River channel adjustment to hydrologic change

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ABSTRACT

The size of an alluvial river channel can adjust in response to changes in the pattern of flows that it carries. An important case of such channel change occurs downstream of dams or water diversions where flow regulation has been observed to cause morphological and ecological impacts.

In this work, an *effective discharge* approach based on excess stream power is proposed to account for change in river channel capacity downstream of a dam or river diversion. This approach uses a frequency distribution of stream flows together with observed or predicted hydraulic characteristics of the channel, to determine the flow that is most effective through time at adjusting the channel boundaries.

The excess stream power *effective discharge* approach is applied to two extreme cases downstream of the Snowy Mountains Scheme in south-east Australia: one a river channel that has enlarged since flow regulation and one a river channel that has contracted since flow regulation. In both cases an *effective discharge* analysis based on excess stream power successfully accounts for post-regulation trends in bankfull channel capacity.

These results provide a preliminary endorsement of an excess stream power based *effective discharge* approach, but in both the cases, the change in flow pattern from pre-regulation to post-regulation is extreme and the frequency distribution of daily flows for the regulated case is acutely modal. Further case studies are required to investigate the validity of the proposition for other situations.

Consideration of the case studies and the physical meaning of the *effective discharge* approach leads to the suggestion that the excess stream power *effective discharge* approach applies more generally to the individual physical processes that dictate channel characteristics rather than to the net effect of these processes as represented by bankfull channel capacity. This suggestion can contribute to a conceptual understanding of channel response.

The excess stream power based *effective discharge* approach could be applied to help to manage the environmental consequences of dams by contributing to predictions of the impact of flow regulation on downstream channel morphology.

DECLARATION

This is to certify that:

(i) *the thesis comprises only my original work;*

(ii) *due acknowledgment has been made in the text to all other material used; and*

(iii) *the thesis is less than 100 000 words in length exclusive of tables, maps, bibliographies, appendices and footnotes.*

John Tilleard 23 October, 2001

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1. INTRODUCTION

A river flowing in alluvium can alter the size or shape of its channel in response to internal or external influences, by removing alluvium from or adding alluvium to the channel boundaries. In practice the influences initiating change often include:

- natural or artificial changes in quantity or rate of water flowing in the river;
- natural or artificial changes in volume, rate or characteristic of sediment available to the river;
- natural or artificial changes in the properties of the channel boundaries that affect hydraulic conditions or vulnerability to erosion for instance; or
- natural or artificial changes in hydraulic conditions such as may result from a change in downstream control.

This work deals principally with the effect on river channel capacity of changes in the rate and volume of water carried by the river.

Changes in the stream flow pattern can affect the physical form of the channel and its associated environmental, aesthetic, recreational and utilitarian values. Regulated rivers provide examples where change to streamflow patterns can be extreme.

1.1. *Context of the work*

Attempts to explain and predict river processes have been successful in various disciplines. For example:

- in *hydrology,* techniques such as time-series analysis are used to describe or predict the characteristics of the flows in a river reach;

- process models (physical or numerical) use principles of *hydraulics* to represent patterns of water and sediment flux in stream channels (see for example Wang (1991));

- conceptual *geomorphic* models, based largely on historical observation or reconstruction, are able to describe qualitatively the broad framework of channel change (for example see (Erskine, Rutherfurd et al. 1990); and

- *empirical* models, such as regime equations or relationships between bend migration rate and lateral migration, can be used quantitatively to predict channel characteristics on the basis of accumulated experience (Ackers 1992).

While examples of the application of any one of the above approaches abound, it is rare to find successful development and application of a concept that is able to provide a rational link:

- from the characteristics of the flow pattern occurring in the river (such as magnitude and frequency of flows);
- via an understanding of the physical processes that underlie the hydraulics of fluvial systems (including open channel flow, sediment entrainment);
- to explain or predict morphologic characteristics of a river channel (such as size, shape, slope, planform).

This severely limits our ability to understand and predict the likely channel response to an artificial perturbation in the hydrologic environment and therefore our ability to manage the impacts of human intervention.

In this work, a linkage is proposed between changes in a river's flow pattern and changes in its channel morphology, based on the hydraulics of the physical processes in the channel.

1.2. *Scope of the work*

In Chapter 2 of this work, an exploration is presented of *effective discharge* as a means of relating the morphologic characteristics of an alluvial river channel (specifically its bankfull channel capacity) to characteristics of its streamflow pattern (specifically the magnitude, duration and frequency of flows in the channel). A summary and comparison of published applications is given in Chapter 3.

Chapters 4, 5 and 6 report on the development of an *effective discharge* approach based on excess stream power and its application in two case studies downstream of the Snowy Mountains Scheme in south eastern Australia. The case studies examine the potential for an excess stream power *effective discharge* approach to explain or even predict the channel enlargement or channel contraction that has been observed after river regulation downstream of dams and diversions.

Subsequent consideration of the case studies reported in Chapters 7 and 8 leads to further discussion about the physical meaning of the excess stream power based *effective discharge* approach, and to development of the suggestion that this approach may apply more rationally to a single physical process rather than to the consolidation of channel characteristics that bankfull channel capacity represents.

1.3. *An introduction to the concept of "effective discharge"*

An alluvial channel carrying a sequence of flows, will be subject to episodes of erosion and/or deposition that depend on the magnitude of the flows in the flow sequence relative to the magnitude of flows that cause motion of bed material, bank material and material in transport. The work done by a river in changing the shape or character of its boundaries generally increases rapidly with discharge. On the other hand the amount of time that a river spends flowing at its highest discharges is generally less than the time it spends flowing at more moderate discharges (Wolman and Miller 1960).

The result of the sequences of erosion and/or deposition is a channel that reflects the entire history of the flow sequence. Within this flow sequence, it is proposed that there is a particular interval of discharge, the *effective discharge*, which by virtue of its duration and its competence is more influential in forming and maintaining the channel than other discharge intervals. Physical characteristics of the channel then reflect this discharge.

The concept of *effective discharge* can be encapsulated as follows.

The largest flows have the highest stream power and can do work on the channel boundaries at the greatest rate. But they usually occur relatively rarely. At the other extreme, low flows can have such low stream powers that they are incapable of altering the channel boundaries, regardless of how often they occur. More moderate flows, with moderate stream power, 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 will be an interval of discharge, the *"effective discharge"*, possibly at neither the high nor the low extremes, that is both sufficiently frequent and sufficiently effective to be *most important* (Leopold 1994) in forming and maintaining the characteristics of the channel.

It is important to note that in linking the channel-forming work done by a particular flow with the frequency of that flow, this explanation of the *effective discharge* concept does not imply that the *effective discharge* must be a moderate discharge. The explanation explicitly accepts the possibility that moderate flows may be ineffective at promulgating some aspects of channel change, in which case a rare event may be the *most important*. Similarly where channel changes are promulgated at low flows, the flow that is *most important* in forming channel characteristics could be a frequent event.

The concept is actually in two parts. First is the concept that there is an interval of flow that can be shown to be *most effective* through time in forming and maintaining the channel. Second is the concept that this *most effective* flow is reflected in the observed physical characteristics of the channel.

To apply the concept requires a means of determining the interval of discharge that is the most influential at forming and maintaining the channel. This can be achieved by jointly analysing the flow pattern together with the physical processes that describe the interaction of the flow with the channel boundaries.

Application of the *effective discharge* concept in this way applies the quantitative statistical techniques typical in engineering hydrology and quantitative process models from engineering hydraulics to reinforce the historical observational approaches typical in geomorphology. This offers the potential to provide a link that is both conceptual and quantitative between:

- the *hydrology* of a river reach specifically the streamflow pattern (eg flow magnitude, flow frequency, flow duration);

- the *fluvial hydraulics* of the reach (eg flow velocity, boundary shear stress, stream power); and

- the *morphology* of the reach (eg bankfull channel capacity).

Strictly, this explanation of the *effective discharge* concept is in terms of the interval of discharge that is most important at forming and maintaining the channel. For convenience in this work, the term *effective discharge* refers to the single discharge which, at the mid point of the most effective flow interval, is representative of that interval.

1.4. *The study hypothesis and some further new directions that are proposed in this work*

In building an *effective discharge* approach to apply to the case studies, and then considering its implications, some directions have been developed that are either new, or are taken beyond the point previously reported in the literature. These directions are introduced below and their development is further reported in subsequent Chapters.

Use of excess stream power in estimating *effective discharge*

Work by others has relied on a definition of *effective discharge* based on the flow interval that is most effective at moving sediment.   For instance, Andrews (1980) defines *effective discharge* as:

> … the increment of discharge that transports the largest fraction of the annual sediment load over a period of years.

In the current work, this definition was considered for application to the case studies to test whether it could be applied to explain or predict observed changes in channels subject to regulated flows. Instead, work on the case studies led to the proposition and development of a modified definition of *effective discharge* based not on sediment transport but on the more fundamental formulation of stream power. This has led to a new definition of *effective discharge* proposed here as:

> … the interval of discharge that, over a period of time, accounts for a greater proportion of flow energy available to do work on the channel boundaries than any other interval of discharge.

In many situations, these two definitions are closely related. But it is suggested that the definition based on excess stream power is the more fundamental, has a clearer physical meaning and has the advantage that it can be applied in the absence of detailed field measurement of sediment flux. On the other hand, the disadvantage of the excess stream power approach is that evaluation of excess stream power relies in part on theoretical and empirical formulations for boundary shear stress that are not always good representations of the complexities of natural river systems and that are difficult to verify in the field.

This excess stream power based definition of *effective discharge* has lead to the specific hypothesis that is tested in the case studies.

> For an alluvial channel subject to regulated flows downstream of dams or diversions, observed changes in channel size can be explained by analysing the flow regime and channel hydraulics to determine the interval of discharge that accounts for the most available flow energy in the channel.

As well as consideration of the specific hypothesis, the case studies have provided insight into the *effective discharge* concept and lead to several suggestions that are recommended for further development as follows.

Effective discharge **and bankfull channel capacity**

In most of the work reported in the literature (for example Andrews 1980; Andrews 1986; Andrews 1994; Andrews and Nankervis 1995; Ashmore and Day 1988; Batalla and Sala 1995; Benson and Thomas 1966; Carling 1987;

Leopold 1992; Lyons, Pucherelli et al. 1992; Nolan, Lisle et al. 1987; Pickup 1976; Pickup and Warner 1976; Webb and Walling 1982) there has been an (often-implicit) proposal that the *effective discharge* is the discharge that dictates *bankfull capacity* of the channel. This association has been carried into the case studies in this work by testing the change in estimated *effective discharge* resulting from flow regulation against observed changes in *bankfull channel capacity.*

Multiple *effective discharges*

The stream power based *effective discharge* approach leads to the suggestion (in concert with Prins (1971)), that a reach of alluvial channel may have more than one *effective discharge* applying over a given period of flow. Each value of *effective discharge* relates to a particular channel forming process that applies to a particular channel characteristic (such as width, depth, shape, planform or profile). For example, an e*ffective discharge for bank processes* will take account of work done on the banks by flow related forces across all flow magnitudes, in proportion to the relative duration of each interval of flow within the flow regime. The *effective discharge for bank processes* (for example) is then the discharge interval that accounts for the most effective work done on the bank by the flow. This may well be a different *effective discharge* from that which determines some other characteristic of the channel (meander pattern for example) if the physical processes that dictate the relationship between discharge and bank attrition are sufficiently different from the physical processes that dictate the relationship between discharge and meander pattern.

This interpretation proposes that the *effective discharge* for a particular channel process is that flow which, taking account of both the magnitude and duration of flow within the flow regime, has the biggest influence through time on the size, shape, planform, profile or other characteristic of the channel.

Bankfull channel capacity is a consolidation of a number of physical characteristics, each of which, according to this proposition, may be produced by its own *effective discharge*. In some situations, this may leave an *effective discharge* related to bankfull channel capacity ill-defined. In reviewing the case studies in Chapter 7 however, it is proposed that the *effective discharge* approach as used in the case studies, can still be related to bankfull channel capacity under certain conditions.

***Effective discharge* and geomorphic thresholds**

It is implied in much of the literature that a discharge that is both sufficiently frequent and sufficiently competent to be the *effective discharge* for a particular morphologic characteristic, can not be at either the high or the low extremes of the range of flows represented in the flow regime and will always be a moderate flow. This conclusion makes assumptions about the variability of the flow patterns and the relationship between flow and morphology that may or may not be valid for a given situation. In particular it gives insufficient credence to the concept of geomorphic thresholds (Schumm 1973).

The concept of geomorphic thresholds accounts for the stepwise response of a morphologic parameter to change in an external variable. For example, as flow in an alluvial channel increases, there will be imperceptible changes in the bed of the channel until the flow reaches a magnitude that is capable of moving the material that makes up the river bed. Beyond this *flow threshold,* change may be sudden and dramatic. Likewise, increases in channel width will not occur until the *threshold of motion* of the bank material is exceeded. But then bank erosion may proceed apace until the forces on the bank material again recede below the threshold level.

Applied to *effective discharge*, an understanding of geomorphic thresholds suggests that an *effective discharge* need not be in the moderate flow range. *Effective discharge* for channel width could conceivably be the equivalent of an event of extreme magnitude if the threshold for change were only exceeded in that event. Catastrophic widening in major floods or the wide braided channels in arid areas of central Australia are examples of channel form responding to large, rare events. Conversely, where channel boundaries can be altered at low flows, by deposition of fine material for example, the *effective discharge* may correspond to very frequent events of low magnitude.

2. THE EFFECTIVE DISCHARGE CONCEPT

This Chapter is used to explain and develop the *effective discharge* concept as it is presented in the literature. *Effective discharge* is then compared to *dominant discharge* and to published work on the frequency of *bankfull discharge*.

2.1. *The concept of a "most effective" discharge*

The notion of *effective discharge* had its origins in 1922 when Schaffernak (1922) is reported (Prins and de Vries 1971) to have proposed that the size and shape of a river channel reflects the discharge at which most of the formative work is done. He went on to propose that this discharge corresponds to that stage at which the bulk of the bed load is carried.

Wolman and Miller (1960), in their landmark paper "Magnitude and frequency of forces in geomorphic processes" did not refer to Schaffernak (1922) but developed and presented the view that the formation of specific landscape features is dictated by both the magnitude and frequency of the forces driving geomorphic processes.

- They presented results from a selection of rivers in the United States of America to demonstrate that, for the rivers studied, 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.

- They concluded that frequently recurring events of moderate intensity rather than rare floods of unusual magnitude are the *effective* events in forming the alluvial landforms that they observed.

The universal applicability of the specific conclusions has been sometimes questioned in the literature, but the concept that evolution of morphologic form relies on both the magnitude and the frequency of forces remains of enduring significance.

The specific conclusions of Wolman and Miller's (1960) work regarding the frequency of the most effective forces strictly only apply to those United States rivers in their data set. To generalise the conclusions amongst other rivers ignores the possible effects of differences in flow frequency relationships, flow hydraulics and thresholds of motion for rivers in different climatic zones or different lithology. More particularly it ignores the dependence of *effective discharge* on the different geomorphic thresholds (Schumm 1973) that apply to different alluvial features.

In fact Wolman and Miller did recognise these limitations and tempered their conclusions about the importance of frequent events, by also recognising the significance of rare, catastrophic events in moulding some features of the landscape. In so doing they introduced (but did not develop) the significance to deliberations on *effective discharge* of understanding the physical processes that actually propel different aspects of channel change and the thresholds that control their initiation (see Section 1.4).

The importance of geomorphic thresholds to the generalisation of the *effective discharge* concept has been recognised by Carling (1987) who proposes that there is a vital threshold between flows that are effective at maintaining channel form and flows that instigate channel change.

Any limitation on the applicability of the specific conclusions does not detract from the conceptual importance that Wolman and Miller's (1960) observations and deductions infer:

> ... that the characteristics of a feature of the landscape are related to a particular magnitude event – the event that occurs with sufficient force and sufficient frequency to have the greatest influence on the geomorphic processes that define the feature.

2.2. *Effective Discharge - the general case*

The general case is illustrated in Figure 1 which is reproduced from Wolman and Miller (1960).

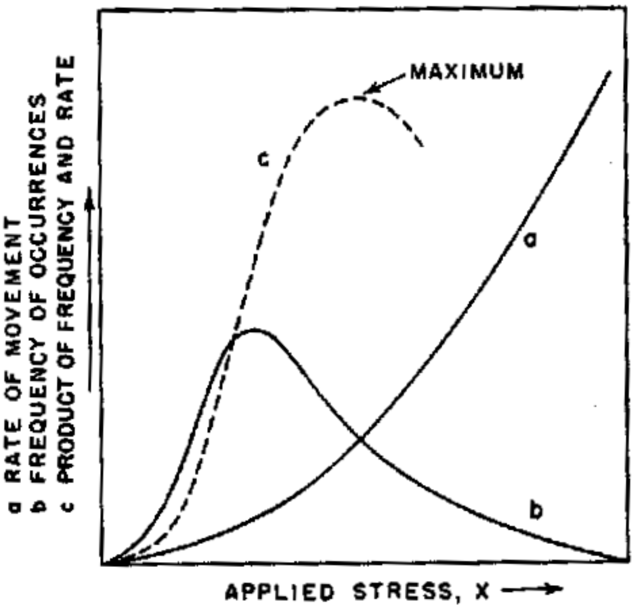


Figure 1 Generalised relationship between applied stress and a. magnitude of response, b. duration or frequency of applied stress and c. the product of a. and b (after Wolman and Miller (1960)).

In the general case, the morphologic response to an applied stress is illustrated by curve a. in Figure 1. The distribution through time of the applied stress is illustrated by curve b. The product of the response function (curve a.) and the frequency function (curve b.) is a relation (curve c.) that describes the relative contribution to overall system response as a function of the applied stress. For example if curve a. is a sediment rating curve and curve b. is a flow frequency curve than curve c. describes the way that sediment flux is distributed across the spectrum of flows.

Wolman and Miller (1960) identified that in general, a morphologic response (such as sediment transport in response to flow) adopts some form of power law, and in nature, the distribution through time of an applied stress (such as the distribution of daily flows) typically approximates a continuous log normal distribution. In these circumstances, the product of the response curve and the frequency curve is likely to produce a relationship that exhibits a maximum. The maximum occurs at the particular value of the applied stress that has the biggest influence over time on the morphologic response.

2.3. *Effective discharge – explanation using a qualitative example*

The concept of an *effective discharge* can be more readily communicated by way of a specific case that:

- uses the “traditional” example of sediment transport already introduced above; and

- replaces the continuous frequency function (curve b. in Figure 1) with a frequency histogram.

Figure 2 is a flow frequency histogram of, for instance, average daily flows. It represents the proportion of time in the period of record that flow is observed to be within each interval of flow.

Figure 3 shows a relationship between flow and sediment transport superimposed on the flow frequency histogram. This sediment transport function could be derived from measured data or estimated from a “theoretical” sediment transport equation.

The curve crosses the abscissa at the flow corresponding to the threshold of motion of the material in transport. At flows less than this, no

Figure 2 Flow frequency histogram

Figure 3 Sediment transport function

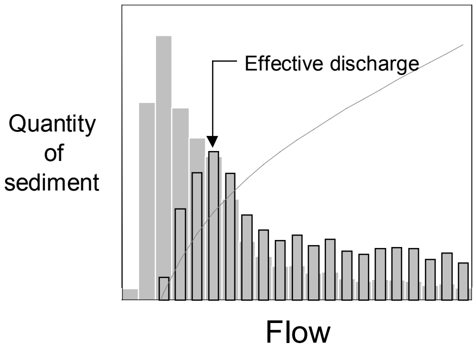


Figure 4 Distribution of sediment with flow

sediment transport is deemed to occur. Beyond the threshold of motion, the shape of the curve may be concave or convex as determined by a complex interaction of channel geometry, flow conditions and sediment entrainment and mobility.

The distribution of sediment flux across the flow range is computed by multiplying the rate of sediment transport for the midpoint of each flow interval (from the ordinate of the function in Figure 3) by the relative frequency with which flows occur within that flow interval (from the height of the histogram in Figure 2). The result gives *the distribution of transported sediment with flow* as illustrated in Figure 4. The height of a column in this chart represents the quantity of sediment that is moved over time by flows in the flow interval, relative to the quantity of sediment that is moved by flows in other flow intervals. The tallest bar results from the flows that move enough sediment often enough to move the most sediment through time. This is the most *effective discharge* at moving sediment.

2.4. ***Defining effective discharge in terms of sediment transport***

Wolman and Miller (1960) wrote their paper in conceptual terms and used the discharge that was *most effective* at moving sediment as a specific example of the concepts that they proposed. Since then, there has been increasing focus on this limited definition of *effective discharge* (Andrews 1980; Andrews 1986; Andrews 1994; Andrews and Nankervis 1995; Ashmore and Day 1988; Batalla and Sala 1995; Benson and Thomas 1966; Carling 1987; Leopold 1992; Lyons, Pucherelli et al. 1992; Nolan, Lisle et al. 1987;

Pickup 1976; Pickup and Warner 1976; Webb and Walling 1982), usually to the exclusion of other more general interpretations and often without acknowledging the implicit diminution of the original concept.

Authors generally have defined the *effective discharge* for a channel subject to a sequence of variable flows as that flow that transports the most sediment through time. For example, Pickup and Warner (1976) define *effective discharge* for a river channel 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.

Andrews' (1980) definition is similar:

> …the increment of discharge that transports the largest fraction of the annual sediment load over a period of years.

In the literature, it appears that the discharge that moves the most sediment through time has been accepted *de facto* as the (one and only) *effective discharge* for a river channel. Moreover, there is little discussion but general acceptance that this *effective discharge* will be reflected in the bankfull capacity of the channel. In general, the suggestion in Section 1.4 that a channel may exhibit a range of *effective discharges* corresponding to a range of physical processes (and a corresponding range of geomorphic thresholds) has not been enthusiastically pursued. Some exceptions to this are reported in Section 2.6 after the term *dominant discharge* is introduced in the next section.

2.5. *Comparison of the effective discharge concept with the notion of dominant discharge*

The literature freely interchanges use of the terms *dominant discharge* and *effective discharge*. Commonly (for example Komura 1969; Marlette and Walker 1968), the term *dominant discharge* is used where, by the definitions adopted here, *effective discharge* would be the more appropriate terminology. Indeed the literature introduces a number of other terms; the most pertinent of which is *channel forming discharge*. The substitution of terms in the literature has contributed to confusion in the debate over relationships between hydrology and morphology. In this section, the background to the term *dominant discharge* is described to clarify subsequent discussion.

In the late 1800s and early 1900s, British engineers working with irrigation canals in India began to publish observations and deductions about the behaviour of canals that were subject to erosion and deposition of the silts and sands that made up their boundaries. They noted that the canals would adjust their size and shape by erosion and deposition until a (relatively) stable configuration was reached. They deduced that the characteristics of the stable configuration were related to the water and sediment discharge that the canal carried (Kennedy 1895). Lindley, (1919) put forward the theory that:

> …. the dimensions, width, depth, and gradient, of a channel to carry a given supply loaded with a given silt charge, were all fixed by nature ….

Various authors (for example Blench 1957; Inglis 1947; Inglis 1949; Lacey 1929; Lacey 1933) then developed this concept to establish relationships between channel characteristics such as depth, width, slope and meander wavelength and the water and sediment discharge in the canal.

The stable channel, able to transport a given flow without significant change occurring to channel geometry became known as the *regime channel.* Similarly the relationships between stable channel geometry and the water and sediment discharge that it carries have become known as *regime equations.* In general, these relationships can be cast in the form:

$$X = aQ^b$$

where:

Q is the water discharge;

X is depth, width, slope or meander wavelength;

and for each relationship:

a takes a value that may depend on the sediment characteristics of the flow and the bed and banks of the channel; and

b is a constant..

Dominant discharge in rivers

Regime equations were derived for canals in which water discharge is controlled and is essentially a constant. When the concept was extended to natural rivers this condition no longer applied and the concept of *dominant discharge* was developed to deal with the problem of assigning a single representative discharge to the varying flow sequences that occur in natural rivers. The *dominant discharge* is (Blench 1957; Inglis 1947; Inglis 1949):

> ... the constant flow rate that would produce the same channel morphology as a sequence of naturally varying flows.

Thus the *dominant discharge* is defined in a circular fashion in terms of its own product – the bankfull capacity of the alluvial channel that the *dominant discharge* produces. The *dominant discharge* is the steady flow that produces a channel capacity that is the same as the capacity of the channel produced from a naturally varying flow sequence.

