the bed-material load than any other flow range.*

4. STREAM POWER BASED "EFFECTIVE DISCHARGE"

A definition of *effective discharge* in terms of sediment transport introduces substantial practical difficulties. The rate of sediment transport is difficult to determine either by direct field measurement or by theoretical or empirically based computational approaches.

In this paper, a modified definition of *effective discharge* is proposed based on the more fundamental hydraulic formulation of *stream power* instead of *sediment transport rate*.

4.1. Stream power

Water can have potential energy by virtue of its elevation. As water flows within a channel this potential energy is converted into kinetic energy of moving water and any debris and sediment load that is carried. Energy is dissipated as the result of turbulence within the flow and by friction between the flow (and any load) and the channel boundaries. Stream power is the rate of energy expenditure.

In a channel, at least part of the energy expenditure occurs as a result of the velocity gradient in the flow close to the boundaries. This shearing of flow close to the boundary occurs as a result of the force exerted on the flow by the irregularities associated with the boundaries at a particle and a bedform scale. Per unit area of boundary, this force is the average boundary shear stress, τ_0.

Energy is expended to overcome this resisting force at a rate given by $\tau_0 U$, where U is the average velocity of flow. $\tau_0 U$ is thus the stream power per unit area of boundary (Rhoads 1987).

4.2. Stream power instead of sediment transport rate

Using stream power instead of sediment transport rate in the *effective discharge* formulation means that *effective discharge* becomes the discharge for which most energy is expended within the channel. Introducing a threshold that relates to the mobility of boundary material accounts for energy that is dissipated without being able to alter the channel boundaries.

This modified definition of *effective discharge* is:

> *…the interval of discharge that, over a period of time, accounts for a greater proportion of excess flow energy in the channel than any other interval of discharge.*

4.3. Quantifying the *effective discharge*

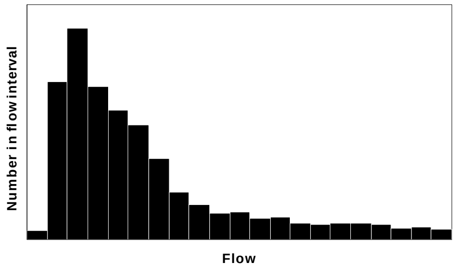
Figure 6(a) is a flow frequency histogram. It would normally represent the histogram of daily flows but other averaging durations such as hourly, weekly or monthly flows may be used depending on the rates of rise and fall of the flow hydrograph. Figure 6(b) shows a derived or measured relationship between flow and available stream power in the channel superimposed on the flow frequency histogram.

The distribution of in-channel energy with flow is then given by the product of stream power for the midpoint of each flow interval (from the function in Figure 6(b)) and the frequency with which flows occur within that flow interval (from the histogram in Figure 6(a)). The result gives *the distribution of in channel energy with flow* as illustrated in Figure 6(c). The tallest bar identifies the flow interval in which most energy is expended and according to the definition above, the mid point of this flow interval, the mode of the distribution of energy with flow, is the *effective discharge*.

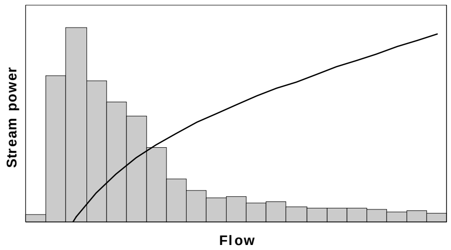
5. APPLICATIONS OF "EFFECTIVE DISCHARGE" TO PREDICTION OF OBSERVED CHANNEL CHANGES FOR THE TUMUT AND SNOWY RIVERS EXAMPLES

5.1. Tumut River at Tumut

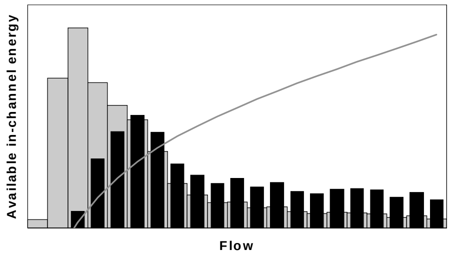
Figure 7 illustrates the results of applying the stream power based *effective discharge* concept to the Tumut River at Tumut for pre-regulation and post-regulation periods using a continuous representation of the frequency function instead of a histogram.



