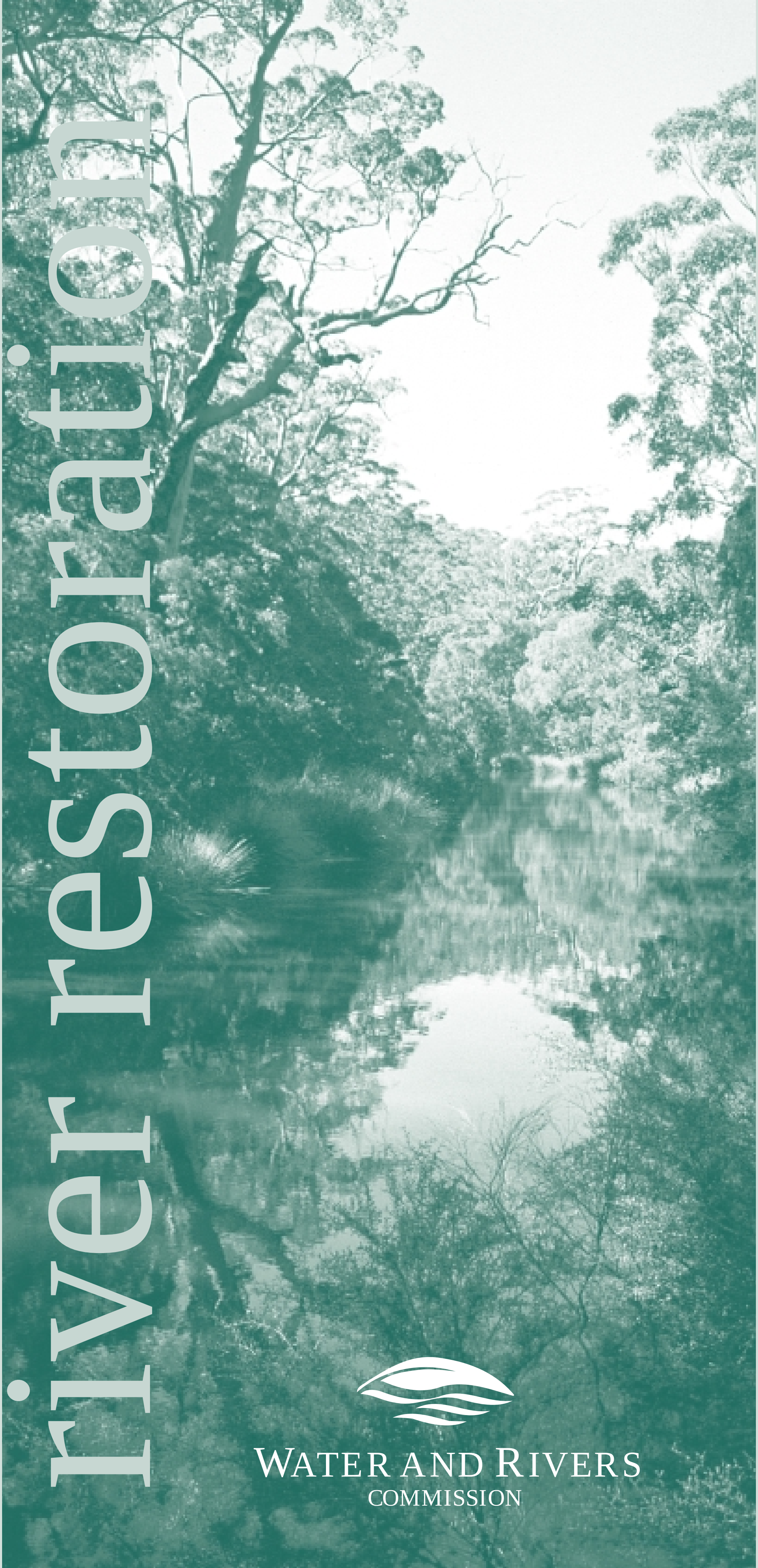


THE GOVERNMENT OF WESTERN AUSTRALIA

Stream Channel Analysis

February 2001
Report No. RR 9

WATER & RIVERS COMMISSION
Hyatt Centre
3 Plain Street
East Perth
Western Australia 6004
Telephone (08) 9278 0300
Facsimile (08) 9278 0301