A difficulty therefore confronts any attempt to use *dominant discharge* concepts in a predictive sense (such as predicting channel response to hydrologic change). *Dominant discharge* is not a property of the flow sequence itself but a property of the response that the flow sequence generates in a particular channel characteristic - the same channel characteristic (bankfull channel capacity) that defines the *dominant discharge* in the first place. *Dominant discharge* can only be useful in <u>predicting</u> channel change if it can be related to some other measurable characteristic of the flow regime.

This is the case for *effective discharge.* While the *effective discharge* is also a single discharge representative of a period of variable flows, it has a clear physical meaning related to the frequency characteristics of the flow pattern and the hydraulic characteristics of the channel.

2.6. *Multiple effective discharge concepts*

Prins and de Vries (1971) take a hydrodynamic approach to calculating what they call *dominant discharge.* Insisting that there is a different *dominant discharge* for each morphologic characteristic, they demonstrate how the *dominant discharge* for a selected characteristic can be estimated by actually running a discharge time-series within a hydrodynamic model coupled to a sediment model and then searching with the same model for a steady state discharge that provides an equivalent response over the same time period.

Ackers and Charlton (1970) had earlier followed a similar path using a physical model to investigate the influence of varying flows on meander geometry and then to determine an equivalent steady state discharge.

Prins and de Vries (1971) describe an application of their approach but make no generalisations. Ackers and Charlton (1970) go further in the case of meander characteristics. They conclude that a steady discharge can produce the same meander pattern as a varying discharge and they go on to conclude that this steady discharge corresponds to the bankfull discharge.

The outcomes of the Prins and de Vries and the Ackers and Charlton experiments are important. They demonstrate that both theoretically (Prins and de Vries 1971) and in a physical model (Ackers and Charlton 1970), it is possible to identify a steady discharge that produces the same selected morphologic characteristics as a regime of varying flows. The Ackers and Charlton work also shows that in their case, the steady state discharge that replicates meander characteristics is the same steady state discharge that replicates the characteristics that determine channel capacity. Further interpreting this in *effective discharge* terms, suggests that the discharge that is *most influential* in determining meander characteristics is the same as the discharge that is *most influential* at adjusting channel size, shape and grade. The *effective discharge* for meander characteristics in this case is the same as the *effective discharge* for channel capacity. Potentially, mathematical or physical models applied in this way offer an opportunity to explore and develop a deductive basis to those aspects of the *effective discharge* approach that otherwise remain intuitive.

2.7. ***Other effective discharge concepts***

Other authors have used other modifications to the above concepts, but still focusing on the quantity of sediment moved through time within an interval of discharge as the basis for determining an *effective discharge*.

For instance, Marlette and Walker (1968) adopt a definition of *effective discharge* (which they incorrectly call *dominant discharge*) based not on the discharge that transports the most sediment (modal value) but on the discharge above which and below which half the sediment is transported (median value). They used this definition together with a sediment transport equation to determine the dominant (or effective) discharge for the Platte and Missouri Rivers at their confluence. They do not report a comparison of the computed values with bankfull channel capacity. The use of the median value as opposed to the modal value is not argued by Marlette and Walker who appear to accept it intuitively.

Another approach is proposed by Komura (1969) who defines the product of the sediment discharge and water discharge in each discharge interval as a sediment moment and computes an *effective discharge* (which he again calls a dominant discharge*)* as the centroid of the distribution of the sediment discharge about the discharge origin. The literature reveals no applications of this concept.

2.8. *Frequency of bankfull discharge*

Wolman and Miller (1960) noted that the bankfull discharge of the river channels that they examined had similar frequency to the *most effective* discharge for moving sediment. They inferred from their model that the channel forming discharge is the bankfull discharge and it equates to the discharge that is *most effective* at moving sediment.

The implication that the bankfull characteristics of a channel and particularly the bankfull discharge are determined by the discharge that is *most effective* at moving sediment has been the subject of many investigators' efforts since (see next Chapter).

But a second theme has tended to preoccupy much of the literature. Even before Wolman and Miller's (1960) paper, authors have persistently attempted to relate observed channel characteristics to a particular incidence on the flow frequency distribution or the flood frequency distribution (for example Dury 1973; Harvey 1969; Nixon 1959). As summarised by Woodyer (1968), they have concluded that (for their data sets), the mean frequencies with which bankfull frequencies are exceeded are "remarkably similar" (Leopold 1964), "the same" (Nixon 1959), or "fixed" (Dury 1961).

Predating Wolman and Miller's work, (Wolman and Miller 1960), Marshall Nixon, Chief Engineer to the Trent River Board studied a number of rivers across England and Wales (Nixon 1959). He concluded that the average frequency of bankfull discharges for the rivers in his study was 0.6% and he proposed that this "standard frequency" may apply to any natural river in alluvium. Dury on the other hand, ignores duration by strongly advocating that bankfull discharge equates to a fixed recurrence interval of 1.58 years on the annual flood series (Dury 1973). Hey and Heritage (1988) recognised the importance of geomorphic thresholds and used a partial duration series with a threshold discharge determined from critical conditions for bed material movement to conclude that bankfull flow for UK rivers is the 0.9 year flood on this partial series. (They also concluded that the bankfull flow is the *effective discharge* but presented no evidence in this regard.) Petit and Pauquet (1997) identified bankfull discharge in some 30 gravel bed rivers with catchments up to 2 700km^2. They conclude that bankfull discharge values and recurrence interval both increase with basin size but did not find any more definitive conclusion and did not make an *effective discharge* comparison. Woodyer (1968) after further refining the definition of bankfull discharge, was encouraged by the similarity of bankfull flow frequencies for sites in New South Wales, Australia.

(Harvey 1969) investigated the frequency of bankfull flows for three streams in southern England. He found variations in the frequency of bankfull flows both between each stream and along each stream and concluded: ".... it is apparent that the relationship between discharge and channel capacity is a complex one and due consideration must be given to magnitude, frequency and duration of discharge ....".

In reviewing the previous work, Williams (1978) suggests that attempts to generalise the relationship between bankfull discharge and flow frequency have been largely unsuccessful. In part this is because the several studies that he reviewed did not use a consistent definition of bankfull condition. He points out that although the modal value for bankfull frequency for the cases that he reviewed is 1.5 years on the annual series, the range is 1.01 to 32 years and only one third of the sites have recurrence intervals near the 1.5 year peak. Williams concludes "...an average recurrence interval ...is a poor estimate of bankfull discharge". In Section 7.5 of this work similar findings are reported based on the case studies.

2.9. *Time-scales of channel change*

Some authors express concern about the *effective discharge* concept on the grounds that it makes no allowance for rates of channel change or for the actual sequence of flows that the channel experiences (Baker, Kochel et al. 1988; Kochel 1988; Lewin 1989; Wolman and Gerson 1978).

This is a fair criticism if the *effective discharge* approach is applied unthinkingly as a universally applicable law, in contradiction of evidence that timing or sequencing of flows is important, but it does not invalidate the *effective discharge* concept. The *effective discharge* is the discharge that has had the most influence on some aspect of the channel over the period of analysis but if the rate of change is slow the condition of the channel at a particular point in time may not reflect the "most influential" discharge. Similarly, if recovery times are slow, the condition of the channel, or at least some aspects of it, may reflect the impact of some prior event rather than the discharge that ought theoretically to have been the most effective over the period. This issue is further discussed in Chapter 8.

3. APPLICATIONS OF THE EFFECTIVE DISCHARGE CONCEPT

In this Chapter, prior applications of the *effective discharge* concept as reported in the literature are reported.

3.1. ***Overview***

Quantitative applications have invariably used a sediment transport based subset of the *effective discharge* concept (Andrews 1980; Andrews 1986; Andrews 1994; Andrews and Nankervis 1995; Ashmore and Day 1988; Batalla and Sala 1995; Benson and Thomas 1966; Carling 1987; Leopold 1992; Lyons, Pucherelli et al. 1992; Nolan, Lisle et al. 1987; Pickup 1976; Pickup and Warner 1976; Webb and Walling 1982). These applications have used measured or calculated sediment transport capacity to represent the ability of a particular flow to alter channel boundaries. The flow that accounts for transport of the most sediment through time across the varying flows has been termed the *effective discharge* for the channel. Many of these authors have successfully demonstrated that channel morphology at bankfull is adjusted to accommodate the *effective discharge* (Andrews 1980; Andrews 1986; Andrews 1994; Andrews and Nankervis 1995; Batalla and Sala 1995; Carling 1987; Leopold 1992; Webb and Walling 1982), but the others report that this relationship is not substantiated by their analyses (Ashmore and Day 1988; Lyons, Pucherelli et al. 1992; Nolan, Lisle et al. 1987; Pickup 1976; Pickup and Warner 1976).

3.2. ***Examples***

Using streams in the Cumberland Basin of eastern Australia, Pickup and Warner (1976) explored the link between streamflow pattern and bankfull capacity. Calculating *effective discharge* from regional flow duration relationships and bed load transport from the Meyer-Peter and Muller relation, led to estimates of *effective discharge* that were at least an order of magnitude less than observed bankfull channel capacity. A more detailed investigation of one site (on Crawfords Creek) led the authors to suggest that the dominant characteristics of the bed were in fact related to the *effective discharge* that they had computed, but adjustments to the banks of the channel only occurred in flood events of much greater magnitude.

In a range of applications reported since 1980 (Andrews 1984; Andrews 1980; Andrews 1986; Andrews 1994; Andrews and Nankervis 1995), Andrews has been a keen proponent of the quantitative application of the *effective discharge* model. His thorough computational approach based on detailed and long term sediment load measurements, has repeatedly demonstrated the numerical equivalence of the sediment transport based *effective discharge* and the bankfull capacity of the channel.

- One of his first rigorous attempts to compare *effective discharge* with bankfull channel capacity was undertaken in the Yampa River basin, Colorado USA (Andrews 1980). Andrews calculated the *effective discharge* at 15 gauging station sites in the basin. Catchment area ranged from 51.8 to 9 960 km2, mean annual discharge from 0.040 to 43.9 m3/s, and the median diameter of bed material from 0.4 to 86 mm. Andrews used total sediment load to determine the *effective discharge*. Total load was estimated by combining measured instantaneous suspended load with an estimate of bed load computed using the Meyer-Peter and Muller relation. The channels were shown to be adjusted to a bankfull discharge which was equalled or exceeded 0.4% to 3.0% of the time with an average recurrence interval of between 1.18 and 3.26 year on the annual flood series. At all gauging stations, the *effective discharge* and the bankfull discharge were shown to be nearly equal.

- Andrews computed *effective discharge* as part of an analysis of the effect of the Flaming Gorge Reservoir on the Green River, a tributary of the Colorado River, USA (Andrews 1986). The *effective discharge* for <u>total sediment load</u> was computed at three locations downstream of the reservoir for pre-reservoir and post-reservoir conditions. The computations used suspended sediment measurements with bed load estimated using the Engelund – Hansen relation (Engelund and Hansen 1967). Computed *effective discharges* suggested that major reductions in bankfull channel capacity would result from the change in flow regime.

Observations confirmed that channel contraction was in fact occurring with channel capacity already reduced to the *effective discharge* at one site.

- In an analysis of marginal bedload transport in a Californian Creek (Andrews 1994), Andrews again computed bankfull discharge and *effective discharge* and this time found the computed *effective discharge* of 1.75 m^3/s to be slightly less than the estimated bankfull discharge of 2.0 m^3/s.

- In some further work on the hydraulic geometry of gravel bed rivers at 24 sites in Colorado (Andrews 1984), Andrews found that the bankfull flow was equalled or exceeded from 0.12% to 6.0% of the time, but he did not compute the *effective discharge*. In more recently published work (Andrews and Nankervis 1995), Andrews took 13 of the sites from this study and 4 others and has applied an *effective discharge* approach using the Parker bedload function (Parker, Klingeman et al. 1982) to extrapolate measured sediment transport rates. Again Andrews found excellent agreement between *effective discharge* and bankfull discharge at all sites and went on to use the *effective discharge* approach to demonstrate design of channel maintenance flows.

The bankfull discharge of the Arbucies River (north-east Spain) has been shown to be of identical magnitude to the *effective discharge* computed from measured data for bedload transport (Batalla and Sala 1995). In this humid Mediterranean forested granitic drainage basin, the measured bedload yield accounts for 65% of the total solid yield of the catchment and bankfull flows are equalled or exceeded for 2.2% of the time.

Using measured suspended sediment data for streams in the Saskatchewan River basin in Canada, Ashmore (1988) computed the *effective discharge* for suspended sediment at 21 sites with catchment areas from 10 to 300 000 km^2. Ashmore found that the form of the *effective discharge* histograms for suspended sediment was highly variable, not always conforming to the unimodal distribution proposed by Wolman and Miller (1960) and demonstrated by Andrews (Andrews 1984; Andrews 1980; Andrews 1986; Andrews 1994; Andrews and Nankervis 1995) and Batalla (1995). Ashmore (1988) presents his conclusions in terms of the duration of the *effective discharge*, observing that the duration is highly variable. For the majority of cases, the duration of the *effective discharge* increases with catchment area and is between 1% and 10%. Ashmore makes no direct comparison between *effective discharge* and bankfull other than to conclude that the relationship is “presumably correspondingly variable”.

A magnitude and frequency analysis for three large rivers in the USA (Mississippi River at Natchez, Red River at Alexandria, Pearl River at Bogulasa) found that the discharge interval that transported the most sediment had a recurrence interval of around 1 year for all three rivers (Biedenharn, Little et al. 1987). No comparison with bankfull discharge was reported.

The concept of *effective discharge* has been applied to two gravel-bed streams, tributaries of the River Tees in northern England, using measurements of bedload trapped in pits excavated in the river bed (Carling 1987). One stream is alluvial and free to adjust its geometry. For the other stream, channel capacity and channel form are partially constrained by cohesive banks and a heavily compacted bed. Both streams are small with catchment areas of 11.7 and 2.2 km2 respectively. The investigation concludes that bankfull discharge is the *effective discharge* for the alluvial stream, but the concept applied “less well” to the “non-alluvial” stream where a series of intrinsic thresholds constrained channel response.

Effective discharge for four stable, incised gravel bed streams in California were computed using sediment rating curves derived for suspended sediment (Nolan, Lisle et al. 1987). In each case, the computed *effective discharge* is substantially less than the observed bankfull discharge by factors of 2 to 4.

Lyons, Pucherelli and Clark (1992) revisited the Green River (Andrews 1986) where it has contracted as a result of the effects of Flaming Gorge Reservoir. They only compared bankfull discharge and *effective discharge* at one site where they found that at 375 m^3/s, their estimate of *effective discharge* was less than the computed bankfull discharge of 500 m^3/s.

3.3. *Discussion*

The results of applying the *effective discharge* concept fall into three camps.

- Those that have not directly compared an *effective discharge* with bankfull discharge, although they may have contributed to the attempt to define the frequency of the bankfull flow (Biedenharn, Little et al. 1987; Harvey 1969; Marlette and Walker 1968).

- Those that have reported that their estimates of *effective discharge* demonstrate poor correlation with bankfull discharge (Ashmore and Day 1988; Nolan, Lisle et al. 1987; Pickup 1976; Pickup and Warner 1976).

- Those who have found close equivalence between *effective discharge* and bankfull discharge (Andrews 1984; Andrews 1980; Andrews 1986; Andrews 1994; Andrews and Nankervis 1995; Batalla and Sala 1995; Carling 1987; Leopold 1992; Webb and Walling 1982).

The results of two of Andrews' investigations for gravel bed rivers in Colorado and Wyoming (Andrews 1980; Andrews and Nankervis 1995) are plotted together on Figure 5. The Figure also includes the result from the Arbucies River (Batalla and Sala 1995), Left Hand Creek (Leopold 1992) and the River Tees catchment (Carling 1987). These results show remarkable agreement between computed *effective discharge* and observed bankfull discharge for all 40 sites. The results appear to reward the care and rigour of Andrews's, Batalla's, Carling's and Leopold's measurements and analyses, by ratifying the equivalence of an *effective discharge for total sediment load* with the bankfull discharge for a selection of sand and gravel bed streams in semi-arid to humid zones.

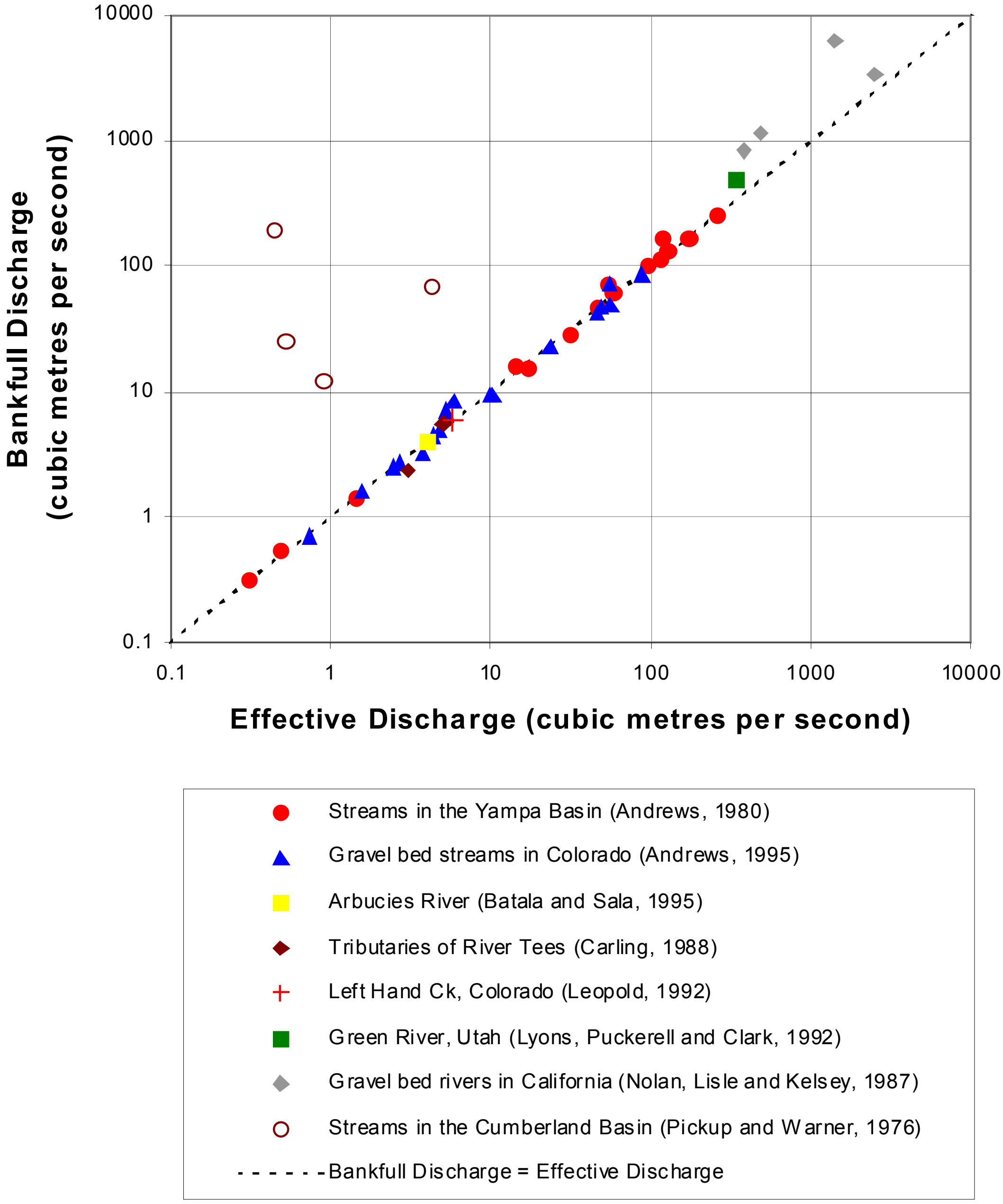


Figure 5 Comparison of estimated *effective discharge* for total sediment load with observed bankfull discharge for a selection of gravel and sand bed streams in USA, Spain and England (Andrews 1980; Andrews and Nankervis 1995; Batalla and Sala 1995; Carling 1987; Leopold 1992; Lyons, Pucherelli et al. 1992; Nolan, Lisle et al. 1987; Pickup and Warner 1976)

Also shown on the Figure are results from the Green River (Lyons, Pucherelli et al. 1992), a selection of gravel bed rivers in California (Nolan, Lisle et al. 1987) and streams from the Cumberland Basin in Australia (Pickup and Warner 1976). With the exception of the Cumberland Basin sites, on the log-log axes, even these results appear in reasonable agreement.

Carling suggests that authors who have been unable to demonstrate this equivalence, "have applied it largely to streams that were never close to steady-state or to streams that have recently undergone catastrophic perturbation, for which the model is invalid" (Carling 1987). Furthermore, as exemplified by Carling (1987), some streams have armoured bed or banks comprising material quite different from the material in transport in the stream. In these circumstances the flow that transports the most sediment does not have direct relevance to adjustment of the boundary and the model should not be expected to apply. Additionally some investigators have used suspended sediment load in their computations rather than bed load or total load, and some investigators have relied on the gross approximations in theoretical sediment transport relations where measured data are unavailable.

3.4. *Effective discharge using stream power*

While the results reported above are generally encouraging, the relationship between the *effective discharge* for sediment transport and bankfull channel capacity still relies on a degree of intuition. Furthermore, successful application has been shown to depend on the availability of detailed sediment transport data, which severely limits its applicability. The next

Chapter reports on the development of an alternative *effective discharge* approach using excess particle stream power.

4. EFFECTIVE DISCHARGE FROM EXCESS STREAM POWER

Later in this work two rivers in south eastern Australia are used as case studies to explore the potential of an *effective discharge* approach to explain or predict adjustments in channel morphology that result from regulated flows. A new approach is examined in these case studies. It responds to the concerns and constraints discussed in the preceding and subsequent sections and to the realities of limited data availability that have otherwise inhibited wider testing and application of *effective discharge* approaches to date. The new approach relates *effective discharge* to the discharge interval that through time accounts for the most available excess stream energy, instead of the discharge interval that through time accounts for the largest quantity of sediment transported.

4.1. *Practical problems with the sediment transport based definition of effective discharge*

A sediment transport based definition of *effective discharge* has been given in Section 1.4 and some examples of its application have been described in Chapter 3. Such a definition of *effective discharge* in terms of sediment transport introduces substantial practical difficulties for general application.

Successful application of a sediment based *effective discharge* approach will be severely limited by the availability of sediment data.

The rate of sediment transport is difficult to determine satisfactorily either by direct field measurement or by theoretical or empirically based computation. Direct field measurement of sediment flux is an expensive and time consuming exercise if the results are to be meaningful, and extrapolation of the findings via a sediment rating curve introduces further difficulties and uncertainties. There are few substantial sediment transport data sets available for rivers in Australia and a limited number internationally. In any case, measured sediment transport rates can only apply to past and present channel conditions and will have limited application in a predictive capacity if substantial change in flows, in channel characteristics or in upstream supply rates are likely.

Prediction of sediment transport rates from one of the numerous sediment transport equations is fraught with inaccuracy. Comparison of the results of the application of commonly used formulae by the ASCE (Vanoni 1975) show predicted rates of sediment transport vary over two orders of magnitude for a single set of channel and flow conditions. Further, many sediment transport relations require an estimate of hydraulic slope for their application — a parameter that is very difficult to measure accurately in the field.

A stable relationship between sediment transport and flow can at best only be expected in a situation where the mechanisms controlling sediment transport are dependent only on the rate of flow of water in the channel. This situation exists only when the rate of transport is limited by the ability of the flow to transport the relevant size fractions of sediment. This "transport-limited" situation is the opposite of "supply-limited" where the flow has capacity to transport more sediment than is available in the system. Then the rate of sediment transport is limited not by the flow conditions in the channel but by the amount of sediment that is made available to be transported. Davis (1997) found supply-limited situations predominate in south eastern Australia.

It is instructive to contemplate what it means to apply a sediment transport equation in a situation where the amount of sediment being transported is limited by the available supply. Sediment transport equations use a combination of physical process modelling and empiricism to establish relationships between channel hydraulics and sediment mobility. This allows the quantity of sediment that can be transported under a given set of hydraulic conditions to be predicted. But what if sediment is not available in sufficient size or quantity to satisfy the transport capacity of the flow? Perhaps the channel bed is armoured, perhaps the channel banks are cohesive, perhaps a tributary is not in flood and not producing its share of sediment. In any of these situations it is likely that a theoretical sediment transport equation will overestimate sediment transport unless it is calibrated for the site based on prior measurement in similar conditions.

4.2. *The alternative approach using excess stream power*

In this work, an alternative approach to the *effective discharge* concept is explored, based on recognition of the importance of the physical processes that lead to channel adjustment. For instance, if we are interested in the enlargement of a channel as the result of a change in flow pattern, the dominant physical processes that could cause that enlargement will be:

- entrainment and removal of material from the river bank leading to widening; and

- entrainment and removal of material from the river bed causing deepening.