(a) Flow frequency histogram



(b) Stream power above a mobility threshold



(c) Effective discharge is the mode of the distribution of energy with flow

Figure 6. Quantifying *effective discharge*. Multiplying the flow frequency histogram (a) by the stream power function (b) gives the distribution of energy with flow (c). The *effective discharge* is the mode of this distribution.

For the pre-scheme case, the effective discharge is not well defined, but is around 80 m^3/s. For the post-scheme case, the distribution of excess energy is very strongly modal, indicating an *effective discharge* at 115 m^3/s.

Over a similar period, the actual change in channel size (represented as the change in bankfull channel capacity) has been deduced from rating tables for the Tumut River at Tumut (station 410006). Figure 8 shows the change in bankfull capacity in the channel through time.

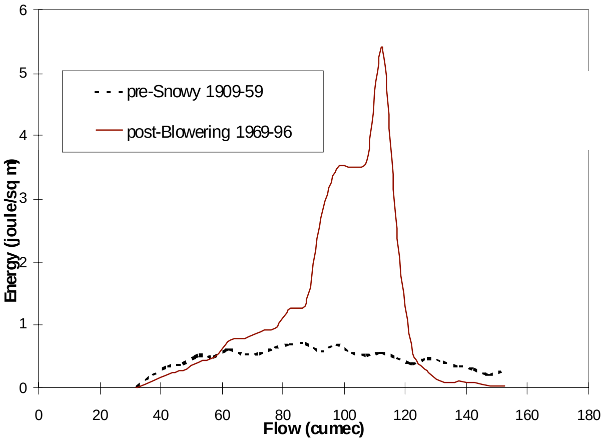


Figure 7. Distribution of excess in-channel energy with flow. Tumut River at Tumut. Pre-regulation and post-regulation periods

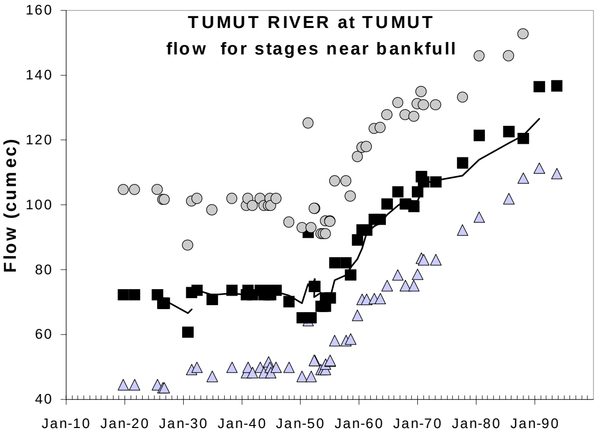


Figure 8. Flows for 3 stages near bankfull deduced from rating tables for Tumut River Gauge 410006 for 1919 to 1994. Solid line is 3 point moving average for stage of 1.6m.

At a gauge level of 1.6m for example, the ratings show a consistent flow in the channel of around 75 m^3/s in the pre-Scheme period. In the 1950s a progressive change commenced such that the flow that occurs at this same water level is now around 120m^3/s.

This evidence, supplemented by other hydraulic analyses, indicates that bankfull discharge has changed from around 75m^3/s pre-regulation to around 120 m^3/s post regulation. These estimates of bankfull discharge correspond closely with the *effective discharge* estimates of 80 m^3/s pre-regulation and 115 m^3/s. post regulation.

5.2. Snowy River at Dalgety

Figure 10 illustrates the results of applying the stream power based effective discharge concept to the Snowy River at Dalgety for pre-regulation and post-regulation periods using a continuous representation of the frequency function instead of a histogram and a very low threshold of motion.

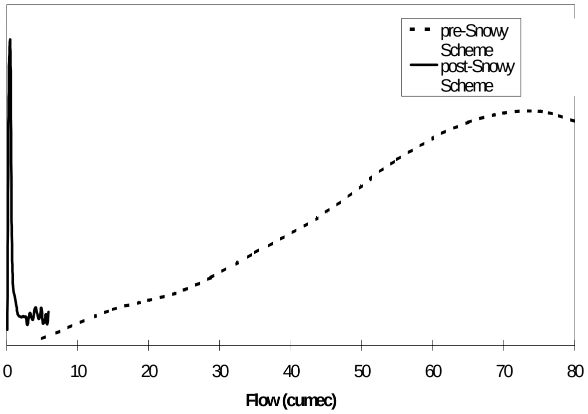


Figure 9. Distribution of excess in-channel energy with flow. Snowy River at Dalgety. Pre-regulation and post-regulation periods (plotted to different scales).