We welcome your feedback
A publication feedback form
can be found at the back of this publication,
or online at http://www.wrc.wa.gov.au/public/feedback

STREAM CHANNEL ANAYLSIS

Prepared by
Luke Pen,
Bill Till,
Steve Janicke,
Peter Muirden

Jointly funded by

Natural Heritage Trust

WATER AND RIVERS COMMISSION

WATER & RIVERS COMMISSION
REPORT NO. RR 9
FEBRUARY 2001

Acknowledgments

This document was prepared by Luke Pen, Bill Till, Steve Janicke and Peter Muirden.

Illustrations by Ian Dickinson.

River Restoration series co-ordinated by Heidi Bucktin and Virginia Shotter, Water and Rivers Commission.

This document has been jointly funded by the Natural Heritage Trust and the Water and Rivers Commission.

Reviewed by Jerome Goh, Main Roads Western Australia.

Reference Details

The recommended reference for this publication is: Water and Rivers Commission 2000, *Stream Channel Analysis* Water and Rivers Commission River Restoration Report No. RR 9.

ISBN 1-9-209-4709-4 [PDF]
ISSN 1449-5147 [PDF]

Text printed on recycled stock,
February 2001

Foreword

Many Western Australian rivers are becoming degraded as a result of human activity within and along waterways and through the off-site effects of catchment land uses. The erosion of foreshores and invasion of weeds and feral animals are some of the more pressing problems. Water quality in our rivers is declining with many carrying excessive loads of nutrients and sediment and in some cases contaminated with synthetic chemicals and other pollutants. Many rivers in the south-west region are also becoming increasingly saline.

The Water and Rivers Commission is responsible for coordinating the management of the State's waterways. Given that Western Australia has some 208 major rivers with a combined length of over 25 000 km, management can only be achieved through the development of partnerships between business, landowners, community groups, local governments and the Western Australian and Commonwealth Governments.

The Water and Rivers Commission is the lead agency for the Waterways WA Program, which is aimed at the protection and enhancement of Western Australia's waterways through support for on-ground action. One of these support functions is the development of river restoration literature that will assist Local Government, community groups and landholders to restore, protect and manage waterways.

This document is part of an ongoing series of river restoration literature aimed at providing a guide to the nature, rehabilitation and long-term management of waterways in Western Australia. It is intended that the series will undergo continuous development and review. As part of this process any feedback on the series is welcomed and may be directed to the Catchment and Waterways Management Branch of the Water and Rivers Commission.

Contents

1. Introduction

1.1 Aim of stream channel analysis

The objective of stream channel analysis is to gain an understanding of the stream channel and of the discharge of water that shapes it, as well as an appreciation of the catchment that generates this flow or discharge[1]. Indeed the analysis begins with measuring the catchment area, locating the subject reach along the full length of the stream and appreciating the range of flows and particularly flood flows that the catchment produces. It is these flood flows that form the channel. In the ideal world the flow would remain constant throughout the year, forming a channel of a particular size and morphology. This ideal situation gives rise to the concept of the channel forming flow. In reality flows vary greatly and the concept of a *channel forming flow* is an 'average' of flood flows. Also in the ideal world the channel forming flow fills the channel to the top of the banks at the level of the floodplain, the bankfull flow. However, channels can be incised and the *bankfull flow* may occur well below the level of the top of the banks. Stream channel analysis seeks primarily to quantify the bankfull channel in relation to it associated channel forming flow.

To do this we need to know the size of the channel, (ie. its cross sectional area), which determines how much water the channel can contain. We also need to know the slope of the channel, which largely determines how fast the water flows. The form of the channel, its twists and turns and shallow and deep areas, has a great bearing on slope, particularly when considering low flows. The flow and weight of the water is the expression of the energy of the stream, which erodes the channel bed and transports material downstream. The roughness of the bed is critical in determining how much the flow of water is slowed and in turn largely determines the capacity of the channel to resist erosion and promote the deposition of sediment.