Corresponding depositional processes are involved in a contracting channel.

There will be an *effective discharge* that is the discharge that is most effective (through time) at removing material from or adding material to the river <u>banks</u>, thereby accounting for the most widening or narrowing. There will also be an *effective discharge* that is the discharge that is most effective (through time) at removing material from or depositing material on the river <u>bed</u>, thereby accounting for the most deepening or shallowing. These discharges may or may not be similar (or even the same) depending on the similarity of the relative processes and the relative thresholds applying to entrainment or deposition of bed and bank material.

If these two values are similar, or if one process clearly dominates over the other, then there may be an *effective discharge* for overall channel capacity that accounts for the most adjustment to channel size through time.

The development of this approach requires a model of the relationship between flow and the ability of that flow to remove material from the bed or the banks. Historically, as reported in the previous chapters, the ability of the flow to transport sediment as represented by measured sediment flux has been used to characterise this relationship.

But there is another more fundamental model that may adequately describe the relationship and avoid the difficulties in amassing the sediment transport data sets discussed above. The alternative model is built on the proposition that entrainment from or deposition on the bed or the banks of the channel is dependent on the shear stress that acts at the boundary as the result of the flow beyond the threshold of motion of the boundary material. The work done by this “excess shear stress” is equivalent to the available stream power and determines the rate at which material is moved from the boundary. Similarly in a contracting channel, assuming a transport-limited situation, the rate at which material is available to deposit on the boundary also depends on the stream power that is available to move material to the site from upstream.

In other words the rate of erosion or deposition depends on the stream power per unit boundary area above the tractive stress threshold that is determined by incipient motion of the bed or bank material or the material in transport.

This is by no means a new concept in general (although its application to *effective discharge* has not been previously reported) nor does it depart markedly from the reported sediment transport based approaches to *effective discharge*. Many sediment transport equations rely on similar formulations (Ackers and White 1973; Bagnold 1966; Engelund and Hansen 1967; Velikanov 1954; Yang 1972).

In this work it is proposed that excess stream power is an appropriate formulation for use in an *effective discharge* approach as a substitute for sediment transport. It relates directly to a wide range of the physical processes that may control channel form. Accepting this, the examples in Chapter 3 suggest that sediment transport can act as a surrogate for excess stream power in some conditions. The more fundamental excess stream power based *effective discharge* approach has been further developed as reported in the remainder of this work.

4.3. *Overall average boundary shear stress*

Water can have potential energy by virtue of its elevation. Steady flow in a channel is maintained by a balance between the rate of potential energy expenditure and the rate of energy dissipation in the channel. 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 or around other obstructions. This shearing of flow occurs as a result of the force exerted on the flow by the irregularities associated with the boundaries at a particle scale, a bedform scale or by other obstructions to flow. Per unit area of boundary, this total force is accumulated as the overall average boundary shear stress, τ_0.

Calculating overall average boundary shear stress

A simple force balance on a volume of water flowing steadily in a wide channel shows that the resisting force per unit area of boundary, τ_0, is balanced by the downstream component of the water's weight.

So:

$$\tau_0 = \rho g d S$$

where:

τ_0 = overall average boundary shear stress

ρ = density of water

g = acceleration due to gravity

d = depth of water

S = bed slope of channel

4.4. *Stream power*

Stream power is the time rate of potential energy expenditure per unit boundary area (Bagnold 1966) given by $\tau_0 U$, where U is the average velocity of flow. Rhoads (1987) defines several measures of stream power that apply at a reach scale or at a single cross section. (Most notably *unit stream power* is defined as the power per unit weight of water which is different from the stream power per unit boundary area that is used here.)

Given basic knowledge of a stream cross section (depth of flow, average velocity and average bed slope) it is therefore possible to compute the stream power per unit boundary area for a range of flows. But this ignores a practical and a theoretical problem.

- The practical problem is the scarcity of accurate data with which to characterise the average slope, particularly at sites where bed slopes are flat. In the author's experience, characteristic bed slopes in active alluvial streams can only be determined by detailed thalweg survey over a stream length equivalent to several meander wavelengths. These data are rarely available even at gauging stations, and slopes measured in other ways are unreliable. On the other hand, at gauging stations, detailed stage discharge relationships, cross section measurements and velocity measurements are generally available for a range of flows.

- The theoretical problem recognises that the rate of energy expenditure given by $\tau_0 U$, is the overall rate of energy expenditure in the channel including energy expended associated with all forms of boundary resistance and form drag. This is not necessarily the rate of energy expenditure that is relevant to work done by the flow on individual particles in the boundary. Instead we need to isolate the rate of energy that is expended at a particle scale.

4.5. *Particle shear stress and particle stream power*

From the work of Einstein and Barbarossa (1952), the total shear stress, τ_0, evaluated as above, is assumed to represent the sum of (Petit 1990):

- the shear stress due to the resistance of the particles that make up the channel boundaries (τ'); and

- a further shear stress (τ'') that accounts for all the other forces acting on the flow including those associated with irregularities in the bed and banks, meanders, bedform, drag from obstructions, etc.

So:
$$\tau_0 = \tau' + \tau''$$

It is only the particle shear stress, τ', that is of relevance to the transport of sediments (Laursen 1958) and hence to adjustment of the channel boundaries.

It follows that there will be a “particle stream power” that is given by $\tau' U$.

4.6. *Particle shear stress and particle stream power from a logarithmic velocity distribution*

Particle boundary shear stress and particle stream power can be related to the shape of the velocity profile near the boundary. A generalised logarithmic velocity distribution based on the Karman-Prandtl equation for turbulent flows near rough boundaries was used by Ackers and White (1973).

$$\frac{U}{U_*'} = \sqrt{32}\log\frac{ad}{D}$$ **Equation 1**

in which:

U = mean velocity of flow in the channel

U_*' = particle shear velocity = $\sqrt{\frac{\tau'}{\rho}}$

τ' = particle - related shear stress

ρ = mass density of fluid

α = factor taken by Ackers and White (1973) to be the value 10

d = mean depth of flow (cross section area/water surface width)

D = particle diameter of boundary material

The factor α as used by Ackers and White (1973) was evaluated empirically on the basis of a range of data. Amongst other things it accounts for the relationship between D and the roughness factor k_s used in the original Karman-Prandtl equation.

substituting for U_*':

$$\tau' = \frac{\rho U^2}{32\left(\log\frac{10d}{D}\right)^2} \qquad \textbf{Equation 2}$$

and particle-related stream power expenditure per unit boundary area is given by $\tau' U$

$$\tau' U = \frac{\rho U^3}{32\left(\log\frac{10d}{D}\right)^2} \qquad \textbf{Equation 3}$$

This formulation allows a calculation of particle-related stream power from readily available information on channel hydraulics and an estimate of the relevant particle material size.

4.7. *Shear stress at initiation of motion*

Critical particle shear stress τ'_C is the shear stress imposed on the boundary at initiation of motion of material in the channel boundary. For non-cohesive material on the bed, this is commonly given in simplified form as:

$$\tau'_C = \mathrm{C}_1 \ \rho g(s-1)D$$ **Equation 4**

where:

C_1 = a constant
s = mass density of sediment relative to mass density of fluid
and other variables are as previously defined.

A typical derivation of Equation 4 is summarised here based on Yang's text (Yang 1996). C_1, C_2, C_3, C_4 are all constants.

White (1940) proposed that the drag force on an individual particle, F_D is proportional to the product of shear stress and the square of the diameter of the particle. Modifying this to make it refer clearly to particle shear stress gives:

$$F_D = \mathrm{C}_2 \tau' D^2$$

then, ignoring lift forces, the overturning moment M_o is given by:

$$\begin{aligned} M_O &= \mathrm{C}_3 F_D D \\ &= \mathrm{C}_2 \mathrm{C}_3 \tau' D^3 \end{aligned}$$

Taking the submerged weight of the particle as proportional to $\rho g(s-1)D^3$ and ignoring all other resisting forces, the moment resisting motion M_R is:

$$M_R = \mathrm{C}_4 \rho g(s-1)D^4$$

At the point of motion:

$$
\begin{aligned}
M_O &= M_R \\
C_2 C_3 \tau'_c D^3 &= C_4 \rho g (s-1) D^4 \\
\text{and for } C_1 &= \frac{C_4}{C_2 C_3} \\
\tau'_c &= C_1 \rho g (s-1) D
\end{aligned}
$$

Evaluation of constant C₁

Ackers and White (1973) used experimental data to evaluate α in Equation 1. Their results can also be used as follows to examine initiation of motion and to confirm values for C_1 that will be consistent with the derivation.

From Equation 4, using the subscript $_c$ to denote the value of the variable at the point of particle motion:

$$(U_*)_c = \sqrt{\frac{\tau_c{}'}{\rho}} = \sqrt{C_1}\sqrt{g(s-1)D}$$

From $\dfrac{U}{U_*{}'} = \sqrt{32}\log\dfrac{ad}{D}$ (Equation 1)

$$\left(U_*\right)_c = \frac{U_c}{\sqrt{32}\,\log\frac{\alpha \mathrm{d}_\mathrm{d}}{\mathrm{D}}}$$

$$\frac{U_c}{\sqrt{32}\,\log\frac{\alpha \mathrm{d}_\mathrm{c}}{\mathrm{D}}} = \sqrt{\mathrm{C}_1}\sqrt{g(s-1)D}$$

$$\frac{U_c}{\sqrt{32g(s-1)D}} = \sqrt{\mathrm{C}_1}\log\frac{\alpha \mathrm{d}_\mathrm{c}}{\mathrm{D}}$$

Ackers and White (1973) plotted $\frac{U}{\sqrt{32g(s-1)D}}$ against $\frac{D}{d}$ at the point of motion and determined that $\alpha = 10$ and $\sqrt{\mathrm{C}_1}$ varies between 0.19 and 0.23.

Comparison with other investigators

Thus, according to the Ackers and White (1973) approach:

$$0.036 \le \mathrm{C}_1 \le 0.053$$

Rearranging Equation 4 gives:

$$\frac{\tau_C'}{\rho g(s-1)D} = \mathrm{C}_1$$

The left hand side is recognisable as Shield's dimensionless critical shear stress (Vanoni 1975). For fully rough conditions this was originally given a value of 0.056 (Shields 1936), although other authors have since suggested 0.049 (Lane 1957) or 0.047 (Meyer-Peter and Muller 1948). A major review of incipient motion studies (Buffington and Montgomery 1997) has concluded that for high Reynolds numbers and for relative roughness typical of gravel bed rivers, critical shear stress determined from visual observation of grain motion is in the range of 0.030 to 0.073. The Ackers and White (1973) values are consistent.

4.8. *"Excess" stream power*

For particle stream power, *P* above a threshold shear stress τ_c:

$$P = U\left(\frac{\rho U^2}{32\left(\log\frac{10d}{D}\right)^2} - \tau_c'\right) \qquad \textbf{Equation 5}$$

This formulation can now be used to evaluate excess stream power at a given flow for a channel whose basic hydraulic and boundary characteristics are known.

In the case studies that follow, gauging information is used to derive relationships between flow and velocity and between flow and depth. Together with information about the boundary material, this allows development of a relationship between flow and excess stream power for use in *effective discharge* computations.

5. APPLICATION OF A STREAM POWER BASED EFFECTIVE DISCHARGE APPROACH TO HYDROLOGIC AND MORPHOLOGIC CHANGES ON THE TUMUT RIVER AT TUMUT, NSW

5.1. *Introduction*

The purpose of the work reported in this chapter is to explore whether an *effective discharge* approach can be used to explain or predict channel enlargement on a river subject to increased flows and flow regulation. The river has a long-term flow record, good gauging data and some limited records of channel change. No data are available on sediment movement in the river.

5.2. *Tumut River*

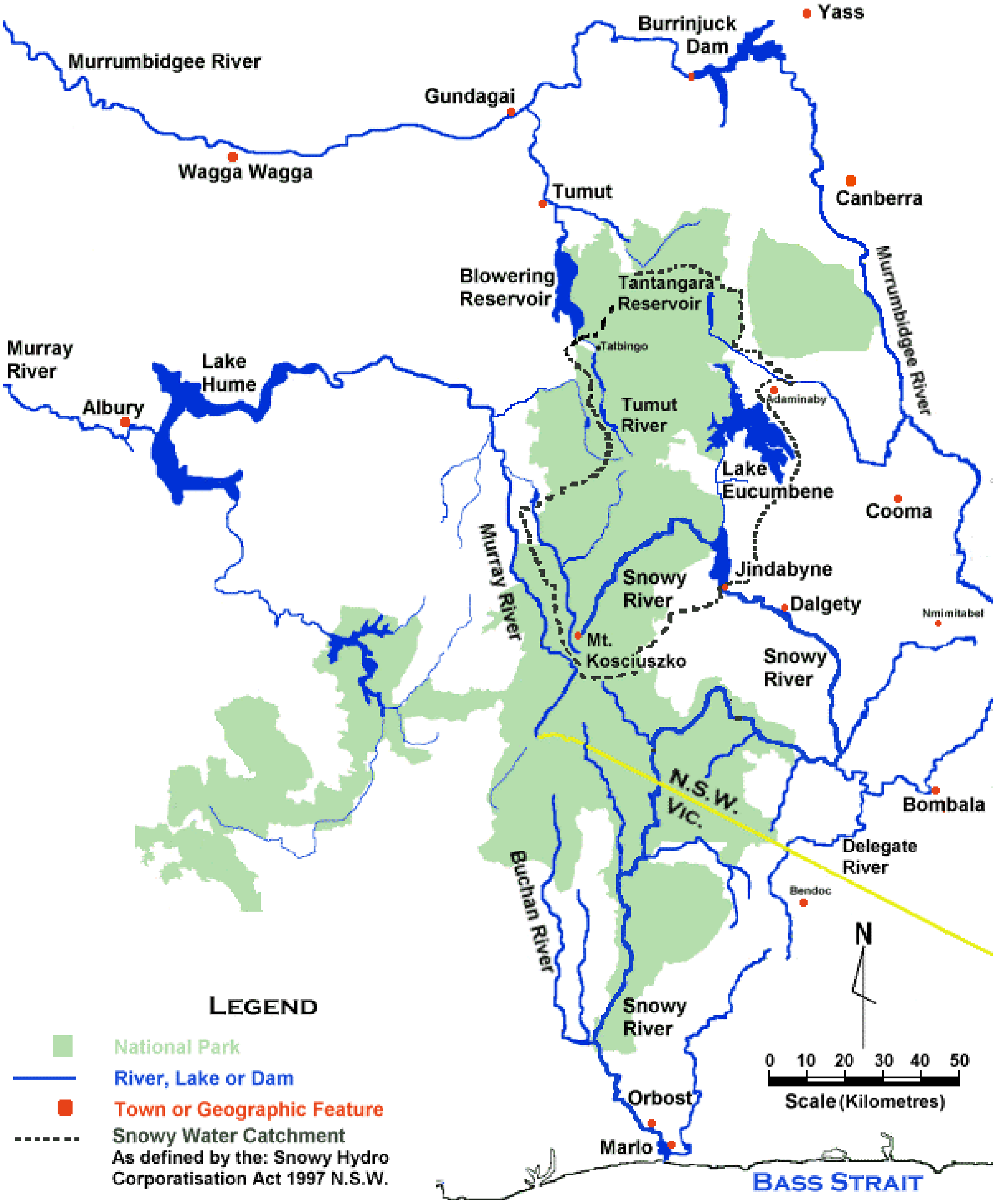
The Tumut River rises in the Great Dividing Range of south eastern Australia (Figure 6) at elevations of around 1 800 m and flows some 160 km to the Murrumbidgee River 220m above sea level (Figure 7).

THE SNOWY WATER INQUIRY
Jointly sponsored by the New South Wales and Victorian Governments.

Artwork by InfoStore info@infostore.com.au

Figure 6 Locality map. Snowy Mountains area. South east Australia. From Snowy Water Inquiry website (Snowy Water Inquiry 1998).

Since June 1959, flows in the Tumut River have been affected by the Snowy Mountains Scheme, a major water conservation and hydro-electricity project that has diverted the Upper Murrumbidgee, Eucumbene and Tooma Rivers to the Murrumbidgee River via the Tumut River. More details of the Scheme and a map of the area are given in the next Chapter and in Figure 7.



Designated area of inquiry: the Snowy Water Catchment (as defined in the Act), the course of the Snowy River flowing from that catchment to Marlo, and the course of rivers and streams flowing from that catchment to Lake Hume Blowering Reservoir and Burrinjuck Reservoir.

Map by Snowy River Inquiry

Artwork by InfoStore info@infostore.com.au

Figure 7 Map of Snowy Mountains Area, south east Australia. Showing Tumut River, Blowering Reservoir and township of Tumut. Also shows Snowy River, Lake Jindabyne and township of Dalgety (refer to next Chapter). From Snowy Water Inquiry website (Snowy Water Inquiry 1998).

Figure 8 Tumut River at Tumut 1996. Note rock bank protection, willow trees, cleared riparian zone and floodplain extent.

Figure 9 Tumut River downstream of Tumut 1996. Note rock bank protection, willow trees, cleared riparian zone and floodplain extent.

In May 1968, flows in the Tumut River were further affected when water commenced storing in Blowering Reservoir on the Tumut River to provide flow regulation and storage for irrigation.

In the vicinity of Tumut township, downstream of these diversions and reservoirs, the Tumut River is an alluvial channel with an irregular meander pattern and a bed gradient of 0.001 (New South Wales Department of Land and Water Conservation 1995). The bed exhibits pools and riffles with exposed areas consisting mainly of armoured gravel with a median size of around 20 mm (Bucinskas 1995). The river channel flows within a wide floodplain although flow regulation now means that this plain rarely floods.

From field observation, the riparian zone is heavily modified. Natural vegetation has been impacted by clearing for grazing or horticulture and unrestricted stock access is common. Riparian over-storey vegetation is dominated by introduced varieties of willow (*salix sp.)*. Figure 8 and Figure 9 illustrate these aspects of the river.

Direct management intervention in the river channel has been sporadic but intense since before river regulation (New South Wales Department of Land and Water Conservation 1996b). Widespread willow planting for erosion control seems to have been carried out by the first settlers as trees were already mature and causing channel blockages by 1928 (New South Wales Department of Water Resources 1991). Management intervention intensified with the onset of flow regulation in the late 1950s. Over $20million (1994 value) had been spent on programs of channel clearing and erosion control by 1994 (New South Wales Department of Land and Water Conservation 1996b) (Figure 10, Figure 11)

Figure 10 Example of bank recently rocked for erosion control, 1996

Figure 11 Example of bank recently cleared of willows, 1996

5.3. *Effects of flow regulation on the frequency distribution of flows*

Analysis of flow records shows that river regulation for electricity generation and irrigation has altered the flow regime in the Tumut River, increasing average flow at Tumut from 41 m^3/s to 62 m^3/s. Flow regulation has also redistributed flows such that floods are now a rarity and there are long periods of flow at or near bankfull river channel capacity.

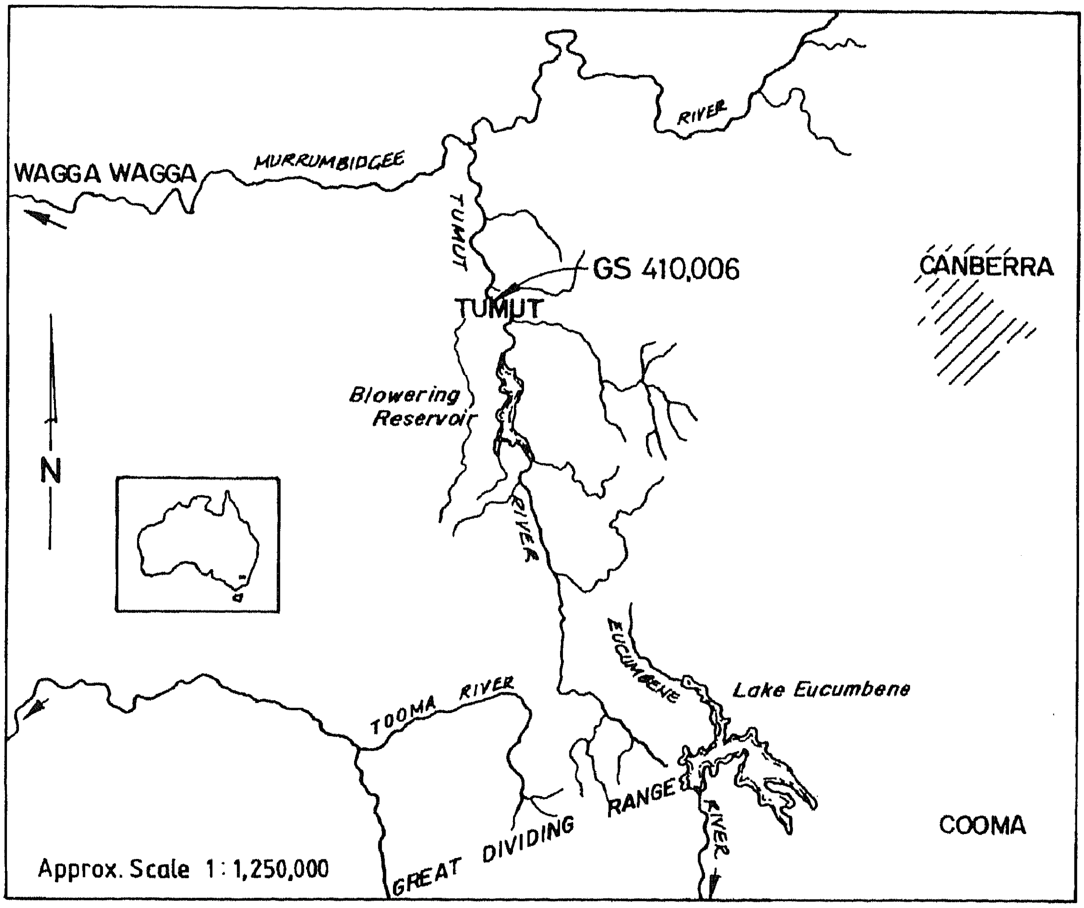


Figure 12 Tumut River locality showing gauging station 410006: Tumut River at Tumut

Figure 12 shows the general location of Gauging Station 410006 operated by the NSW Department of Land and Water Conservation since 1909 at two different sites adjacent to Tumut township. Water levels and flows were measured at the "Town Bridge" until April 25th 1932 when the station was measured at the “Town Bridge” until April 25th 1932 when the station was relocated upstream by several hundred metres to a section known as the “pump station” gauge. Review of station files shows that this has been treated as an important station within the Department’s network. Flow measurements have been conducted regularly over a full range of flows using standard current meter techniques and ratings have been regularly updated.

For this study, flow records have been obtained from Pinneena – the Department’s database on CD ROM (New South Wales Department of Land and Water Conservation 1996a).

The cumulative frequency distributions of monthly or daily flows, have been presented in several previous reports (Bucinskas 1995; Snowy Mountains Council 1991). For the purposes of this investigation, the original flow record for the Tumut River at Tumut has been re-analysed to establish the frequency distribution of daily flows.

The frequency analysis has used daily flow data to determine the number of daily flows that fall into each of thirty-one 5 m^3/s increments from zero to 155 m^3/s. Typically plotted as a histogram, the relative frequency distribution represents the proportion of daily flows in each bin. The probability density function of daily flows is a standardised representation obtained by dividing the relative frequency distribution by bin size and plotted as a continuous function.

Table 1 and Figure 13 show the probability density function of daily flows at this site for three periods as follows.

1. ***pre Snowy:*** 1909 - 1959: represents flows before river regulation.

2. ***pre Blowering:*** 1960 - 1968: is the period when the Snowy Mountains Scheme was operative but Blowering Reservoir was not storing water.

3. ***post Blowering:*** 1969 - 1996: represents a period of regulation with both the Snowy Mountains Scheme and Blowering Reservoir operative.

Table 1 Probability density function of daily flows.
410006 Tumut River at Tumut.