For the pre-scheme case, the effective discharge is indicated at 75 m^3/s. For the post-Scheme case the effective discharge is 0.5 m^3/s. Over a similar period, the actual change in channel size (represented as the change in bankfull channel capacity) has been deduced from rating tables for the Snowy River at Dalgety (station 222006). Figure 15shows how the flow in the channel has changed through time for a stage level corresponding to current bankfull stage.

Between 1970 and 1984, the measured flow for a stage that corresponds to the current bankfull level has reduced from 6.6 m^3/s to 0.5 m^3/s. The ratings for flows at this level prior to 1970 and after 1984 were reasonably stable. (Note that channel change has altered bankfull stage from the pre-regulation case. Therefore 6.6 m^3/s does not represent the pre-regulation bankfull discharge.)

Prior to 1970, the active channel occupied a much larger cross section and “bankfull” occurred at a higher stage. There is uncertainty about bankfull stage and bankfull discharge for this period but rating tables suggest that it was in excess of 100 m^3/s.

The current bankfull flow corresponds closely to the estimate of current *effective discharge.*

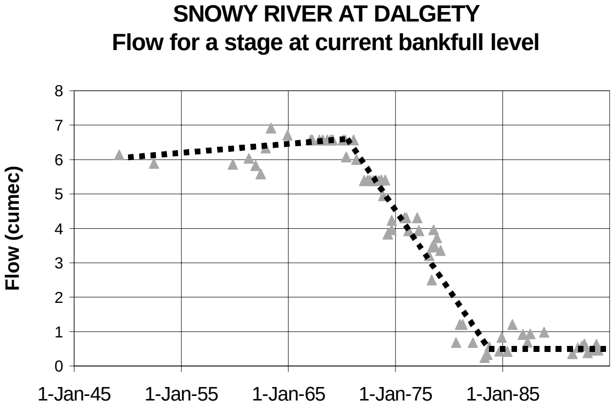


Figure 10. Flows for a stage equivalent to current bankfull level. Deduced from rating tables for Snowy River at Dalgety Gauge 222006 for 1950 to 1994.

6. DISCUSSION

6.1. Results

In two examples of major hydrologic change resulting from flow regulation, the bankfull discharge of the post regulation channel corresponds closely to the *effective discharge* calculated using a stream power approach.

Of course, two (imperfect) examples can not imply a general validity either of the *effective discharge* approach in general or of the stream power variation that was used here. However for the two case studies the stream power development of the *effective discharge* approach could have predicted the channel change that has occurred if it had been applied before flow regulation was implemented.

6.2. Interpretation

The *effective discharge* approach is not a physical process model. It is not directly representative of actual mechanisms occurring in the channel. It should not be seen as providing a prescriptive model of channel change. It should not even be interpreted to suggest that all channels will adopt a long term equilibrium state.

The stream power based *effective discharge* approach may however provide a useful indication of the likely magnitude and direction of geomorphic response to hydrologic change in an alluvial channel provided that the physical mechanisms exist for the change to occur.

In the case of the Tumut River, channel enlargement was actually triggered prior to regulation. Figure 8 shows that the change commenced around 1955 whereas regulation did not commence until 1959 and Blowering was not completed until 1969. Gippel et al (1992) suggests a sequence of floods or commencement of de-snagging operations as possible triggers. The same channel enlargement occurred in the adjacent unregulated Goobarragandra River. However, while the Goobarragandra River has narrowed and shallowed since the episode of enlargement, the Tumut River has continued to slowly widen, and this would seem to be a response to the regulated flows. Whatever the trigger and whatever the mechanism, an enlarged channel persists in the post regulation period.

On the Snowy River at Dalgety, channel contraction may not have occurred had not vegetative encroachment provided the mechanism of channel change. Indeed, further downstream at Jarrahmond, the predicted reduction in bankfull channel capacity is presumed not to be happening because no mechanism is occurring to allow channel contraction to persist.

6.3. Conclusion

The Tumut and Dalgety examples suggest that the stream power based *effective discharge* approach can assist in predicting channel response to hydrologic change under certain conditions.

In both the examples, a stream power based *effective discharge* approach applied before the change in hydrology, could have predicted the change in channel size that has subsequently been observed. Such an understanding of the likely magnitude and direction of this impact on downstream river channels may have influenced design of the Scheme, its operations or subsequent river rehabilitation activities.

The stream power based *effective discharge* approach has potential to contribute to river rehabilitation considerations.

7. ACKNOWLEDGEMENTS

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