Stream analysis involves field surveys and measurements, using sketch maps and standard surveying and assessment methods. Data is collected for the subject reach to be rehabilitated, and also ideally for a relatively natural 'reference' reach to provide a template of the types of macro and micro-habitat conditions that may be restored. Armed with this information, formulas are available to calculate (predict) flow velocity, flow discharge and the power of the stream in relation to flow level. The primary aim here is to obtain this information for the channel forming flow, but it can also be obtained for lower or higher flows, which is recommended for unstable channels that are affected by both minor and major flows.

The information provided by the stream channel analysis can be used to design channel restoration works with appropriate form and bed materials that conform to and are reinforced by the natural flow regime of the stream, and particularly the channel forming flow. This design would ideally incorporate the channel form, flow conditions and habitat elements similar to a natural channel with the same annual flow patterns.

1.2 Where the method is applicable

The approach to stream channel analysis described in this document was developed in North America, where the geology of the land is relatively young and stream channels are mainly well defined (Newbury and Gaboury, 1993). Braided streams with a multiplicity of channels, characteristic of inland rivers of arid, flattish regions, and streams dominated by sediment, woody debris or vegetation, without a well-defined channel, cannot be analysed accurately using this method. The method is however quite suitable for stream channels in coastal high rainfall areas of the south-west, such as the Darling Range, the hilly or well dissected landscapes of the north-west, such as the Pilbara and Kimberley and for well defined channels on the south-coast and Swan Coastal Plain.

1.3 A note on the maths

Stream analysis requires a small amount of mathematical work. For those not proficient in maths or who have left it behind at high school, college or university, it may seem like a lot of maths. But a mathematical description of the physics of rivers cannot be ignored. The management of rivers involves a

[1] In this document flow and discharge are synonymous and refers to the volume of water moving down a channel per unit of time (cubic metres per second, m^3/s).

respect for the motion of water or more precisely the science of *fluid mechanics*. Fluids are a collection of particles moving and interacting with one another and with the medium through and/or over which they are moving. In this case it is water moving along a solid channel[2]. The motion of the water is not uniform, as is the movement of a car on a road. For example, some of the water will be dragging on the channel bed, while some of it, well above the bed, will be moving more freely and more swiftly. Also water moving around a curve will move faster on the outside of the curve than on the inside, and will tend to roll (just like a car going around a corner without braking). So the formulas of fluid mechanics (better described as relationships) do not so much describe the exact forces of motion at work, but rather the empirical averages of the total motion of the fluid. We will be using the simpler of these equations to predict flow velocity and stream power, among other parameters, of water moving in the stream channel. We will also compare these predictions with actual measurements.

1.4 The practical work: what you will need to do

The order in which the stream analysis work is presented here complies with the Water and Rivers Commission's River Restoration Course and is as follows:

Preliminary desk top investigations

- measure the catchment area;
- investigate the flood (or annual maximum flow) history;
- compare the catchment area and channel forming flow with known relationships;
- examine relationships between channel forming flow and channel size with catchment area; and
- plot and examine the longitudinal profile of the full stream and locate the subject reach.

Field measurements

- longitudinal survey of the subject reach using a dumpy level;
- identify the bankfull level;
- measure cross sections;
- measure existing flow velocity at the time of survey (if there is flow);
- assess bed composition and measuring bed paving if the stream is stony;
- draw up a sketch map of the reach; and
- foreshore and habitat assessment using a suitable standard survey methods.

* note: all survey levels must be related to the same datum.

Class room calculations and predictions

- determine overall channel slope;
- calculate cross sectional areas, particularly for bankfull flow;
- calculate wetted perimeters (that part of the cross section where the water and channel bed are in contact);
- estimate channel roughness (Mannings 'n' value);
- determine hydraulic radius (a measure of cross sectional shape and depth of flow which has a large bearing on the velocity of flow);
- median bed paving (for stony bed streams only);
- determine the existing flow of water in cubic metres per second (called discharge);
- predict flow velocity and discharge for bankfull flow level;
- compare predicted and actual measured discharges;
- predict the stream power of bankfull flow;
- relate stream power (tractive force) to bed paving; and
- consider the concept of critical flow and its applicability to the stream channel form.