Flow (cumec)	**PDF of daily flows (%/cumec)**		
mid point of flow bin	pre Snowy 1909-59	pre Blowering 1960-68	post Blowering 1969-96
2.5	0.13	0.00	0.09
7.5	2.35	0.13	0.58
12.5	3.14	1.36	1.80
17.5	2.28	1.48	1.66
22.5	1.93	1.55	1.05
27.5	1.23	1.12	0.73
32.5	0.90	1.00	0.56
37.5	0.81	1.00	0.40
42.5	0.74	1.06	0.47
47.5	0.57	1.10	0.40
52.5	0.59	1.25	0.47
57.5	0.46	1.09	0.44
62.5	0.48	1.11	0.58
67.5	0.36	1.13	0.53
72.5	0.33	1.03	0.54
77.5	0.35	0.85	0.51
82.5	0.34	0.72	0.61
87.5	0.32	0.46	0.60
92.5	0.24	0.34	1.13
97.5	0.27	0.35	1.36
102.5	0.21	0.22	1.28
107.5	0.18	0.21	1.25
112.5	0.18	0.17	1.76
117.5	0.15	0.16	0.73
122.5	0.12	0.08	0.16
127.5	0.13	0.15	0.07
132.5	0.11	0.10	0.02
137.5	0.09	0.09	0.03
142.5	0.08	0.08	0.02
147.5	0.05	0.08	0.01
152.5	0.07	0.06	0.01

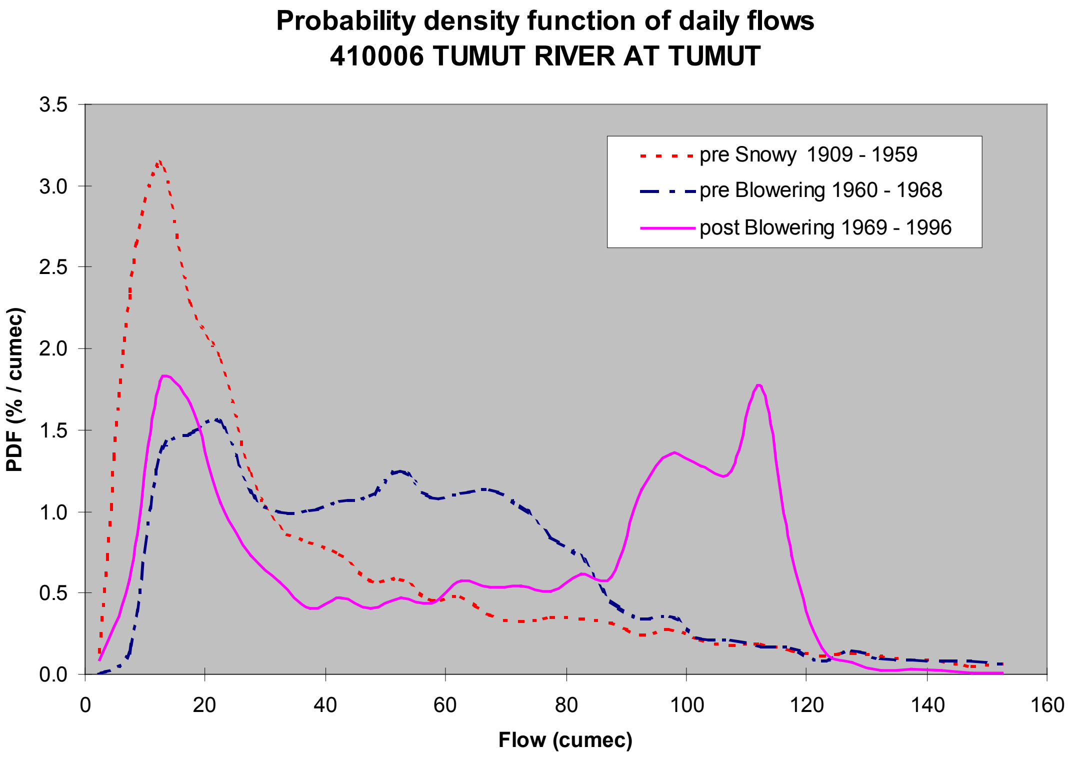


Figure 13 Probability density function of daily flows. Tumut River at Tumut.

This way of analysing and presenting the data emphasises which flow intervals have been most affected by the changes. Comparing pre Snowy and post Blowering periods shows a significant reduction in the probability of low flows (around 12 m^3/s) and a greatly increased probability of flows at around 100 m^3/s. Flows are now in the interval between 90 m^3/s and 120 m^3/s for 38% of the time compared to 6% of the time prior to 1959.

The pre Snowy and post Blowering plots demonstrate a major shift in the distribution of daily flows as a result of flow regulation. The strongly modal pre Snowy distribution has been replaced by a bimodal post Blowering distribution. The original mode at 12.5 m³/s has been supplemented by a strong second mode at 112 m³/s.

The Figure also shows the impact of the Snowy scheme before construction of Blowering reservoir and indicates that in that period, the frequency of daily flows less than about 30 m³/s was decreased in favour of flows between about 30 and 80 m³/s. There was negligible change in the frequency of those flows exceeding about 90 m³/s.

5.4. *Changes in channel capacity at the Tumut gauging station*

Changes to the rating at the Tumut gauge have been used as a means of tracking any changes to channel capacity over the period of record.

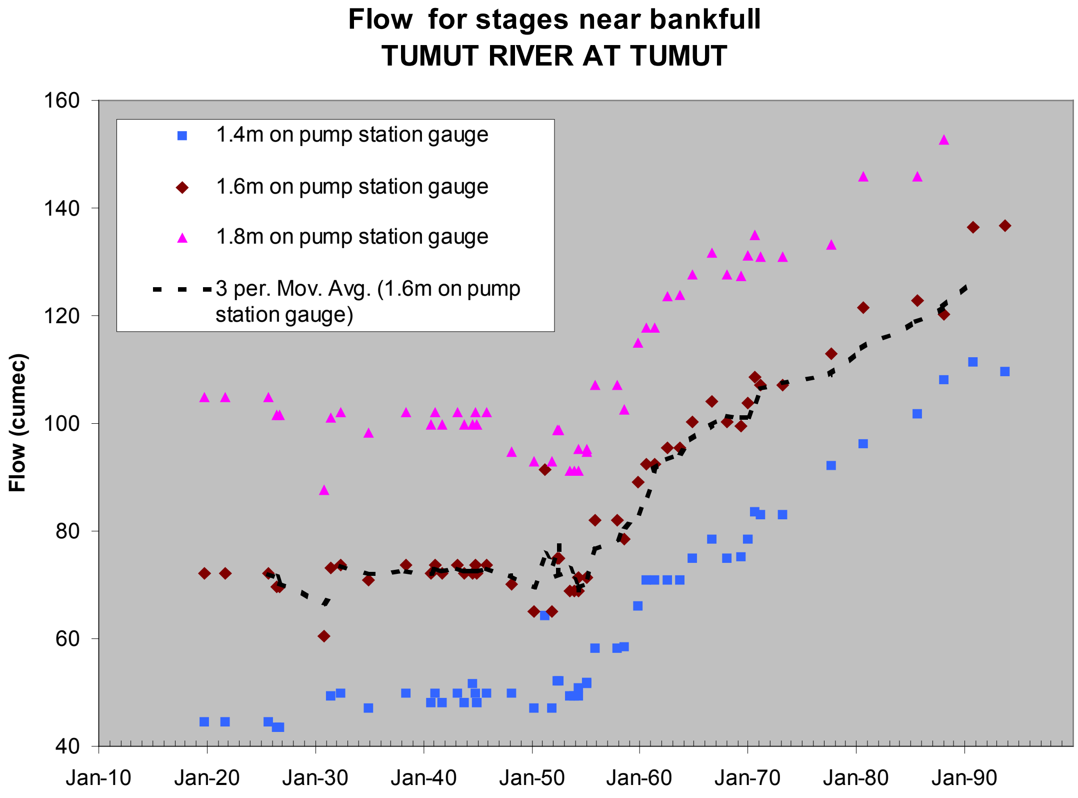


Figure 14 Time-series of flows at selected stages close to bankfull. From rating tables applying at Tumut River pump station gauge from 1919 to 1993.

Forty-eight rating tables have been analysed starting with Table 1 at the old "town gauge" (commencing in 1919) through to table 210 at the pump station gauge (commencing in 1993). The rating tables are based on 753 flow measurements in the period. For each table, the flow at an equivalent pump station gauge height of 1.4m, 1.6m and 1.8m has been extracted and plotted as a time series in Figure 14 to be indicative of flows near bankfull.

At a gauge level of 1.6m for example, the ratings show a consistent flow in the channel of around 75 m^3/s from 1919 until the mid 1950s. In the late 1950s a progressive change commenced such that channel capacity at this water level nearly doubled by the mid 1990s.

Comparison of surveyed cross sections (Gippel, O'Neill et al. 1992) and descriptive material (New South Wales Department of Land and Water Conservation 1996b) indicates that this increase in channel capacity is the result of deepening and widening of the channel by erosion, some natural and some artificial channel straightening and widespread clearing of willows, snags and debris. The same information suggests that the results at the gauging station are not anomalous but are representative of changes over at least 30km of river. On the basis of repeat surveys of 6 cross sections between 1945 and 1988, Gippel (1992) concluded that "the Tumut River has generally widened and deepened since the original 1945 survey".

5.5. *Pre Snowy bankfull discharge*

The *bankfull discharge* of a river channel is a physical measure of the flow capacity of the channel. It is the discharge at which a channel is just flowing full and is about to overflow on to the floodplain. *Bankfull discharge* can refer to channel capacity at a discrete channel cross section but more usefully, in recognition of natural variability from section to section, it is a representative value for channel capacity over a river reach.

Bankfull discharge for the pre Snowy condition in the vicinity of Tumut has been estimated from gauging station data supplemented by steady state modeling based on 1945 surveyed cross sections. Modelled water levels, calibrated to the pump station gauge, indicate that channel capacity is first exceeded at 80 m^3/s[1]. On the rating tables of the day, 80 m^3/s corresponds to a stage at the pump station gauge of 1.65 m which correlates well with current estimates of bankfull water levels in this vicinity.

5.6. *Post Blowering bankfull discharge*

A detailed monitoring program in 1977 recommended an operational limit for long term releases of 105 m^3/s at Tumut to minimise floodplain problems (New South Wales Department of Water Resources 1991). The same report

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[1] This estimate of bankfull flow is substantially less than that provided by a 1958 report (Snowy Mountains Authority 1958) in which a river capacity of 4 000 to 8 000 cusec (113 to 227m^3/s) was suggested. In fact the turbines on the Blowering Dam power station were designed for 113m^3/s. Subsequent events have shown that this estimate was optimistic, since flows more than 113 m^3/s have never been conveyed without inundation on the floodplain.

found that flows of 110 m^3/s at Tumut caused some minor spills on to private property. Using the rating applying at the time, these flows correspond to 1.53m and 1.57m on the pump station gauge respectively. Detailed survey along the river at that time showed that the 110 m^3/s flow (1.57m on the gauge) was close to bankfull over some 55 km of river upstream and downstream of Tumut.

Current river operating rules restrict releases from Blowering such that flow in the Tumut River at Tumut is limited to 111 m^3/s. By the current rating, this is 1.4m on the Tumut pump station gauge. At this level no major channel capacity problems occur in the Tumut area and there is generally minor freeboard (New South Wales Department of Land and Water Conservation 1995). Bankfull stage is estimated to be about 100mm higher than this indicating a bankfull discharge of approximately 120 m^3/s.

5.7. *Channel hydraulics*

Particle shear stress for a flow, Q has been given by:

$$\tau' = \frac{\rho U^2}{32\left(\log \frac{10d}{D}\right)^2} \qquad \text{(Equation 2)}$$

where U and d are functions of Q.

Representing typical channel hydraulics using the properties of a single cross section

It remains to determine the typical nature of these functions *U* and *d* for the Tumut River in the vicinity of the gauging station. The difficulty of selecting a single relationship to describe *U* or *d* as a function of *Q* should not be underestimated. The problem and the errors associated with representing a variable that is continuously varying in space with a relationship derived from a single cross section has been investigated previously (Tilleard 1980). In that study, selection of cross section locations was found to have a profound impact on the outcomes of hydraulic and geomorphic modelling.

In the current study, this potential source of error is exemplified by the observed differences in the hydraulic properties of the river channel revealed from gauging data. Looking only at the limited sample of pre Snowy data for the period after the gauging station was moved, Figure 15 plots actual measurements of velocity and discharge between 1932 and 1958.

The data reveals that the relationship between *Q* and *U* falls into at least two groups, and for one of those groups, *Q* is not a good predictor of *U*. Further investigation indicates that the grouping results from flow measurements at different locations. For high flows (generally above about 30 m^3/s) the measurement section is shifted for convenience and safety from the pump station to the old Tumut River bridge. The group of high flow gaugings are measurements from the bridge and the balance of the gaugings are by wading or from the continuous wire at the pump station. The rating is not affected, remaining quite stable as shown in Figure 16, however the hydraulic characteristics of the two nearby cross sections are clearly quite different.

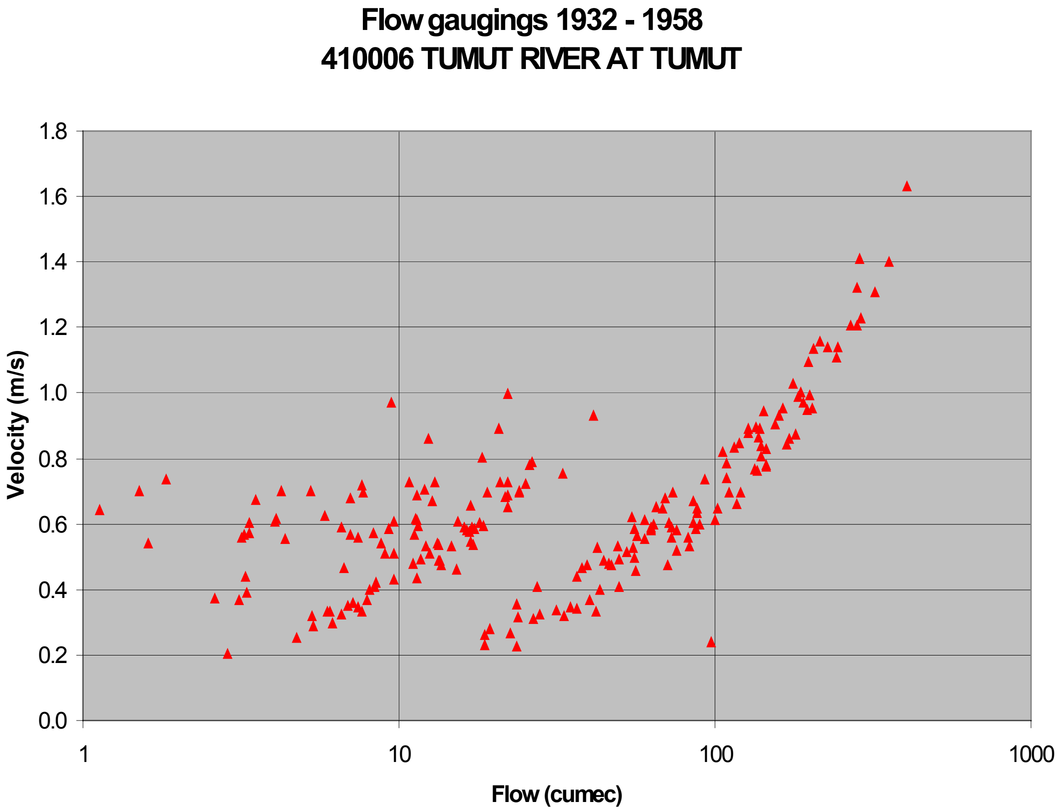


Figure 15 Measurements of velocity and discharge for station 410006 Tumut River at Tumut. Shows at least two groups of measurements representing flow gaugings at different cross sections. Demonstrates differences in hydraulic properties between nearby cross sections.

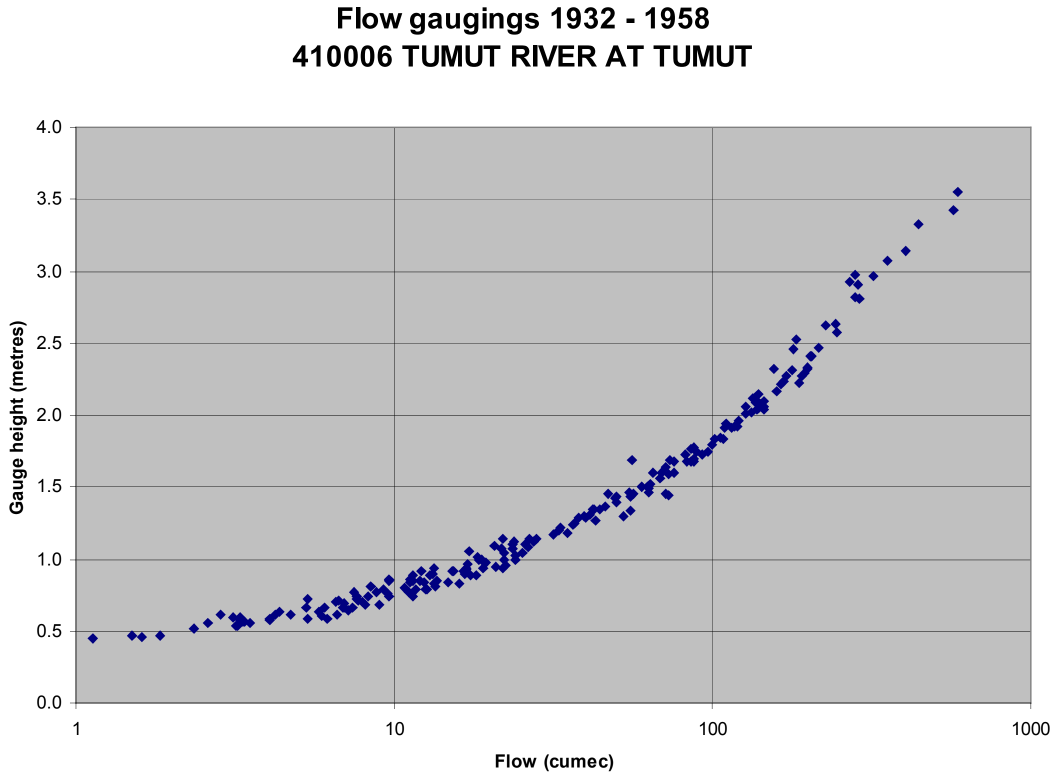


Figure 16 Flow measurements versus gauge height for 410006, Tumut River at Tumut for period 1932 – 1958.

To further investigate this problem, in the current study, two sets of relationships between *d*, *U,* and Q were developed from the available gauging data. A steady state backwater model was also developed for the reach using 1945 cross section data as a means of assessing the variability of hydraulic relations between cross sections. The historical reports and results were then reviewed in the field, comparing channel form and cross sections over several kilometres of river, before eliminating the results from the Tumut bridge site as being less representative of the reach. Relations between Q and U and Q and d were determined for the pump station gauge by fitting power curves to the relevant data.

Particle shear stress

Using Equation 2 together with the Q versus U and Q versus d relations fitted to the gauging data in Figure 15 and Figure 16 for the pump station gauge, the variation of particle shear stress with flow has been derived as shown in Figure 17.

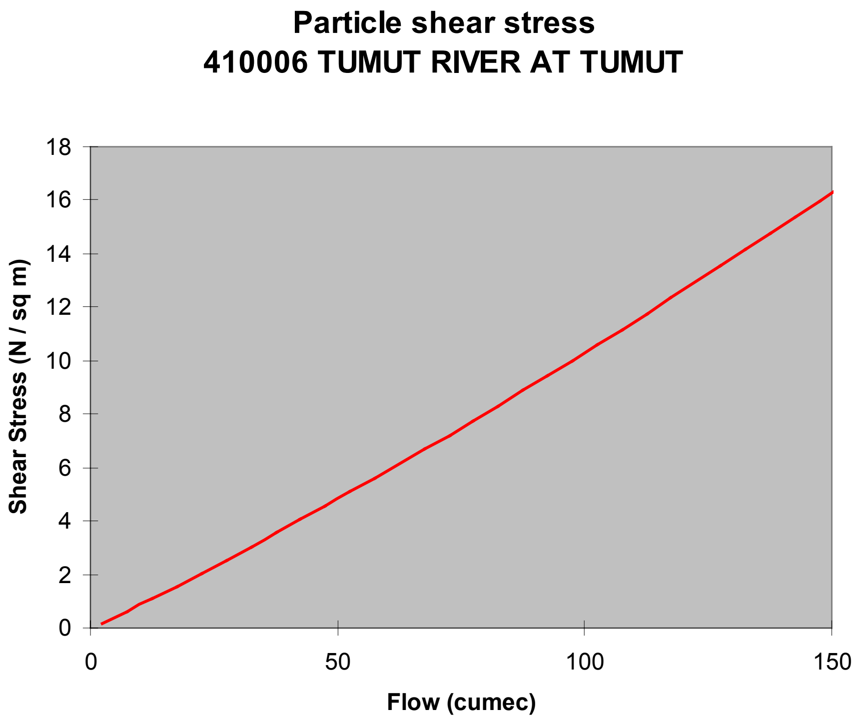


Figure 17 Variation of particle shear stress with flow computed for section at the pump station gauge using Equation 2 together with the *Q* versus *U* and *Q* versus *d* relations fitted to the gauging data in Figure 15 and Figure 16.

5.8. *"Excess" stream power*

For particle stream power, *P* above a threshold shear stress τ_c:

$$P = U\left(\frac{\rho U^2}{32\left(\log\frac{10d}{D}\right)^2} - \tau_c'\right) \qquad \text{(Equation 5)}$$

Critical particle shear stress τ'_c can be estimated by reference to Equation 4

$$\tau_C' = \mathrm{C}_1\ \rho g(s-1)D \qquad \text{(Equation 4)}$$

with values of C_1 from the discussion in Section 4.7 and particle size measurements reported by Bucinskas (1995) for bed and banks.

The form of the stream power relation depends on the hydraulics of the channel, but the excess stream power relation will start from a different threshold for bed and for banks if the bed and bank material (and hence the critical particle shear stress) is different.

Critical particle shear for bed material

For a bed gravel armour layer size of 20 mm (Bucinskas 1995), and values of C_1 as recommended by Ackers and White (Ackers and White 1973)

$$0.036 \le \mathrm{C}_1 \le 0.053$$

critical shear stress is in the range of 12 - 17 Nm^{-2}. According to the relationship in Figure 17 movement of bed material can therefore be expected to commence at flows of 120 – 150 m^3/s.

Critical particle shear for bank material

The critical particle shear stress for bank material will be substantially lower than the critical particle shear stress for the bed material since the material forming the bank is of smaller size, however Equation 4 is limited in application to non cohesive material (and strictly only applies to material on the bed). From field observation and analyses reported in Bucinskas (1995), bank material is cohesive silty sand and is at least partially bound or protected by vegetation on most banks. The literature is ambiguous on the treatment of critical shear stress in these situations. On the basis of Bucinskas's (1995) work and with reference to other observations (Lane 1955; Vanoni 1975), a nominal critical shear stress for the bank material of 2 Nm^{-2} is adopted for trial. The adoption of this value is tested by sensitivity analysis as reported in Sections 5.15 and 7.1.

5.9. *Distribution of excess energy with flow. Pre Snowy*

Excess energy using estimated critical shear stress for bank material

Using the selected relationships between U, d and Q, the relationship between excess stream power and discharge for the Tumut River at Tumut is illustrated as curve 2 in Figure 18 for τ'_c = 2 Nm^{-2}.

This Figure also demonstrates the effect of multiplying the pre Snowy probability density function of daily flows (curve 1) by the excess stream power - discharge relationship (curve 2) to produce a curve (curve 3) that represents the distribution of excess stream energy with flow. Note that this curve has been smoothed by averaging over two flow intervals to remove oscillations associated with the discretisation process. The value of the ordinates of this curve (curve 3) have been multiplied by 31 536 000 (the number of seconds in a year) and further factored by 0.01 (to account for the use of percentage in curve 1) so that the units become joule metre^{-2} cumec^{-1} year^{-1} (plotted on the graph as megajoule metre^{-2} cumec^{-1} year^{-1}). The area under curve 3 represents the total energy expended in the channel in excess of the critical shear stress for bank material in an average year in the pre-Snowy period.