The procedure is summarised by Table 1.1, "The 10 step Stream Rehabilitation Process" of Newbury and Gaboury (1993).

[2] The effect of another fluid, the air above the water, is insignificant and can be ignored.

Table 1.1: The 10 step Stream Rehabilitation Process

1. Drainage basin	Trace catchment lines on topographical and geological maps to identify sample and rehabilitation reaches.
2. Profiles	Sketch mainstream and tributary longitudinal profiles to identify discontinuity's, which may cause abrupt changes in stream characteristics.
3. Flow	Prepare a flow summary for rehabilitation reach using existing or nearby records if available (flood frequency, minimum flows, historical mass curve).
4. Channel geometry survey	Select and survey sample reaches to establish the relationship between the channel geometry, drainage area and the bankfull discharge.
5. Rehabilitation reach survey	Survey rehabilitation reaches in sufficient detail to prepare construction drawings and establish survey reference markers.
6. Preferred habitats	Prepare a summary of habitat factors for biologically preferred reaches using regional references and surveys. Where possible undertake reach surveys in reference streams with proven populations to identify local flow conditions, substrate, refugia, etc.
7. Selecting and sizing rehabilitation works	Select potential schemes and structures that will be reinforced by the existing stream dynamics and geometry.
8. Instream flow requirements	Test designs for minimum and maximum flows, set target flows for critical periods derived from the historical mass curve.
9. Supervise	Arrange for on-site location and elevation surveys and provide construction advice for finishing details in the stream.
10. Monitor and adjust design	Arrange for periodic surveys of the rehabilitation reach and reference reaches to improve the design as planting matures and the re-constructed channel ages.

2. Getting to know your catchment and flood history – desktop analysis

The size of your river channel (width, depth and cross-sectional area) at the reach in which you are working is a reflection of the size of the upstream catchment. The catchment determines the size of the 'average flood' that builds a channel of sufficient size to contain this flood. Generally the larger the catchment the larger the average flood that it generates, and thus the larger the channel it builds. The average flood appears to be of a size that occurs once every 1 to 2 years (Leopold et al 1964).[3] We call this the channel forming flood or flow. This average flood (considered as discharge in cubic metres per second) is contained within a channel of a certain size. This channel is known as the *bankfull channel* and the level to which the bankfull flood reaches on the banks as the bankfull level (or stage[4]). The bankfull channel can be looked upon as a sort of average[5]. Often it is at the level of the floodplain, but in a deepened (incised) channel this level may be below the top of the bank.

2.1 Catchment area

The first step in stream analysis is to measure the area of the catchment upstream of the end of the subject reach[6]. It is necessary to gain a respect for the fact that all the water leaving the catchment as run-off will pass through the reach. There is a strong relationship between catchment area and channel forming flows and hence channel size (see Figure 2.2).

Exercise: Plot the catchment area on a map or on tracing paper over a map, by interpolating across the contour lines (ridge tops), starting at the middle of the subject reach. If there is a large dam on the main channel of the stream, determine the catchment area for both the entire catchment and up to the dam wall.

Use a planimeter or transparent grid placed over the catchment to estimate the catchment area. Remember to correct for scale.