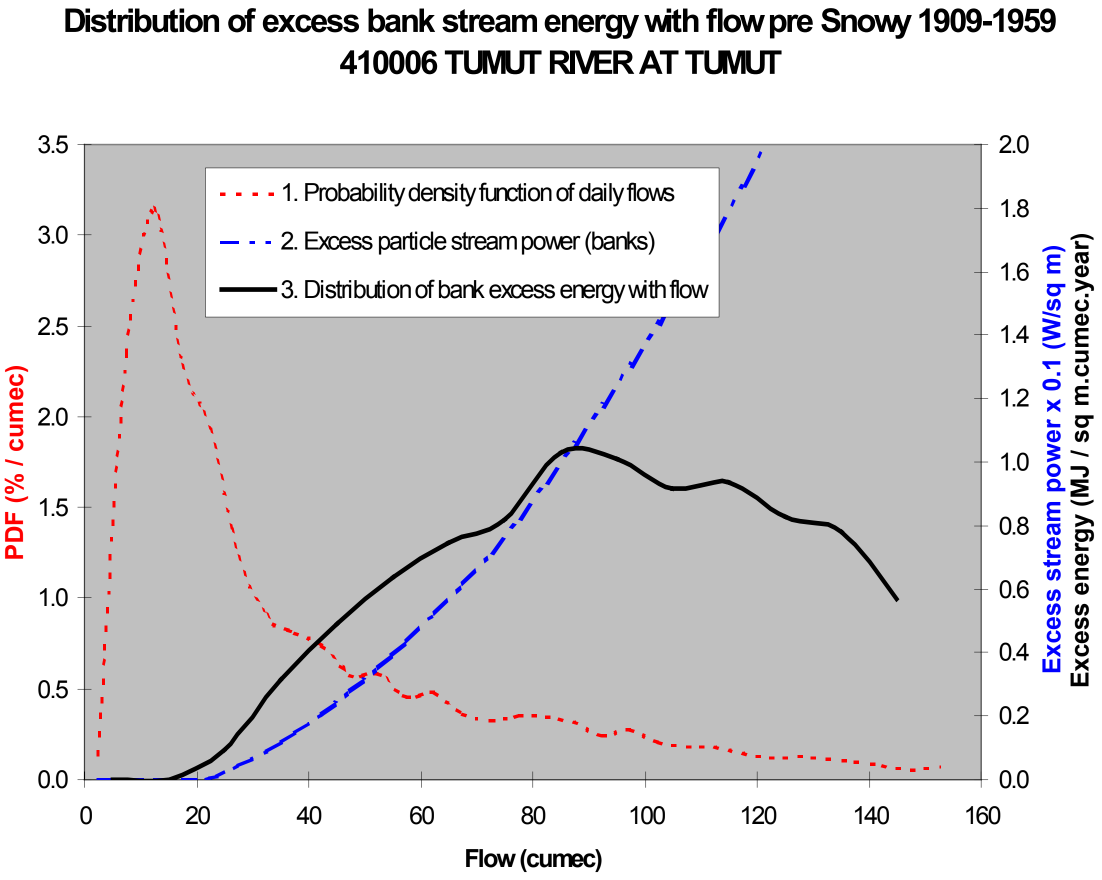


Figure 18 Excess stream power and distribution of excess energy with flow based on estimated critical shear stress for bank material. Tumut River at Tumut. 1909 – 1959.

Excess energy based on estimated critical shear stress for bed material

The same process can be followed using an estimated critical shear stress for bed material $\tau_c' = 14 \text{ Nm}^{-2}$. The resulting distribution of excess energy with flow is shown in Figure 19.

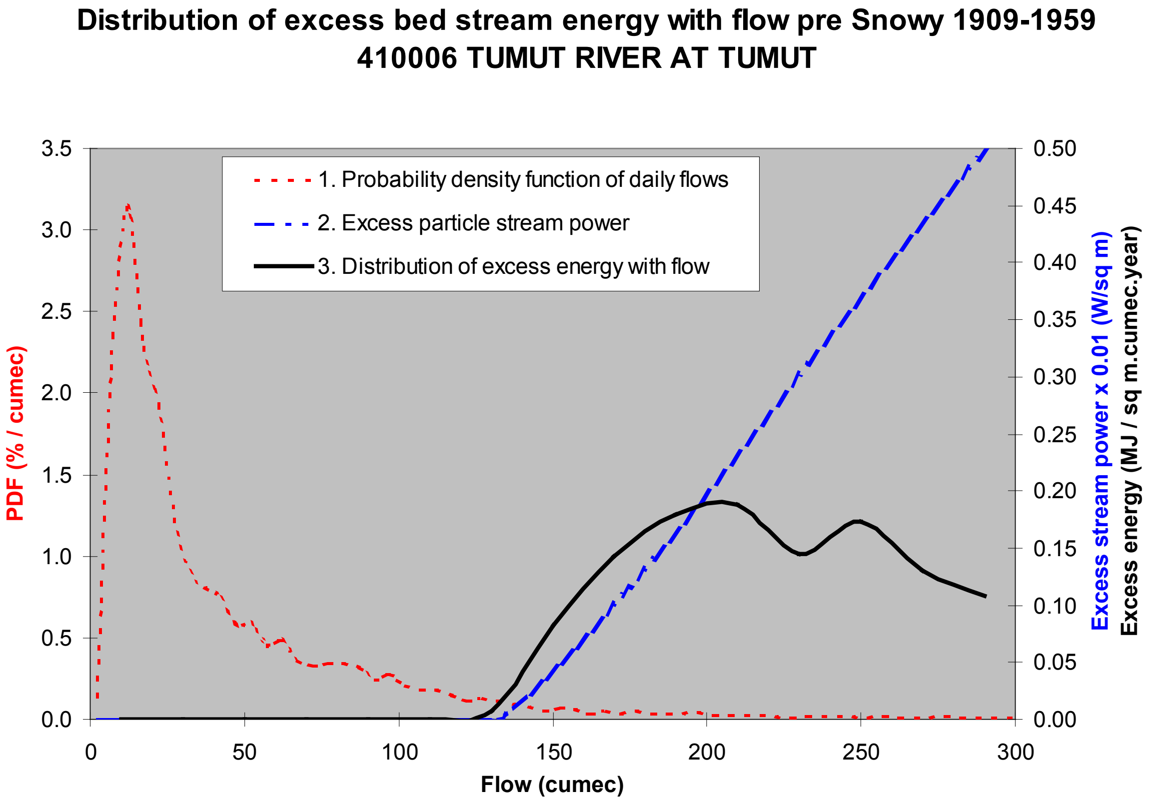


Figure 19 Excess stream power and distribution of excess energy with flow based on estimated critical shear stress for bed material. Tumut River at Tumut. 1909 – 1959.

5.10. *Effective discharge – pre Snowy*

The maximum of the distributions of excess energy with flow can be estimated at approximately 85m^3/s using the critical shear stress adopted for the bank, or approximately 210 m^3/s using the critical shear stress estimated for the bed. These are the flows that account for the greatest amount of work done on the channel banks or the channel bed respectively and are two estimates of stream power based *effective discharge* for the river system in the pre Snowy period.

5.11. *Effective discharge post Blowering*

As a first approximation, the same relationships for U, d and τ'_c were used to estimate post Blowering distributions of excess energy using critical shear stress for bed and banks. The results using the critical shear stress for the bed are not substantially different from those in Figure 19 and are not repeated. The post Blowering results using the critical shear stress for the banks are given in Figure 20 showing:

- the post Blowering probability density function;
- the same relationship between excess particle stream power and flow as for the pre Snowy case; and
- the result of multiplying these two curves (and adjusting units) to give the distribution of excess energy with flow.

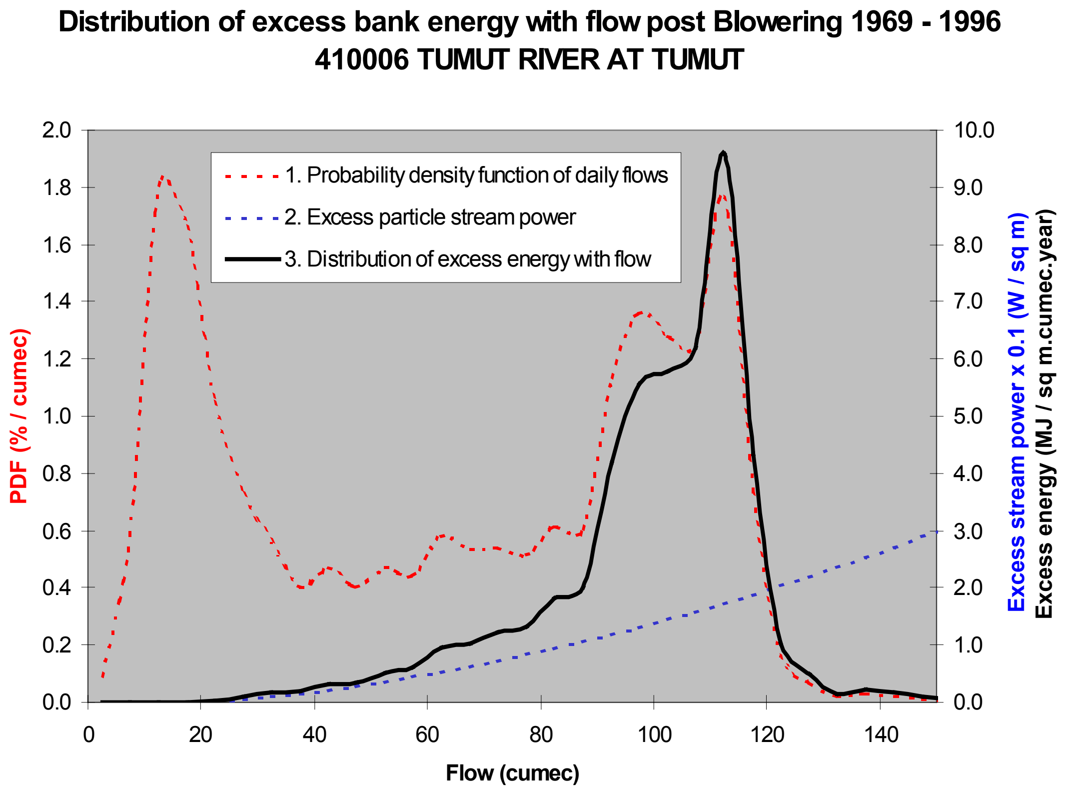


Figure 20 Excess stream power and distribution of excess energy with flow based on estimated critical shear stress for bank material. Tumut River at Tumut. 1969 – 1996.

This distribution of excess energy shows a much stronger mode than the equivalent pre Snowy distribution reflecting the correspondingly strong mode in the probability density function of daily flows. The mode is at 112 m^3/s indicating a stream power based *effective discharge* for the post Blowering period of 112 m^3/s. This estimate is based on a nominal threshold shear stress of 2 Nm^{-2} adopted for the banks and is subject to sensitivity analysis as reported in Section 5.15. The sensitivity analysis indicates that this estimate of *effective discharge* is robust for threshold shear stress less than 3 Nm-2. The sensitivity analysis also confirms that the result would not be altered by using new hydraulic relations derived for the post Blowering period.

5.12. *Comparison of effective discharge pre Snowy and post Blowering*

Figure 21 presents a comparison of the distributions of excess stream energy with flow for the pre Snowy and post Blowering periods using critical shear stress for the bed and critical shear stress for the bank. An *effective discharge* for the pre Snowy period of 85 m^3/s and for the post Blowering period of 112 m^3/s is indicated using a critical shear stress for the bank and an *effective discharge* of 210 m^3/s is indicated for both periods using a critical shear stress for the bed.

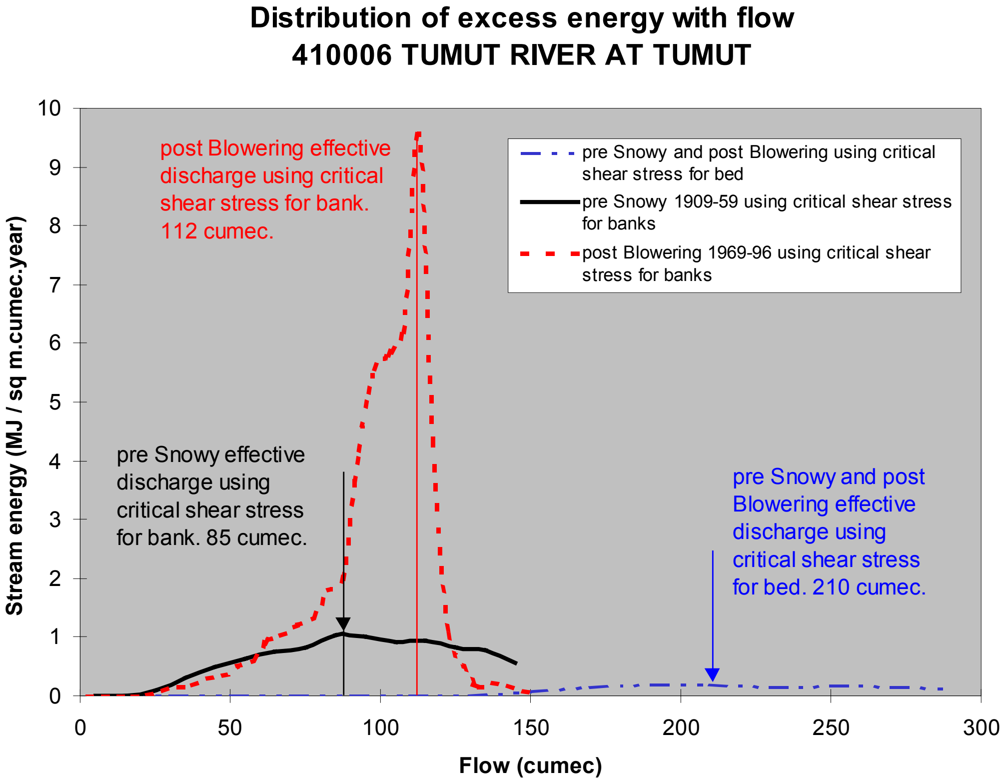


Figure 21 Distribution of excess energy with flow for pre Snowy and post Blowering periods showing estimates of *effective discharge.*

5.13. *Comparison of estimates of bankfull channel capacity and effective discharge*

These estimates are summarised in Table 2.

Table 2 *Effective discharge* and bankfull channel capacity for Tumut River at Tumut for pre Snowy and post Blowering periods.

Period	**Years**	**Effective discharge** (using critical shear stress for bed) (m^3/s)	**Effective discharge** (using critical shear stress for bank) (m^3/s)	**Bankfull discharge** (m^3/s)
pre Snowy	1909-1959	210	85	80
post Blowering	1969-1996	210	112	120

5.14. *Discussion of Tumut River results*

The stream power based *effective discharge* approach proposes that channel characteristics will adjust toward the flow that accounts for the most energy expenditure through time.

Application of the stream power based *effective discharge* approach to the Tumut River data (using a bank-related threshold shear stress value of 2 N m^{-2}) suggests a pre regulation *effective discharge* of 85 m^3/s and a post regulation *effective discharge* of 112 m^3/s. By comparison, bankfull discharge is estimated to be 80 m^3/s pre regulation and 120 m^3/s post regulation. Observed change in bankfull channel capacity is therefore consistent with the stream power based *effective discharge* proposal for this case. In contrast, the same application using the bed related shear stress threshold of 14 N m^{-2} shows no change from pre Snowy to post Blowering.

There are several striking outcomes of the analysis using critical shear for bank material that are further discussed in Chapter 7. These are:

- the significant post regulation increase in the average annual energy excess in the channel over the entire flow spectrum (as represented by the area under the graphs in Figure 21);

- the many fold increase in stream energy available at the discharge that does most work (as represented by the size of the peak of the distribution); and

- the well defined *effective discharge* for the post Blowering case compared to the pre Snowy case because of the strongly modal distribution of excess energy with flow for the post Blowering case compared to the relatively flat distribution for the pre Snowy case (Figure 21).

It is also of interest that the *effective discharge* based on movement of bed material is comparatively ill defined, with the shape of the distribution of excess energy in the vicinity of the mode dependent on heavily amplified but minor variations in the shape of the tail of the probability density function for daily flows. The excess energy available for bed movement in both the pre Snowy and post Blowering cases is small compared to the energy available for bank movement.

5.15. *Sensitivity of the results using critical shear stress for bank material*

For the pre Snowy condition the mode of the probability density function of daily flows occurs at low values of stream power. The resulting distribution of excess stream energy with flow is relatively flat between about 80 and 110 m^3/s and in the case study was subject to minor numerical oscillations before averaging. Sensitivity analysis shows that the estimate of *effective discharge* in this case is sensitive to assumptions and variables adopted in the computations. In particular, it is sensitive to choice of critical shear stress τ'_c, which is a significant issue since this value is poorly defined in the case study but the result is robust for $\tau'_c < 3Nm^{-2}$. The results of sensitivity calculations for critical shear stress are presented and discussed in Section 7.1.

The post Blowering distribution is heavily dominated by the second mode of the probability density function of daily flows and is not subject to these variations. The location of this mode means that its effect is reinforced by the stream power - discharge relationship to produce a strong mode in the excess stream energy distribution. The strength of the mode is such that it is not sensitive to assumptions and variables adopted in the calculations (such as cross section characteristics, critical shear stress, etc). In fact the mode of 112 m^3/s remains robust within a range of assumptions.

This is an important finding since it means that for prolonged regulated flows near bankfull, the potential value of this technique as an indicator of trends in channel change is not diminished by uncertainty about future cross section characteristics or future changes in composition of sediments.

6. APPLICATION OF A STREAM POWER BASED EFFECTIVE DISCHARGE APPROACH TO HYDROLOGIC AND MORPHOLOGIC CHANGES ON THE SNOWY RIVER, NSW.

6.1. *Introduction*

In the previous Chapter it is reported that an *effective discharge* approach based on stream power can account for the channel enlargement recorded in the Tumut River in South Eastern Australia.

The purpose of the work reported in this Chapter is to investigate whether the stream power based *effective discharge* approach can account for the channel contraction that has been observed on the Snowy River after a substantial decrease in channel flows resulting from upstream diversions.

6.2. *The Snowy River*

The Snowy River rises in the Great Dividing Range of south east Australia at elevations of around 1800m and flows through New South Wales and Victoria to the sea at Orbost (Figure 6, Figure 7*)*.

Snowy Mountains Hydro-electric Scheme

As part of the Snowy Mountains Hydro-electric Scheme, two major dams and two minor dams together with a system of tunnels and aqueducts divert water from the upper Snowy River into adjacent catchments. Eucumbene dam commenced storing water in 1957 and Jindabyne dam was completed in 1967 (ID&A Pty Ltd 1995). The Mowamba River aqueduct that diverts low and moderate flows back to the Jindabyne Dam pondage intercepts two tributaries immediately downstream of Jindabyne dam. Table 3 summarises the chronology of these events (Erskine and Tilleard 1997; ID&A Pty Ltd 1995).

Table 3 Key dates in the development of the Snowy Mountains Scheme within the Snowy River catchment (ID&A Pty Ltd 1995)

May 1956	Construction of Eucumbene Dam commences	Capacity 4 798 GL
April 1957	Storage in Eucumbene commences	
December 1965	Construction of Jindabyne Dam commences	Capacity 690 GL
17 April 1967	Storage in Jindabyne commences	
10 July 1967	Diversion through Mowamba River aqueduct to Jindabyne commences	Capacity 4.8 m^3/s

Downstream of Jindabyne, natural flows in the Snowy River are severely curtailed by the diversions from Lake Eucumbene and Lake Jindabyne (New South Wales Department of Land and Water Conservation, Victoria Department of Conservation and Natural Resources et al. 1996). Downstream of Jindabyne Dam, flows are reduced to about 1% of natural flows (Snowy Genoa Catchment Management Committee 1996). Hydro-geomorphic and environmental impacts of the diversions and possible remedial measures have been reported in several recent investigations (Brizga and Finlayson 1992; Erskine and Tilleard 1997; ID&A Pty Ltd 1995; New South Wales Department of Land and Water Conservation, Victoria Department of Conservation and Natural Resources et al. 1996; Snowy Genoa Catchment Management Committee 1996).

Snowy River at Dalgety

Dalgety is located approximately 30 km downstream of Jindabyne Dam (Figure 7). The catchment area at Dalgety is 3044 km^2, of which 1854 km^2 is commanded by Jindabyne Dam (New South Wales Department of Land and Water Conservation, Victoria Department of Conservation and Natural Resources et al. 1996).

In the vicinity of the township of Dalgety, the river is:

“slightly sinuous with well developed and vegetated side bars, point bars and mid-channel bars of sand and gravel. Pools are relatively shallow and often floored by bio-clastic sediment” (Snowy Genoa Catchment Management Committee 1996). The Snowy River at Dalgety is illustrated in Figure 22.

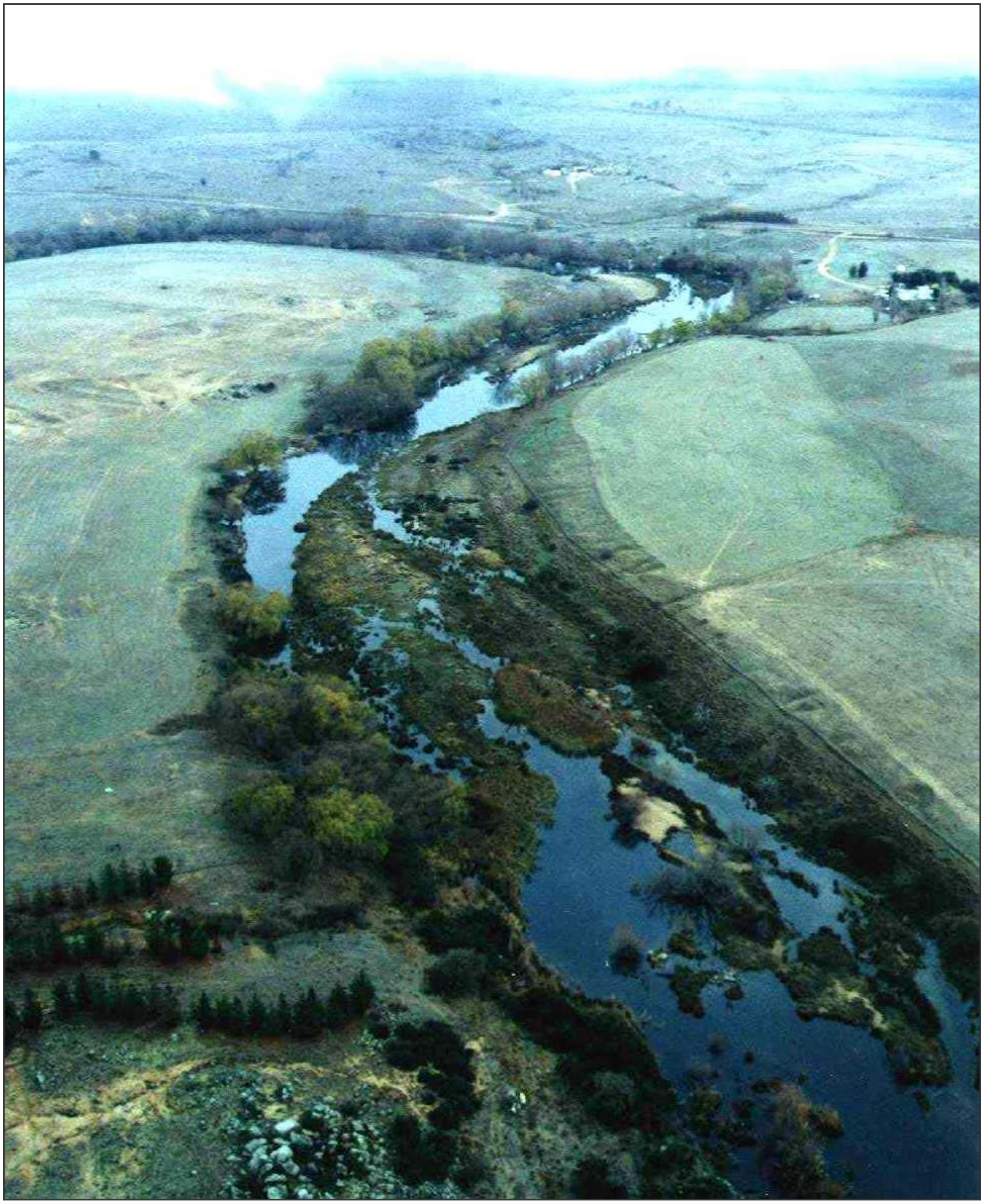
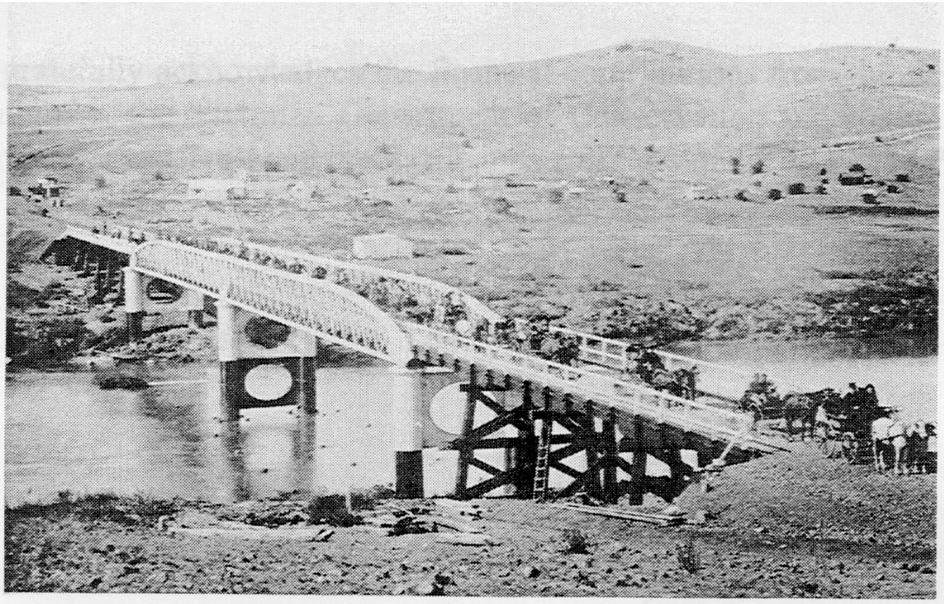


Figure 22 Aerial oblique view of Snowy River just upstream of Dalgety, 1997. Note in-channel bars as evidence of channel contraction.



Buckley's Crossing Bridge, Dalgety, 1889

Buckley's Crossing Bridge, Dalgety, 1995

Figure 23 Snowy River at Dalgety. Comparison 1889 to 1995. (Brizga and Finlayson 1992; Terrazzolo 1990).

Terrazzolo (1990) reports major channel contraction at this site between 1884 and 1990. Photographs published by Terrazzolo (1990) and Brizga and Finlayson (1992) show substantial encroachment of vegetation since construction of the Snowy Mountains Hydro-electric Scheme (Figure 23). Exotic species especially Weeping Willow *(Salix babylonica)* are dominant but other species of willow and poplar are also present together with native species including Woolly Tea Tree *(Leptospermum lanigerum)* and Prickly Tea Tree *(L. juniperium)* (ID&A Pty Ltd 1995).

6.3. *Changes in channel capacity for pre Snowy Scheme and post Snowy Scheme periods*

Two cross sections surveyed in 1949 and 1986 at the gauging site are shown later in this section (Figure 28). Figure 29 also shows rating curves at the site applicable in 1951 and 1986.

The only source of data to estimate bankfull discharge for the Snowy River at Dalgety for the pre Snowy Scheme period is at the gauging station. The single recorded cross section survey (1949), coupled with rating curves at the site and the evidence of Figure 23, suggest a bankfull discharge of 230 m^3/s.

Bankfull discharge at Dalgety post Snowy Scheme can be estimated from the 1986 cross section survey coupled with rating curves applicable at the sites since 1976. In addition, Figure 24 is derived from all the available rating curves at the Dalgety gauge. The plot represents the variation through time of the flow that occurs at a constant gauge height of 0.5 m. A gauge height of

0.5 m (which is 0.6 m above the cease to flow level) is taken to represent the shoulder of the current low flow channel and hence bankfull flow.

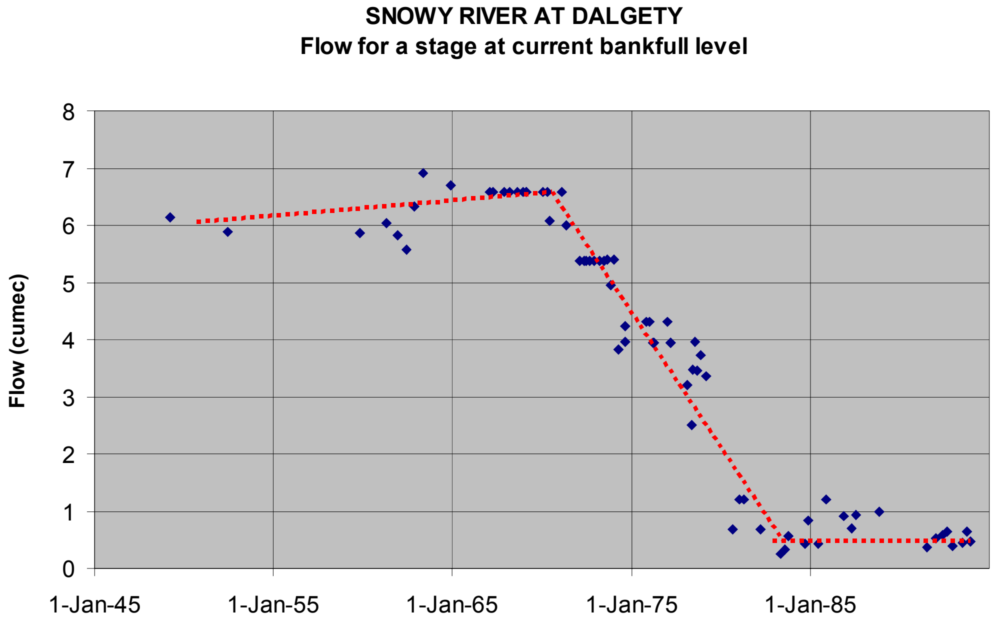


Figure 24 Snowy River at Dalgety. Time-series of the flow corresponding to a stage that is representative of the current bankfull stage. Derived from actual flow gauging data recorded in Pinneena (New South Wales Department of Land and Water Conservation 1996a). Dashed line fitted by eye.

This plot shows that at the gauging station, flow for a constant water level reduced from about 6.5 m^3/s in the early 1970s to around 0.5 m^3/s 10 years later. Similar changes occurred at other water levels. Bankfull flow is now estimated at only 0.5 m^3/s.

6.4. *Effects of Snowy Mountains Hydro-electric Scheme on the flow regime at Dalgety*

Terrazzolo (1990) reports a detailed comparison of monthly and annual runoff, flow duration and flood frequency at Dalgety (and other stations on the Snowy River) for pre Scheme and post Scheme periods, and drew conclusions as follows.

- Comparison with a control station on the Murray River at Biggera, confirms that the Snowy Scheme rather than climatic change is largely responsible for an observed reduction in annual flows and for a major change in monthly flows.

- Median and low mean daily discharges are dramatically reduced downstream of Jindabyne for the post Scheme period.

- A comparative flood frequency analysis indicates that the unregulated part of the Snowy catchment above Dalgety still generates large floods of a magnitude comparable to pre Scheme floods: however a substantial reduction in the frequency of smaller floods indicates that the part of the catchment that is now effectively isolated had previously been important for generating smaller snow-melt floods.

6.5. *Frequency distribution of mean daily flows*

In the current investigation, the flow record from gauging station reference 222006: Snowy River at Dalgety, has been extended by correlation with a neighbouring station. The resulting data set has then been analysed for the frequency of mean daily flows. The period up to April 1957 has been adopted as representative of pre Scheme hydrologic conditions, and the period after July 1967 has been adopted as representative of post Scheme hydrologic conditions.

Mean daily flows are available at Dalgety for the period commencing 22 March 1949 (New South Wales Department of Land and Water Conservation 1996a). This record has been extended back to 1902 by correlation with data from station 222501: Snowy River at Jindabyne. Figure 25 illustrates mean daily flow at Dalgety plotted against mean daily flow for the same day at Jindabyne (on log scales) for the period of overlapping record: 22 March 1949 to 16 April 1967. A least squares regression of this data provided the following best fit power function with an R^2 value of 0.94.

$$Q_{Da\lg ety} = 1.0842(Q_{Jindabyne})^{0.9985}$$

The power function was used to generate a mean daily flow series at Dalgety for the period 1902 to 1957 based on the mean daily flow series at Jindabyne.

The frequency distribution of mean daily flows at Dalgety was derived from the generated data using the period May 1902 – April 1957 to represent the pre Scheme period and the period April 1967 – January 1996 to represent the post Scheme period. The results of the frequency analysis are presented as relative frequency distributions in Figure 26 and as probability density functions in Figure 27.

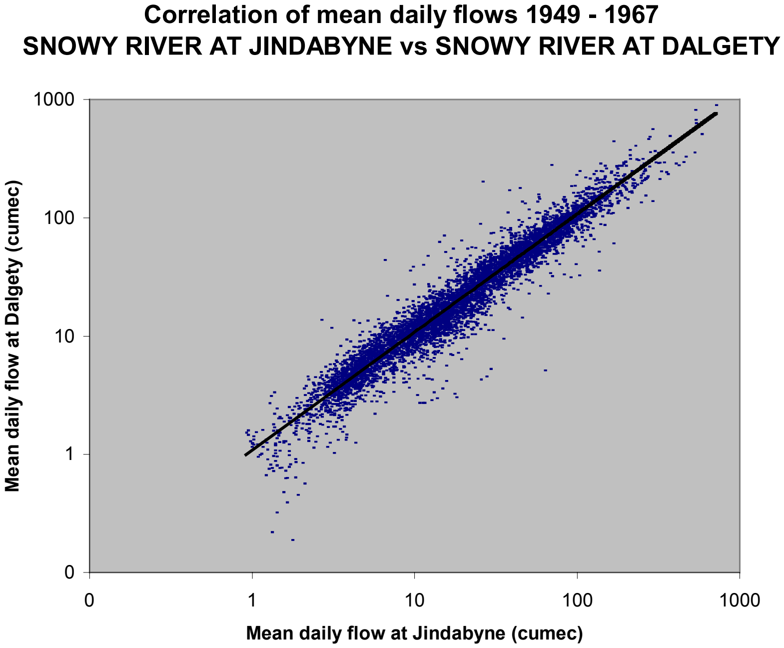


Figure 25 Correlation of mean daily flow between stations 222006: Snowy River at Dalgety and 222501: Snowy River at Jindabyne for overlapping period of record, 1949 - 1967.

Note the different flow scales in Figure 26(a) and (b) and the different probability density scales in Figure 27.

The frequency distribution of mean daily flows is clearly very different for the pre Scheme and post Scheme periods.

In the pre Scheme period, daily flows occur over a wide range. The mode of the distribution is in the 5 to 10 m^3/s interval accounting for around 16% of all flows, but even the larger 5 to 15 m^3/s interval still only accounts for 29% of flows. The median flow is 20 m^3/s.

By contrast, the post Scheme distribution is very strongly modal with daily flows occurring in the narrow range of 0.2 to 0.6 m^3/s for 66% of the time. Flow now exceeds 5 m^3/s for only 5% of the time compared to over 80% of the time in the pre Scheme period. The median flow is reduced by a factor of 50 to 0.4 m^3/s.

These changes in flow regime are profound. Not only has the total flow volume been reduced by a factor of nearly 20 (from a mean annual flow of around 1 250 Gl to a mean annual flow of around 67 Gl), but the variability of the distribution of flow has also been severely curtailed. These hydrologic changes would be expected to reflect in morphologic changes to the channel as discussed below.

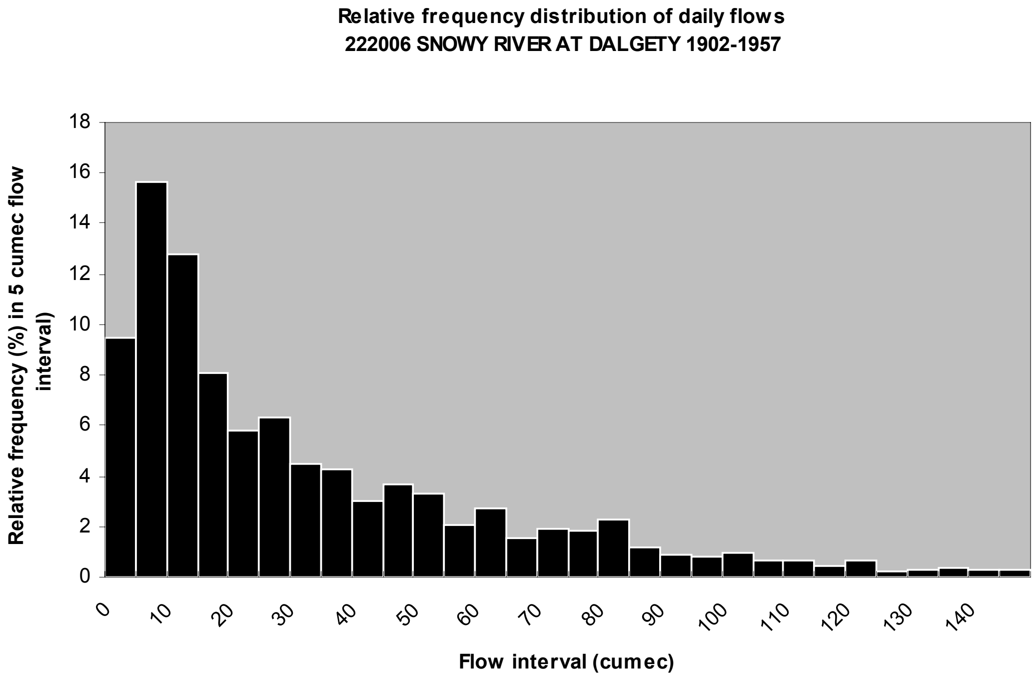


Figure 26(a) Relative frequency distribution of mean daily flows. Snowy River at Dalgety. 1902-1957.

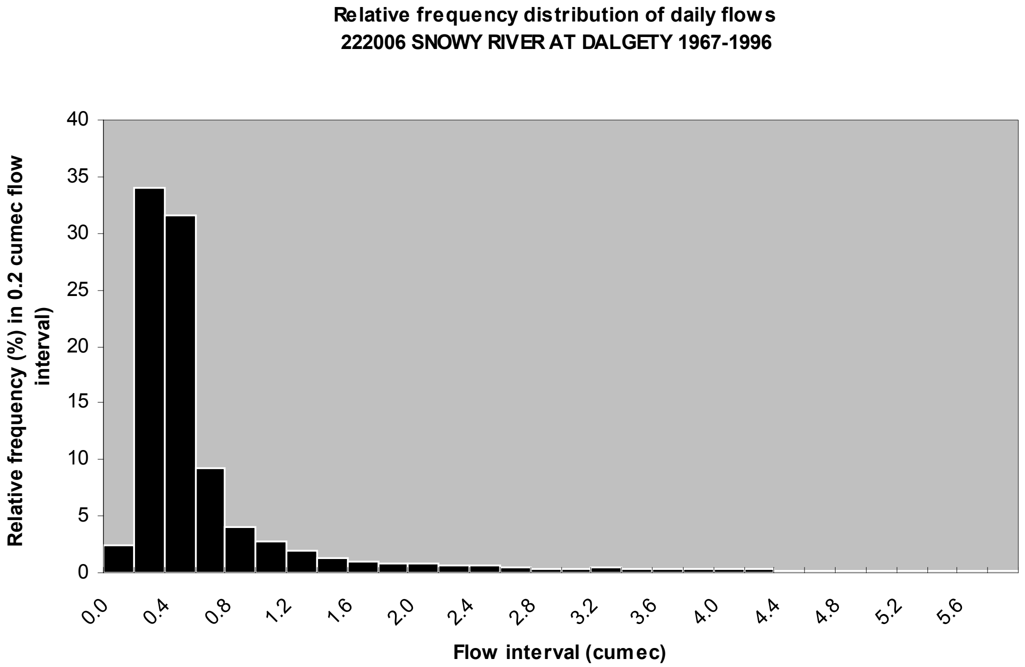


Figure 26(b). Relative frequency distributions of mean daily flows. Snowy River at Dalgety. 1967-1996.

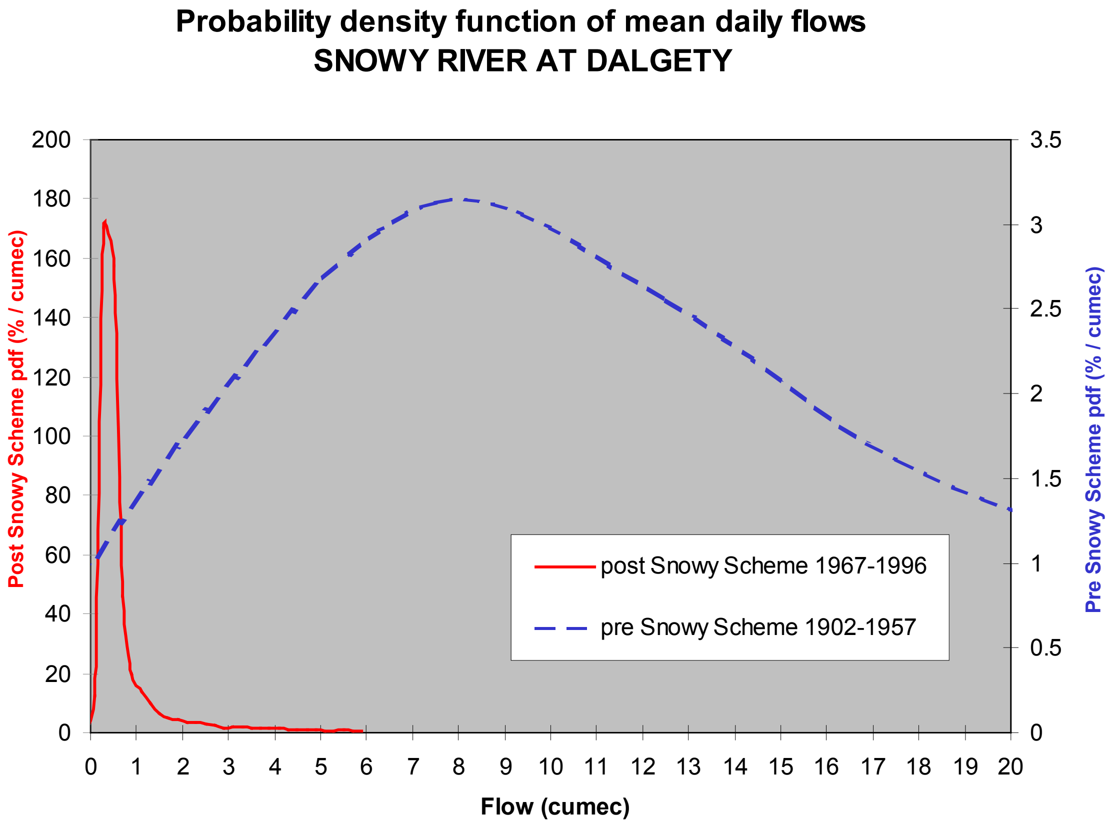
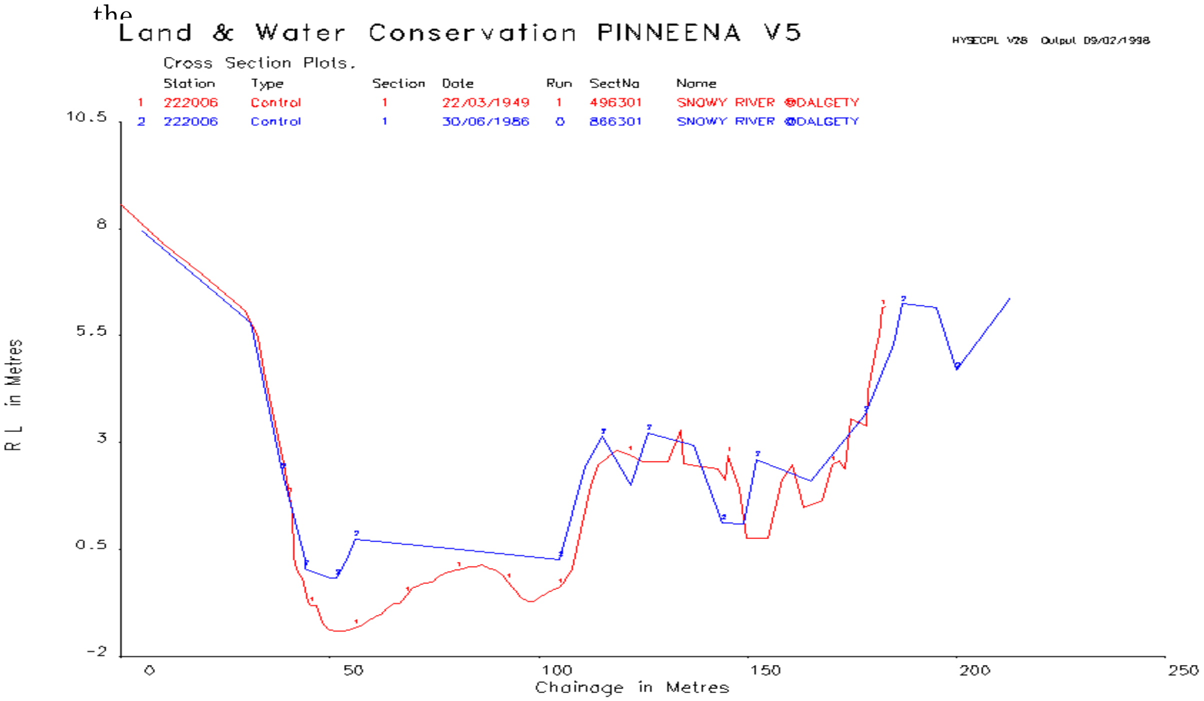


Figure 27 Probability density function of mean daily flows. Snowy River at Dalgety. Pre Snowy Scheme and post Snowy Scheme.

6.6. *Hydraulic conditions*

Hydraulic relationships for the channel have been derived by analysis of rating curves and cross section survey at station 222006: Snowy River at Dalgety.

Figure 28 shows a surveyed cross section at the gauging site in 1949. This data has been extracted from Pinneena: the New South Wales water resources data base available on CD ROM (New South Wales Department of Land and Water Conservation 1996a). The same source also provides the rating curve derived from flow measurements at the station and in use at the



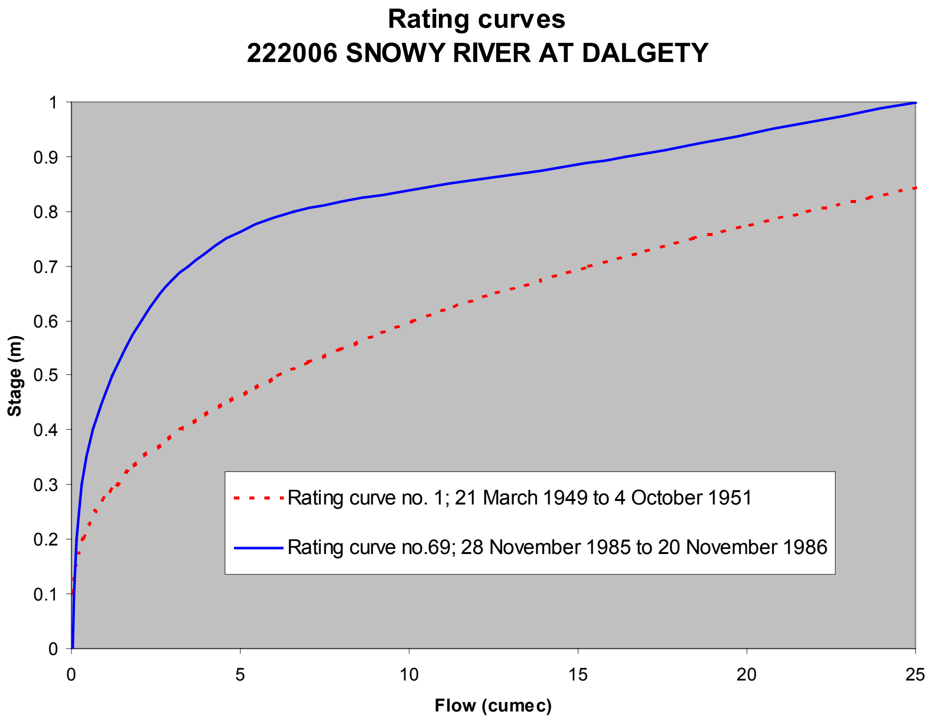


Figure 29 Rating curves number 1 and 69 for Station 222006 (Snowy River at Dalgety) in 1949 and 1986. (New South Wales Department of Land and Water Conservation 1996a) time of the cross section survey (Figure 29). Combined analysis of these two sets of data provides a relationship between flow and average channel velocity and a relationship between flow and hydraulic depth for this cross section at the time. This analysis has been carried out using the cross section analysis module of HYDSYS; a time series data management system that is packaged with Pinneena (New South Wales Department of Land and Water Conservation 1996a). The results are presented in Figure 30.

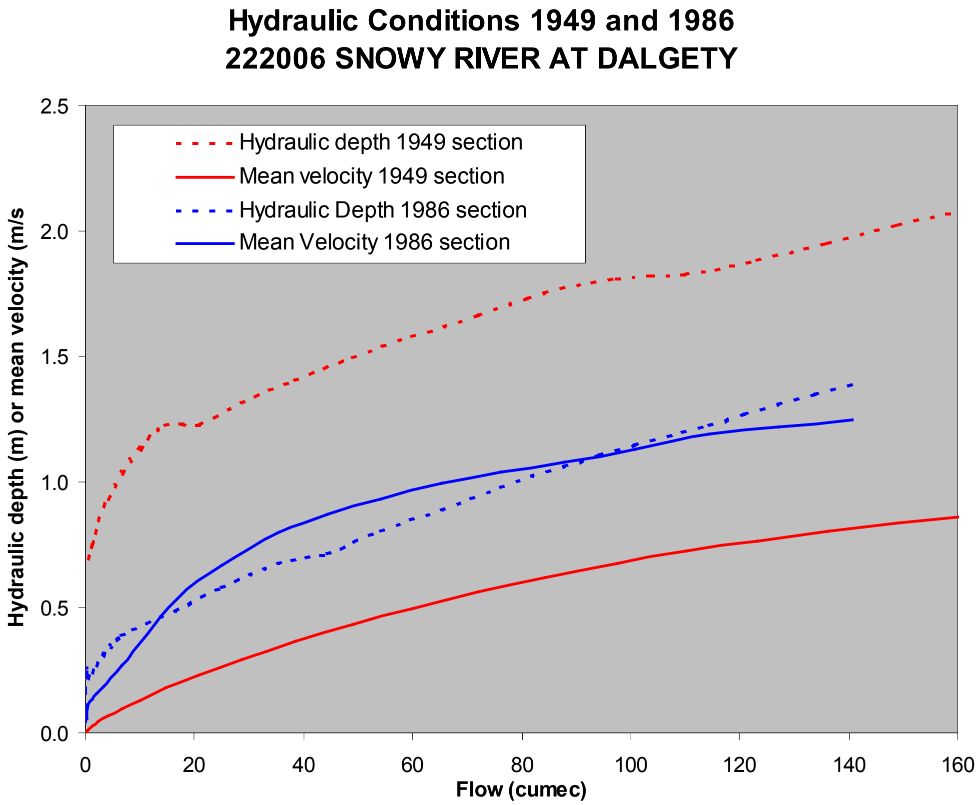


Figure 30 Snowy River at Dalgety, station 222006. Relationship between flow and average channel velocity and between flow and hydraulic depth in 1949 and 1986 (New South Wales Department of Land and Water Conservation 1996a). Derived from rating curves (Figure 29) and surveyed cross sections (Figure 24).

6.7. *Excess particle stream power*

The relationship between flow and stream power per unit boundary area is derived by using the above results in equation 5:

$$P = U\left(\frac{\rho U^2}{32\left(\log\frac{10d}{D}\right)^2} - \tau_c'\right)$$

The resulting relationships are shown in Figure 31. In this instance the physical meaning of τ_c' is not as clear as it is for the Tumut River case study where τ_c' represents the threshold of motion of bank material. In the Snowy case τ_c' represents the shear stress below which no sediment of any size is deposited in the reach. As a first approximation, it is reasonable to consider this as infinitesimally small (that is $\tau_c' = 0$). Unlike the Tumut case study, no distinction need be made between excess stream power for bed and for banks.

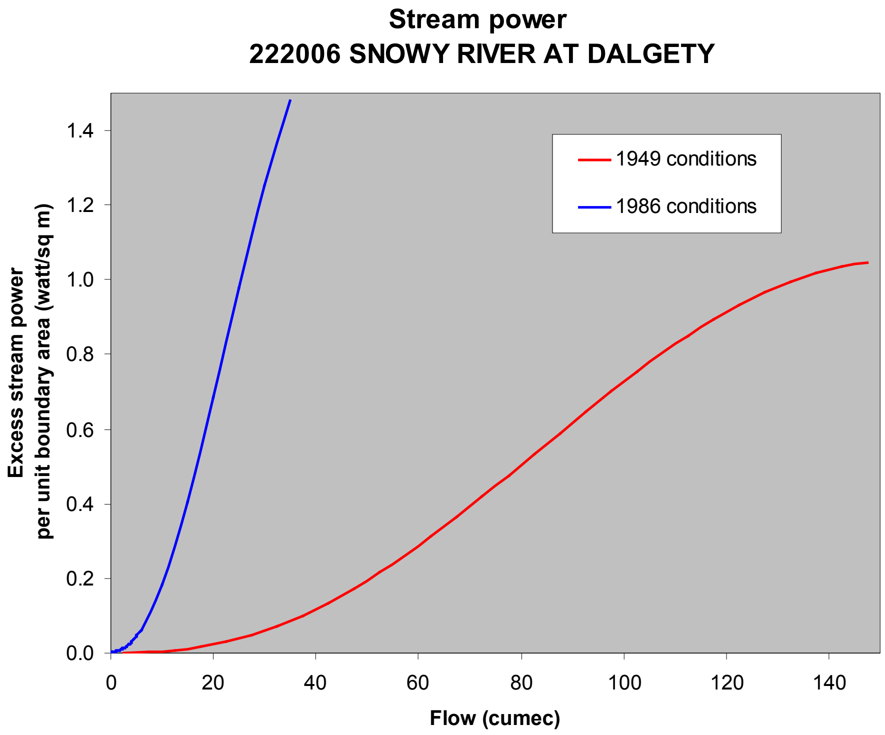


Figure 31 Relationship between flow and excess stream power per unit boundary area. Snowy River at Dalgety. 1949 conditions and 1986 conditions.

6.8. *Distribution of in-channel energy expenditure with flow*

For a given interval of flow, the corresponding stream power indicates the rate at which flow energy is available to change the channel boundary; either by removing material from the bed or bank (erosion), or by delivering material to be deposited on the bed or bank (deposition). From the frequency distribution of daily flows, we also know the proportion of time that the flow has spent in each flow interval during a chosen period. Referring to Figure 32, multiplying the pre Snowy probability density function of daily flows (curve 1) by the excess stream power - discharge relationship (curve 2) produces a curve (curve 3) that represents the distribution of excess stream energy with flow. The value of the ordinates of this curve (curve 3) have been multiplied by 31 536 000 (the number of seconds in a year) and further factored by 0.01 (to account for the use of percentage in curve 1) so that the units become joule metre^{-2} cumec^{-1} year^{-1} (plotted on the graph as megajoule metre^{-2} cumec^{-1} year^{-1}). The area under curve 3 represents the total energy expended in the channel in excess of the critical shear stress for bank material on average in a year in the pre Snowy period.

Using the probability density function (Figure 27), this calculation has been undertaken for a range of flows for the Snowy River at Dalgety using pre Snowy Scheme and post Snowy Scheme conditions. The results give the *distribution of in-channel energy expenditure with flow*. These distributions are illustrated in Figure 32(a) and (b) for pre and post Snowy Scheme periods respectively. Note the different flow scales in these two Figures.

Sensitivity of the results

For the post Snowy period (Figure 32(b)), this distribution is dominated by the very strong characteristics of the frequency distribution of mean daily flows, to the extent that, within reason, the distribution of energy with flow is insensitive to the shape of the stream power versus flow relationship. The mode of the distribution is strong and unique at approximately 0.5 m^3/s – clearly dominated by the mode of the frequency distribution of mean daily flows. Note however, that the introduction of a larger value of τ'_c could influence this result and move the mode of the energy distribution to a higher flow.

The occurrence of a strong mode in the frequency distribution of daily flows leading to a strong mode in the distribution of excess energy for the case of regulated flows is common to both case studies (see further discussion in Section 6.10).

This is not the case for the pre Snowy period (Figure 32(a)). Here the distribution of excess energy with flow is influenced by the tail of the frequency distribution of mean daily flows, such that the mode of the frequency distribution of daily flows does not dominate. The resulting distribution is not as strongly modal as the post Snowy distribution, but the mode occurs at 70 m^3/s. Compared with the post Snowy case, the shape of the distribution is more sensitive to the detail of the stream power versus flow relationship. However sensitivity analysis shows that the mode does not change significantly while varying the shape of the stream power versus flow relationship within reasonable limits.

Note that the discretisation interval used in the derivation of curve 3 in Figure 32(a) was increased from 5 m^3/s to 10 m^3/s to remove oscillations induced in the original derivation by the smaller discretisation interval.

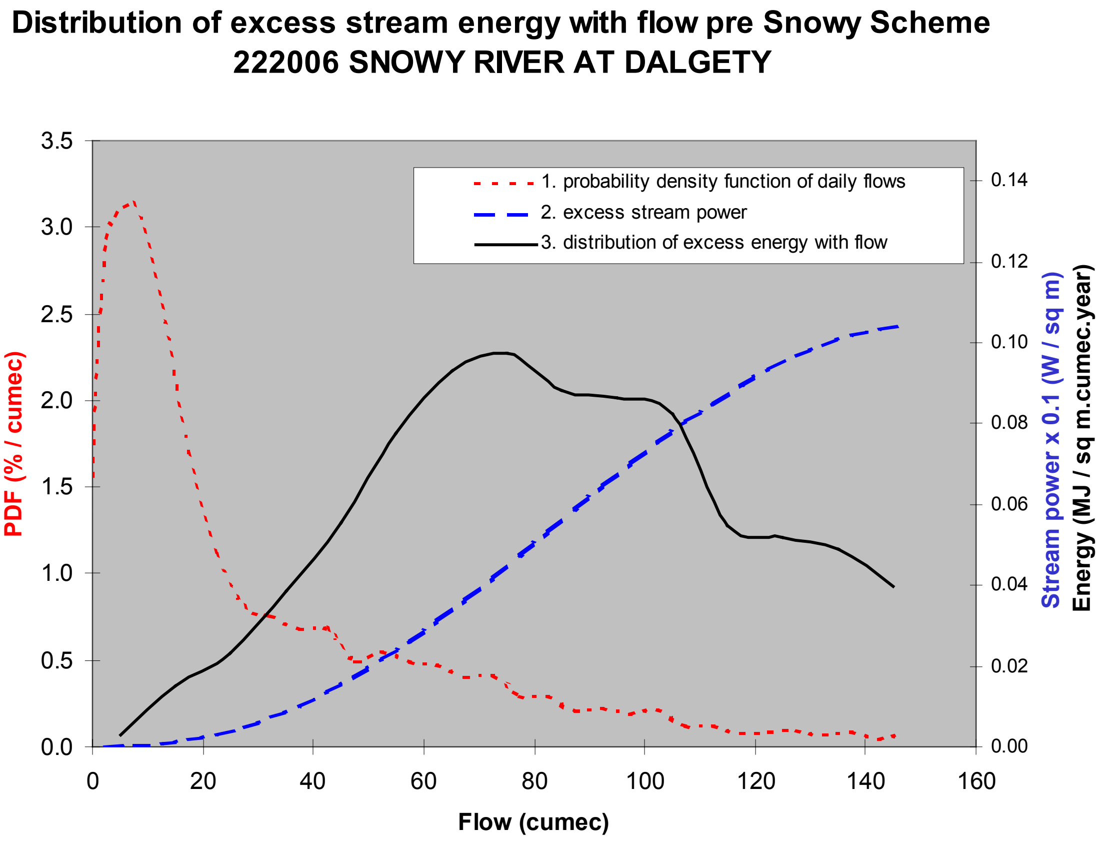


Figure 32(a) Distribution of excess energy with flow. Snowy River at Dalgety. Pre Snowy period.

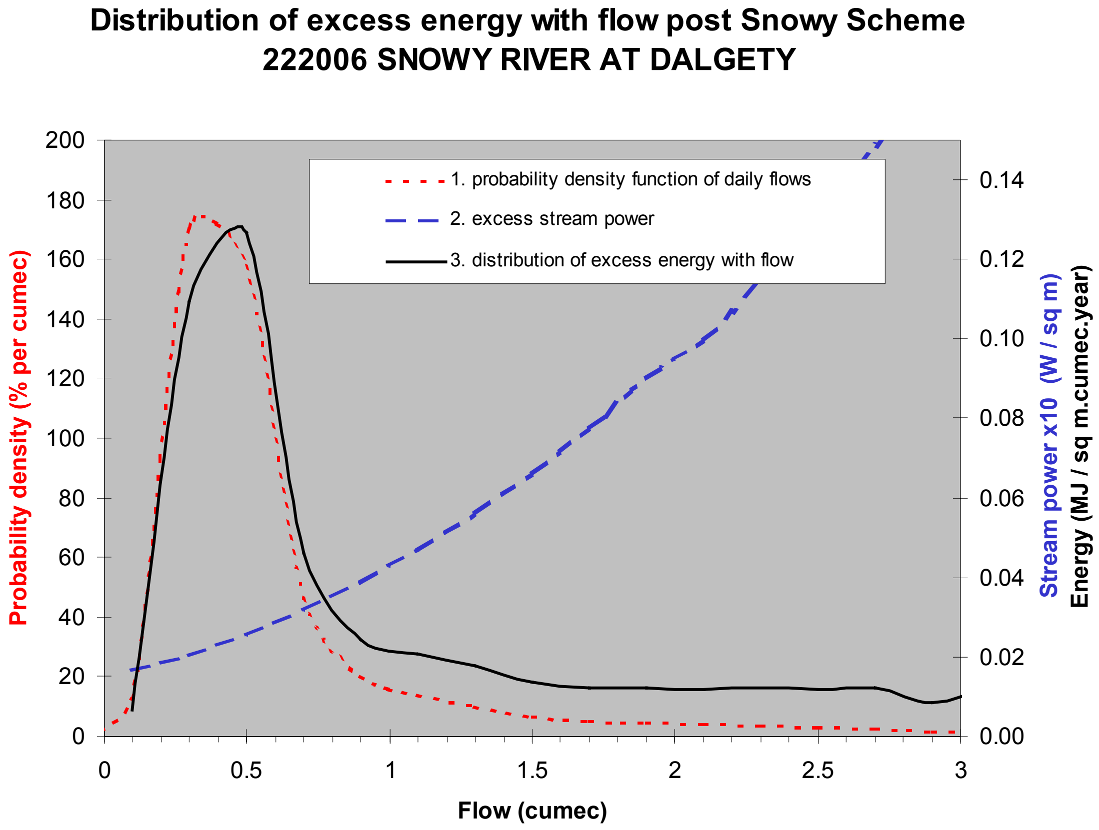


Figure 32(b) Distribution of excess energy with flow. Snowy River at Dalgety. Post Snowy period.

6.9. *Effective Discharge*

The mode of the distribution of energy expenditure with flow is the discharge that, over a period of time, accounts for a greater proportion of available flow energy than any other discharge. The mode can be estimated from Figure 32(a) and (b). According to the definition that is proposed in Chapter 1, this is the *effective discharge* based on excess stream power. The *effective discharge* estimated in this way is 70 m^3/s for the pre Snowy Scheme case and 0.5 m^3/s for the post Snowy Scheme case.

Table 4 summarises effective and bankfull discharges for the Snowy River at Dalgety.

Table 4 Comparison of computed *effective discharge* with bankfull discharge for pre Snowy Scheme and post Snowy Scheme periods.

Period	**Years**	**Effective Discharge** (m^3/s)	**Bankfull Discharge** (m^3/s)
Pre Snowy Scheme	1902 - 1957	70	230
Post Snowy Scheme	1967 - 1996	0.5	0.5

6.10. *Discussion*

Some implications of the two case studies are discussed in the next Chapter.

7. SOME IMPLICATIONS OF THE CASE STUDIES

7.1. *Channel Change*

One of the most striking revelations of the case studies is the amount, the rate and the consistency of channel change that has taken place at the two sites.

Tumut River

In the case of the Tumut River, the rating curves (Figure 14) have indicated that substantial channel enlargement was initiated in the second half of the 1950s, continuing apace for around 5 years. Channel enlargement then continued at a reduced but relatively uniform rate for at least the next 35 years. Over this 40-year period, channel capacity increased by around 50%.

The initiation of this channel change appears to predate the commencement of operations at Blowering reservoir by a year or two. It is likely that the period of rapid change in capacity was triggered by a concentrated program of channel clearing works reported to have commenced in the mid 1950s (New South Wales Department of Land and Water Conservation 1995) rather than directly by the hydrologic change. Initiation of channel enlargement may also have been influenced by a series of floods and several consecutive years with above average flows in the mid 1950s (New South Wales Department of Land and Water Conservation 1996a).

This need not diminish the assessment of the impact of the longer-term hydrologic change on channel capacity. Over the period of flow regulation, the bankfull capacity of the regime channel has changed from 80 m^3/s to 120 m^3/s. Without the change in streamflow pattern, the changes initiated by floods and by the direct intervention in the 1950s may not have promulgated or may not have persisted to date.

It is also possible that without the triggers provided by the events of the 1950s, the change in flow pattern alone may not have caused the channel change that has occurred or the change might only be occurring gradually. The observed channel change is the result of the combined effect of the triggers from intervention and flooding, and any underlying trends driven by the impacts of flow regulation

Snowy River

For the Snowy River at Dalgety the channel change has been at least as impressive in the opposite direction. Figure 24 has shown that over the 13 years to 1983, for a constant water level close to current bankfull level, flow reduced to less than 10% of its initial value and has remained stable around that value since. The change was both rapid and consistent and appears to have stopped as quickly as it started.

Again, it is likely that other processes have influenced the observed change – not just sediment deposition on the bed and banks. For instance it is apparent from the photographs in Chapter 6 that a proliferation of exotic vegetation played a part in the channel encroachment process. It is also apparent from Figure 28 and from field observation that much of the cross section remains unchanged in elevation, even though it has been colonised by vegetation and is no longer part of the active flow channel. So at least two processes have been active: first, infilling causing contraction of the low flow channel, and second, vegetative encroachment into areas of the previously active channel where the frequency or magnitude of flows has reduced.

7.2. *Use of bed or bank critical shear stress for the Tumut River case study*

The Tumut River *effective discharge* analysis has been carried out with two different excess stream power relations: one using power calculated from the available shear stress above a critical shear stress for the bed, and one using power calculated from the available shear stress above a critical shear stress for the <u>bank</u>. Results using critical shear stress for <u>bed</u> material indicate no substantial change in the mode of the excess energy distribution pre and post regulation. In both these cases, the mode is not well defined and its actual location can depend on minor fluctuations in the tail of the probability density function for daily flows. The flow that has the most influence on bed processes is uncertain, but has not substantially changed from pre regulation to post regulation periods. The *effective discharge* estimated using critical shear stress for the bed does not contribute to an explanation of channel change. Further discussion of this result appears in Chapter 8. The subsequent sections of this Chapter concentrate instead on the estimate of *effective discharge* obtained by using critical shear stress for the bank.

7.3. *Post regulation effective discharge*

In both the Tumut River (using bank critical shear) and the Snowy River case studies, the stream power based *effective discharge* approach successfully accounts for the capacity of the river channel in the post regulation period. In both these instances, the impact of controlled releases from upstream storages has made the mode of the probability density function of daily flows very strong (see Figure 13 and Figure 27). In fact this mode is so strong in both these cases that it prevails in the *effective discharge* calculation, dictating the mode of the distribution of excess energy with flow almost regardless of the shape of the stream power versus flow relationship or the threshold that applies.

In the case of the Snowy River, the mode of the probability density function for daily flows occurs at low flows where stream power is also low. Nevertheless the mode is so stark that it more than compensates for the low stream power and still dominates the distribution of stream power with flow.

In the Tumut case, the new mode of the probability density function for daily flows is not as stark but it occurs at higher flows. At higher flows the cube of the velocity in the stream power versus flow relationship means that stream power generally increases rapidly with flow at least until bankfull. The net effect is that a new mode in the frequency distribution at higher discharges is reinforced by the characteristics of channel hydraulics to ensure that this mode dominates in the distribution of excess energy with flow.

In both these instances, the flow that accounts for the most available energy in the channel is dictated directly by the mode of the probability density function of daily flows and not by the subsequent manipulation of the function to obtain an excess stream energy (or a sediment transport) distribution. The *effective discharge* is determined by the strength of the mode of the flow frequency relationship.

Generalisation

This finding has potential broad and immediate application for any rivers (such as the Tumut) where flow regulation (by dams and/or diversions) has resulted in a new mode in the flow frequency distribution, at moderate to high flows, beyond the threshold of motion of bed or bank material. In such circumstances, almost regardless of the detail of subsequent *effective* *discharge* manipulations, the analyses will yield an estimate of *effective discharge* that is close to the mode of the probability density function for daily flows. This finding can be used to give a first estimate of an *effective discharge* for a river where flow regulation introduces a new peak in the probability density function for daily flows at a moderate to high flow.

The impact is not such a foregone conclusion for situations such as the Snowy River at Dalgety. Here, the frequency of low flows has been boosted relative to the frequency of moderate to high flows, and the new mode of the frequency distribution is at a low flow. The mode must then be exceptionally strong (as it is in the case study) if it is to prevail over the low stream power at that flow, to still dominate the excess energy distribution.

A less extreme example of channel enlargement associated with regulation – the Murray River downstream of Hume Dam

A less extreme example of flow regulation, where the mode of the frequency distribution of daily flows for the regulated case is not as strong, is provided by the Murray River at Doctors Point near Albury in New South Wales (Figure 6 and Figure 7) and is reported here briefly for comparison. Note that this example has not been subject to the rigour of the Snowy and Tumut case studies and is therefore reported illustratively only.

Flows in the Murray River are also affected by the Snowy Scheme, but the change in flow pattern is not so much influenced through inter-catchment diversion (although there is a 6% increase in average annual discharge of the Murray River) as it is by a substantial increase in the frequency of moderate to high in-channel flows with a corresponding decrease in flood flows and low flows. Water is stored in Hume and Dartmouth Dams (mainly) during winter and spring and subsequently released at moderate to high flows in Summer and Autumn (Erskine, Rutherfurd et al. 1993).

Flow frequency is illustrated in Figure 33 for periods pre and post 1961, reflecting periods before and after the enlargement of Hume Dam. (Note that flows are regulated in both periods.) Regulation in the post 1961 period has introduced a flat secondary mode to the probability distribution and relocated the primary mode. The two modes in the post 1961 relative frequency distribution for daily flows represent irrigation and pre-flood releases (140 – 210 m^3/s) and minimum releases during dam filling (around 50 m^3/s) (Erskine, Rutherfurd et al. 1993). Although the higher mode is weaker than the lower mode (at least at this discretisation interval) the shape of the function relating stream power to flow ensures that the higher mode at about 210m^3/s becomes the *effective discharge* (see Figure 34).

Data have shown that the channels of the Murray River system in this vicinity have enlarged in recent time and now have a channel capacity of around 230 m^3/s (Erskine, Rutherfurd et al. 1993). In this illustrative example, where the mode of the post regulation flow frequency distribution is less extreme, and the total change in flow volume is relatively minor, the stream power based *effective discharge* approach does account for an observed change in channel capacity.

Frequency of daily flows
MURRAY RIVER AT DOCTORS POINT

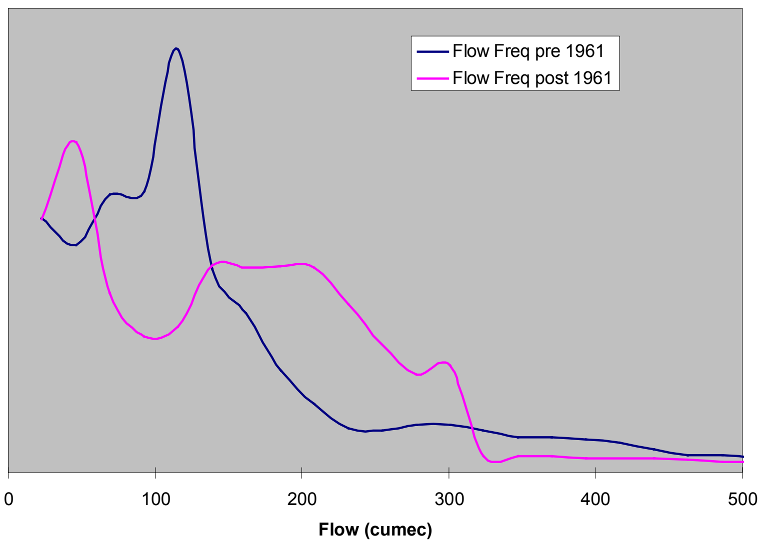


Figure 33 Relative frequency distribution of daily flows for the Murray River at Doctors Point. Pre 1961 represents a period of moderate regulation before the upgrade of Hume Dam. The post 1961 period combines the effects of the upgrade of Hume Dam and (later) the construction of Dartmouth Dam.

Distribution of excess energy with flow
MURRAY RIVER AT DOCTORS POINT

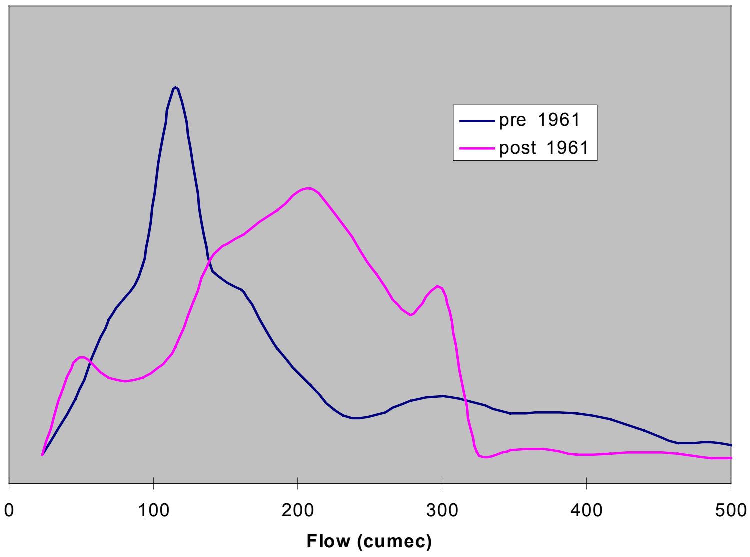


Figure 34 Distribution of excess energy with flow. Murray River at Doctors Point. Pre- and post- Hume Dam upgrade.

Endorsement of the *effective discharge* concept

The post regulation results for the Tumut and Snowy cases provide preliminary endorsement of an excess stream power based *effective discharge* approach. However in both cases the strength of the mode of the probability density function for daily flows has dictated the shape of the excess energy distribution and hence the estimated *effective discharge*.

The case studies have shown that in the particular circumstances, the flow that accounts for the greatest expenditure of in-channel excess energy equates to the bankfull channel capacity after the channel has been through a substantial adjustment in the post regulation period. Further detailed case studies are required before the validity of this proposition can be confirmed for more general situations. The post regulation results for the two case studies sanction the broad excess stream power based *effective discharge* approach but they have not demonstrated that some other approach based on the probability density function for daily flows may not have also been successful.

7.4. *Pre-regulation effective discharge*

By comparison with the post regulation case, the pre regulation flows do not produce clear results. There are several reasons for this as discussed below.

For natural flow regimes, the mode of the probability density function for daily flows tends to occur at low flows around or below the threshold of movement of bed or bank material. This is the case for the Tumut River pre

Snowy as has been shown in Figure 18. When this happens, the mode of the distribution of excess stream energy with flow occurs on the recession or the tail of the probability density function for daily flows and is effectively independent of the mode of that distribution. Instead the location of the mode of the distribution of excess stream energy with flow becomes very sensitive to the detail of the hydraulic computations for stream power and the choice of threshold values for boundary movement. In natural systems, neither the detail of channel hydraulics nor the choice of threshold values for boundary movement can be determined practically without significant assumptions and approximation. This is partly because of the uncertainties involved in the hydraulic formulations and the selection of empirical values and constants, and partly because of the practical difficulties of selecting discrete values for channel or flow characteristics to represent characteristics that actually vary continuously in space. In these cases, where the flow versus stream power relationship dominates the outcome, the inherent uncertainties in the relationship and its thresholds are carried through and reflected in a reduced confidence in the location of the mode of the distribution of excess energy with flow.

For example, the *effective discharge* for the Tumut River pre regulation case has been reported in Section 5.15 to be sensitive to the choice of boundary movement threshold – a parameter that is difficult to estimate for cohesive floodplain soils (Osman and Thorne 1988a; Osman and Thorne 1988b) (if in fact it even remains a valid concept for such material). Figure 35 shows the effect of different assumptions about the threshold of motion on the estimate of *effective discharge* for the pre regulation case on the Tumut River. The example shows that, depending on the relative characteristics of the probability density function for daily flows and the power curve (in particular the choice of critical shear stress), the *effective discharge* can vary substantially within a range of assumptions. In these circumstances, the excess stream energy approach may not be sufficiently discriminatory to be confident about the location of the mode of the excess energy distribution or hence the estimated *effective discharge.* Note that in the Tumut case study the sensitivity analysis shows that the *effective discharge* result is robust for any critical shear stress less than 3 Nm^{-2}.

Reported applications of the *effective discharge* concept that have relied on measured data for sediment transport rather than hydraulic computations based on characteristics of discrete cross sections (Andrews 1980; Andrews 1986; Andrews 1994; Andrews and Nankervis 1995; Batalla and Sala 1995; Carling 1987; Leopold 1992; Webb and Walling 1982), can avoid some of these difficulties because the measured data effectively integrate across cross sections and avoid the inaccuracies inherent in the assumptions and simplifications of the excess energy calculation.

The pre regulation case for the Snowy River provides a poor match between estimated *effective discharge* and estimated bankfull channel capacity. This mismatch has not been investigated in detail because of insufficient information about bankfull conditions for the pre regulation channel.

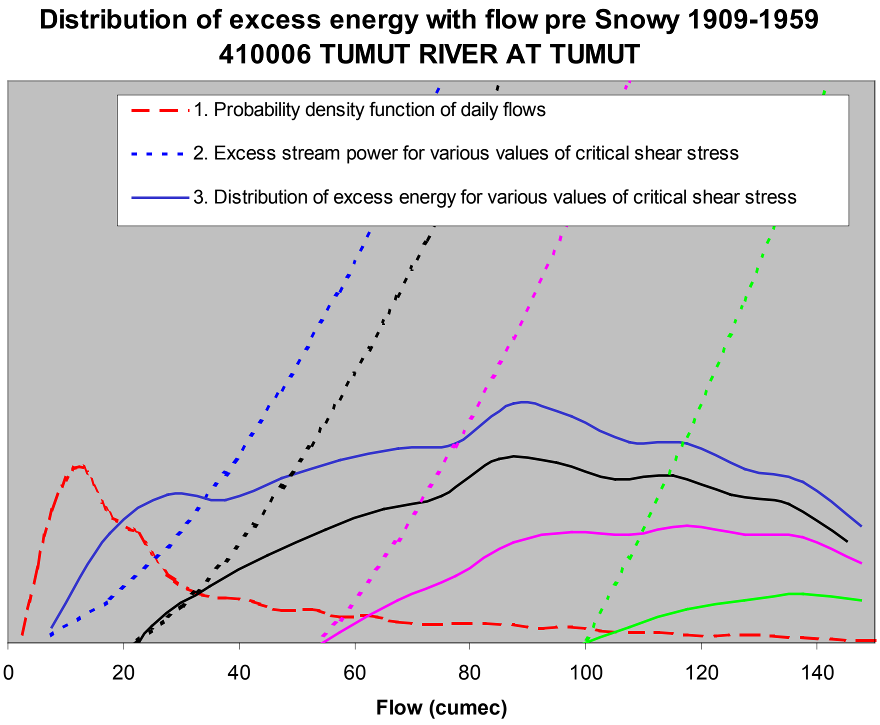


Figure 35 Illustration of the effect of different assumptions about the threshold of motion on the distribution of excess energy with flow for the pre regulation case on the Tumut River. Blue: critical shear stress of zero, Black: critical shear stress of 2 N/sq m (adopted value), Pink: critical shear stress of 5 N/sq m, Green: critical shear stress of 10N/sq m. Estimated *effective discharge* varies from 85m^3/s to 135 m^3/s over this range of values for critical shear stress.

7.5. *Flood frequency and flow duration as models to predict bankfull channel capacity*

Flood frequency

As reported in Chapter 3, several investigators have attempted to find a simple universal model that equates bankfull channel capacity to the magnitude of a flood of a given recurrence interval. It is conceivable that this may be a useful and valid concept within a very limited range of circumstances. But by ignoring the duration of flows and any measure of the interaction between flow and the channel boundary, the dominant mechanisms of the fundamental physical processes are ignored and the universality of any relation must therefore be severely compromised. For instance, in the Tumut Case study, the peak annual series (Figure 36) shows that pre Snowy floods were consistently higher (by a factor of around 2) than post Blowering floods of the same recurrence interval. Using Dury's (1973) favoured 1.58 year recurrence interval (on the annual series), the pre Snowy flood is 280 m^3/s compared to a post Blowering flood of 140 m^3/s. Despite the 1.58 year post Blowering flood being half the size of the pre Snowy flood, the post Blowering channel is now larger than the pre Snowy channel. In this case, a decrease in the 1.58 year flood has been associated with an increase in channel size. The same result would be obtained using a partial series.

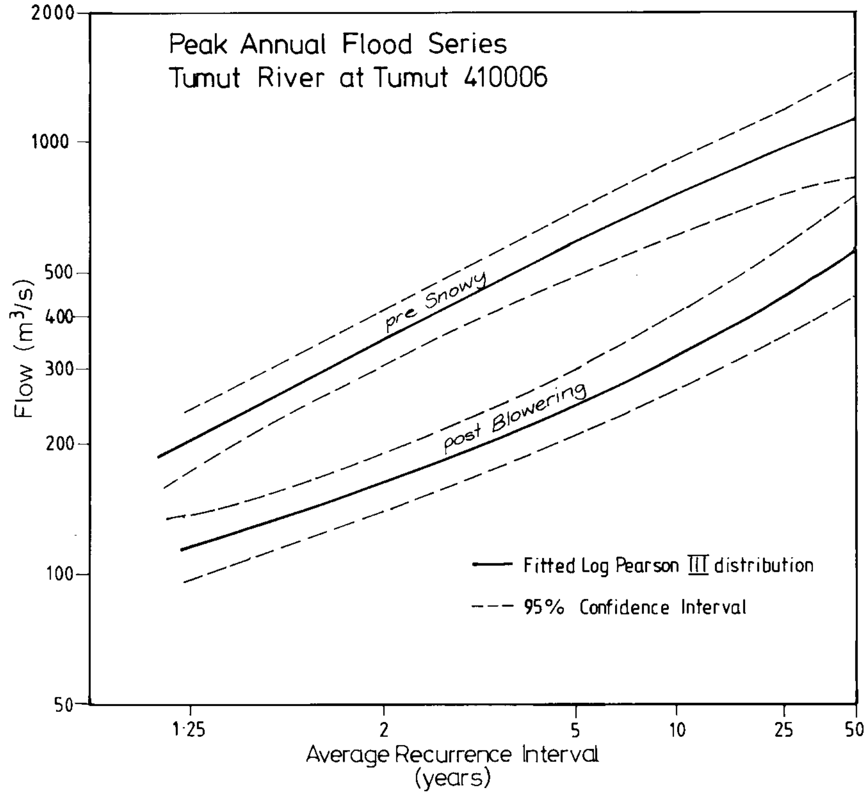


Figure 36 Tumut River at Tumut. Log Pearson Type III fit to the peak annual flow series for the period 1902 to 1996

For the Snowy River at Dalgety, flood peak discharges have also been substantially reduced by the Snowy Mountains Scheme for recurrence intervals of 20 years or less. The comparisons are shown in Table 5

Table 5 Comparison of bankfull flow with the 1.58 year flood on the peak annual series for case studies

		Estimated bankfull flow (m^3/s)	**1.58 year flood on the annual series** (m^3/s)
Tumut River at Tumut	pre Snowy	80	280
	post Blowering	120	140
Snowy River at Dalgety	pre Snowy	230	290
	post Snowy	0.5	46

In these cases, the change in magnitude of a flood of given return period is a poor predictor of the change in channel size.

Flow duration as a predictor of channel capacity

Some authors have been more sympathetic to physical processes by accounting for flow duration in their analyses instead of just peak flow. For instance Nixon (1959) used flow frequency analysis to reach the conclusion that the bankfull discharge was the discharge that was equalled or exceeded for 0.6% of the time (based on a daily flow series). Table 6 summarises the case study results in terms of cumulative flow frequencies from the daily flow series.

Table 6 Frequency of bankfull flow for case studies and examples

		Estimated bankfull flow (m^3/s)	**Frequency** (% of time flow is equalled or exceeded)
Tumut River at Tumut	pre Snowy	80	1.65
	post Blowering	120	1.80
Snowy River at Dalgety	pre Snowy	230	1.13
	post Snowy	0.5	32
Murray River at Doctors Point	pre 1961	175	1.9
	post 1961	290	1.4

Nixon's (1959) value of 0.6% appears inapplicable to rivers in this region, but there is nevertheless a degree of consistency in the results: five of the six examples have bankfull discharge that is equalled or exceeded between 1% and 2% of the time. This encourages a view that there may be some consistency between the frequency of bankfull discharges at these sites; perhaps not altogether surprising since their headwaters are adjacent and they share similar climatic and geologic characteristics. (It may also be noteworthy that the inconsistent figure is from the contracting channel.)

As a model of river behaviour, a direct relationship between flow duration and channel capacity consolidates a number of physical processes. While it may capture the essence of the processes that dictate channel size within a region of similar hydrologic and geologic characteristics, the data do not support the model's ability to represent the impact of changes in the flow regime at a particular site.

For instance, the post regulation Snowy result indicates a bankfull flow that is equalled or exceeded 32% of the time. This is at the extreme of the Williams (1978) observations – not entirely unexpected as this is a most unusual frequency distribution.

While flow duration may be a useful indicator of bankfull channel capacity under sets of natural conditions, it is unlikely that flow duration alone can account for channel response to flow regulation where major changes in the characteristics of the flow duration relations are expected. For instance, bankfull flow for the Murray site is now rarer following an increase in channel capacity but at the Tumut site where channel capacity has also increased, the bankfull flow is more frequent. The data support the contention that a simple relationship between flow frequency and channel size ignores some of the important physical interactions that are important and is unlikely to be transferable between catchment scales nor is it likely to be applicable following a major change such as flow regulation.

7.6. *Use of "particle shear stress"*

Another interesting outcome of the case studies relates to the use of a particle shear stress computed from a velocity distribution instead of overall average shear stress computed from ρgRS.

A comparison of the overall average shear stress and the particle shear stress computed for the Tumut River case study shows that the overall average shear stress is an order of magnitude greater than the particle shear stress. The immediate physical explanation for this is that overall average shear stress represents the sum of all the forces that are balancing gravity to maintain steady flow, whereas the particle shear stress only reflects those forces that are induced by particle-based roughness of the boundaries as distinct from forces associated with form drag, bedforms, vegetation, etc..

The relative magnitude of this difference implies that energy spent as the result of direct resistance at the particle scale is only a very small component of overall energy expenditure. This has implications for the commonly used flow resistance equations and casts significant doubt on the validity of techniques (such as Manning – Strickler style equations) when used in natural channels to estimate flow resistance coefficients directly from the particle size characteristics of boundary materials.

Einstein and Barbarossa (1952) first addressed this issue in 1952. Petit (1990) undertook a detailed analysis of the relationship between overall average shear stress τ_0 and particle shear stress τ' in two natural channels. He also found that τ' was only a small component of τ_0, but not as small as the example above. In the riffle section of a meandering pebble bedload river (the Rulles) and the gravelly section of another river (Rouge Eau) he found that particle shear stress accounted for 30% of average shear stress. For pools in the Rulles and for sand sections of the Rouge Eau this proportion dropped to 15% with some instances as low as 2% depending on the computation methods used. It is clear that there is a substantial difference between shear stress, τ_0 computed from the average grade line, S and shear stress, τ' computed from average shear velocity U_*.

It is instructive to note that the overall average shear stress ($\tau_0 = \rho gRS$) calculated at the Tumut River bridge is consistently higher than the average shear stress calculated at the pump station section, whereas particle shear stress (τ') is higher at the pump station than at the bridge section. This results from the dependence of average shear stress calculations on depth and the dependence of particle shear stress calculations on velocity so that the shallower faster section has a high particle shear stress and a low average shear stress and the deeper slower section has a low particle shear stress and a high average shear stress. This may well be more of an artefact of the computation than a true representation of reality. For instance, in the comparison above, the computation for average shear stress has used a value for slope that is averaged over several sections in an attempt to represent uniform flow conditions, but a site-specific value for hydraulic depth. The computation for particle shear stress has used a site-specific average velocity and a site-specific hydraulic depth.

The distinction between particle shear stress and average shear stress, and the observed difference between them, also raises doubts about the strict applicability to natural river conditions of critical shear stress criteria that have been developed and reported in the literature based on measured data and observation in laboratory situations. For instance, in the Tumut case, the critical shear stress for the bed (20mm particles) is estimated from Equation 3 to be approximately 14 Nm^{-2}. Using average shear stress, this value is exceeded at all flows above 2.5 m^3/s – an unrealistic scenario. Using particle shear stress gives a much more realistic result.

More work is needed before we can claim that the physical processes that dictate the behaviour of the interface between the flowing water and the boundary material in natural channels have been accurately represented . In the meantime, the particle shear stress approach used here has a logical basis and appears to give the more accurate results.

8. CONCLUSIONS AND DISCUSSION

For the two case studies presented, a stream power based *effective discharge* approach has successfully accounted for the change in channel capacity that has been observed in the river downstream of a major series of dams and diversions. In both cases, if the post regulation flow pattern were estimated from historical records and dam operating rules, then the approach could have been used to contribute to a prediction of the magnitude and direction of the change in river channel capacity before flow regulation. However this small sample represents two extremes of channel response, and further detailed investigations are required to validate the approach. From the work reported herein, it is concluded that a stream power based *effective discharge* approach is a technique that is worthy of further development and investigation by application to other case studies.

It is not claimed however that an excess stream power based *effective discharge* approach is likely to provide a universal means of predicting channel characteristics. A range of limitations is discussed below.

8.1. *The importance of physical processes in channel adjustment*

An important outcome of this work is to emphasise that landscape evolution in general and river channel change in particular only happens as the result of physical processes. In a river, the fundamental processes are erosion and deposition of material from or on the bed or banks in response to the hydraulic characteristics of the channel and the properties of the bed and bank. The channel will only adjust if a mechanism exists for the change to take place. For example even if a change in flow pattern suggests that a channel contraction will occur, this will not happen unless sediment, vegetation or organic material is available to physically promulgate the change. Likewise physical processes can also pre-empt or prevent channel enlargement.

Despite the tendency toward anthropomorphism in some of the literature, rivers do not have a will of their own, working conspiratorially toward a pre-planned outcome. Instead, physical processes cause changes in river channels. The physical interactions are driven by the combination of forces to which they are exposed: their magnitude, their frequency and their duration. The ongoing challenge in predicting response to change is to construct a conceptual and quantitative model that is simple to use and supply with data, while it adequately represents the essentials of the complex combination of physical processes occurring through time.

A successful model will consolidate and simplify the processes as far as practical while maintaining the essence of those processes to which the outcomes are most sensitive. At one unsatisfactory extreme, all the possible processes might be lumped together to develop an empirical black box representation of reality. At the other equally unsatisfactory extreme, numerous individual physical processes are analysed, stylised and represented indiscriminately in a model that becomes so complex that it often fails to represent adequately the process or processes that are most important in a given situation.

At our current stage of understanding of the complexities of physical processes in rivers, it is important that analyses of river response avoid both these extremes. If there is a universal law of river behaviour then we are yet to discover it, and in the meantime both "cookbook" solutions and all-encompassing models of river behaviour should be used cautiously with due regard for the underlying physical processes.

This caution applies equally to the *effective discharge* proposition that has been developed in this work. While the work suggests a potentially useful new approach, the results of applying an *effective discharge* analysis should always be interpreted cautiously and with due regard for the reality of the physical processes that must actually promulgate any change. In particular the *effective discharge* approach makes no allowance for the sequencing of flows, the time scale of change or the recovery time from rare events.

8.2. *Context and limitations of the excess stream power effective discharge approach*

The excess stream power *effective discharge* approach takes the flow frequency model (Section 7.5) and introduces a further component that describes the likely channel response to each flow. Or, coming from the other direction, it could be said that the *effective discharge* approach take Brookes's (1987) model that relates stream power and channel stability and uses the flow frequency relationship to introduce a temporal component that describes the duration of flows at each level of stream power. In either case the *effective discharge* model still does not account for the effects of sequencing of flows or time rates of channel response or recovery.

In the excess stream power *effective discharge* approach reported here, the characteristic to be modelled is bankfull channel capacity. The physical process considered most important is erosion from or deposition on the bed and/or banks of the channel. This process has been represented in the model by the simplified relationship between excess stream energy and flow with an allowance for a threshold value for boundary material movement.

In the work by others discussed in Chapter 3, the size of the channel is linked to the amount of sediment moving in the channel. In that case, the flow frequency model is extended by further information about the relationship between flow and sediment movement with the assumption that the flow that moves the most sediment dominates the size and shape of the channel. The *effective discharge* model has been shown to reflect reality best in those cases where the relationship between flow and sediment movement has been defined by field measurement. In those cases, the assumptions and simplifications in the model are minimised by the use of measured data to provide an empirical "black box" that consolidates all the processes of hydraulics and interaction with the boundary material.

In most real situations, in Australia at least, there is insufficient sediment data to establish an effective relationship between sediment load and flow. Furthermore, in supply limited situations, a stable relationship is unlikely. Even if it were possible to establish a good relationship between sediment load and flow in a given case, it will generally be inappropriate to use the same relationship in a predictive situation where channel characteristics and channel hydrology have changed.

In the excess stream power approach used in this work, the measured relationship between flow and sediment flux has been replaced by a (largely) theoretical relationship between flow and excess stream power. This more theoretical approach substantially widens the applicability of the technique by removing the requirement for detailed sediment data, but it involves inevitable assumptions and simplifications about channel hydraulics and the threshold of motion of bed and bank material. The universal applicability of this model is restricted by the ability to model faithfully the processes of channel hydraulics and boundary interaction because of:

- uncertainties in the formulation of the relations used in computation of shear stress and hence stream power;

- lack of knowledge about the relationship between shear stress and removal of material from the channel boundary (particularly for cohesive material); and

- the inaccuracies involved in using a discrete set of values to represent channel properties that vary continuously in space.

8.3. *Different effective discharges for different degrees of freedom of the river channel*

As reported in Chapter 3, most authors have considered that a channel has only one *effective discharge*: the *effective discharge for bankfull channel capacity*. In this section, the proposition that a channel can have many *effective discharges* – one (or more) for each degree of freedom of the river channel – is briefly revisited.

According to Hey, a river channel has nine degrees of freedom (Hey 1978): width, mean depth, maximum depth, slope, sinuosity, meander arc length, bedform height, bedform width and flow resistance. Each of these characteristics can vary with time as the result of a complex interaction of physical processes within the river channel. In this work it is proposed that there is actually an *effective discharge* for each physical process taking place in the channel leading to a suite of *effective discharges* applicable to the characteristics of a channel, some more important and more influential than others.

For instance, in the Tumut River case study, bed and bank material are substantially different. The bed exhibits an armour layer of uncompacted gravels with a median size of 20mm. The banks are typically cohesive silts. It is unreasonable to expect that the flow will interact with these different materials in the same way. However it <u>is</u> proposed that in both cases, the interaction is dominated by the amount of available flow energy. As described in Chapter 5 the difference in the response of bed and banks derives from the different values of critical shear stress applicable to the two materials.

In the Tumut River Case Study, as reported in Chapter 5, two different *effective discharges* are calculated for the same channel for the same period. One *effective discharge* (for the banks) is a relatively frequent event and the other (for the bed) is relatively rare. In this circumstance, is there an *effective discharge* for bankfull channel capacity?

Strictly speaking, the answer to this question is no. There are different *effective discharges* controlling each of a number of different channel characteristics, all of which combine to determine bankfull channel capacity. In the analysis however, the *effective discharge* for bank processes is shown to be close to bankfull channel capacity for both pre and post regulation conditions. In the Tumut case there is the additional complication that some bed deepening and armouring was probably initiated by channel clearing operations prior to flow regulation. A possible conclusion is that bank processes have dominated channel adjustment in the Tumut River in recent times.

The practical interpretation is that with an armoured bed, an increase in channel width may be the only available channel response to a change in streamflow pattern. Then the *effective discharge* calculated using bank properties would also be the discharge that controls bankfull channel capacity.

The same problem does not exist for the Snowy River case study. In the depositional environment, the one process dominates both bed and bank changes.

8.4. *Applications*

Further development of this concept and in particular, recognition of the importance, of geomorphic thresholds to the stream power based *effective discharge* calculation, may contribute to an improved understanding of the importance of flood and drought dominated regimes in channel evolution and could contribute to the debate about the importance of "catastrophic" events in landscape evolution.

The existence of different thresholds for different physical processes leads to different *effective discharges*. For example depositional processes may build in-channel benches up until a flow threshold is reached, beyond which the bench is destroyed by erosion. Conceptually at least there may be a different *effective discharge* for each of these processes: one that applies to the channel with benches and one that applies to the channel without benches. Which characteristics the channel exhibits at any time will then depend on the actual historic sequence of flows, the time dependence of the process and the recovery time of the system (Baker 1977),(Wolman and Gerson 1978),(Lewin 1989),(Kochel 1988),(Brookes 1987).

The excess stream power based *effective discharge* approach could be applied to help to manage the environmental consequences of flow regulation by contributing to predictions of the effect of possible release patterns on downstream channel morphology. This has immediate relevance to managing the impacts of regulated releases downstream of dams and river diversions (Petts 1980a; Petts 1980b; Petts 1982; Petts and Lewin 1979).

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