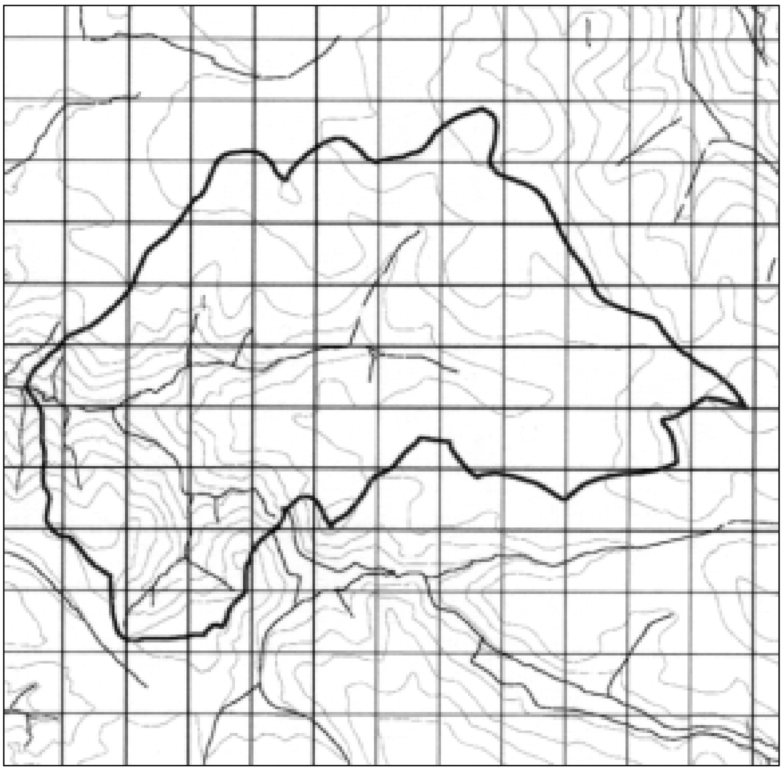


Figure 2.1: Catchment – Overlaid with a grid.

[3] If you were a betting person you would offer odds of 2 to 3.

[4] Hydrographers, the people who make a living measuring flows, often use the term stage to refer to water level.

[5] You may be wondering why the channel is not much larger, the product of the largest of floods. After all wouldn't a large flood carve out a huge channel? In some circumstances they do, such as in the case of the Columbia River, in the USA and Canada, that lies in a deep valley produced when an enormous ice dam in an old glacier gave way releasing a flood of catastrophic proportions. Boulders the size of houses were moved in this flood, which occurred about 17,000 years ago. But this is an exceptional circumstance. Most large floods spill out over the floodplains and seldom overcome the channel protection afforded by fringing vegetation. In places there will be damage, but this will be repaired naturally over the long time periods that occur between floods of this size. Most of the work done by large floods, in eroding the channel, is soon undone by the many ensuing small floods, that wash in new sediment along the channel. In other words very large floods occur too infrequently to be 'meaningful' to the channel in the long term.

The idea of an average channel can be compared to a highway. Traffic jams will ultimately occur on any highway. A road engineer does not design a highway to cope with the largest flow of traffic ever recorded, but to cope with the average of peak flows, the designers accept that every now and then a traffic jam will occur.

[6] 'Reach' is the term used to identify a particular length of river.

What if there is a large dam in the catchment?

If there is a large dam in the upstream catchment it will have the effect of diverting water out of the catchment and/or altering the flow downstream. The capacity a dam has in isolating the upstream catchment from the reach depends on its size and how it is managed. Ideally dams should be managed to release channel-forming flows at a meaningful frequency. If this is not the case the upstream catchment can be considered excluded from the catchment of the reach. However, if the reach is in a relatively natural state, its form may still be a reflection of the whole catchment. On the other hand if the reach has undergone considerable change, eg it is denuded of vegetation or overgrown with weeds and shows signs of recent erosion and sediment deposition, the lower catchment can be considered the effective catchment. This is providing of course the dam was not built recently (eg within the last ten years).

2.2 Estimates of channel dimensions and channel forming flows from catchment area

In different parts of the world engineers and hydrographers have related catchment area to discharge, particularly channel forming flows, and to the dimensions of the channel. Across different parts of the world there is a surprising agreement in the relationships, despite the fact that some catchments are much wetter than others. Nevertheless, the best relationships to use to get an idea of the channel size and channel forming flows in relation to catchment area are those for catchments as near as possible to the reach in which you are working, the subject reach. Such information is needed where the aim is to restore a channel that has become deeper and wider than it should be normally. For the south-west of Western Australia, the relationship between catchment and channel forming flows (bankfull flows) is presented in Figure 2.2. Unfortunately the relationship for channel dimensions (width and depth) has yet to be determined.

Exercise: From the graph provided (Figure 2.2), use catchment area to estimate the channel forming flow (bankfull flow) for your reach.

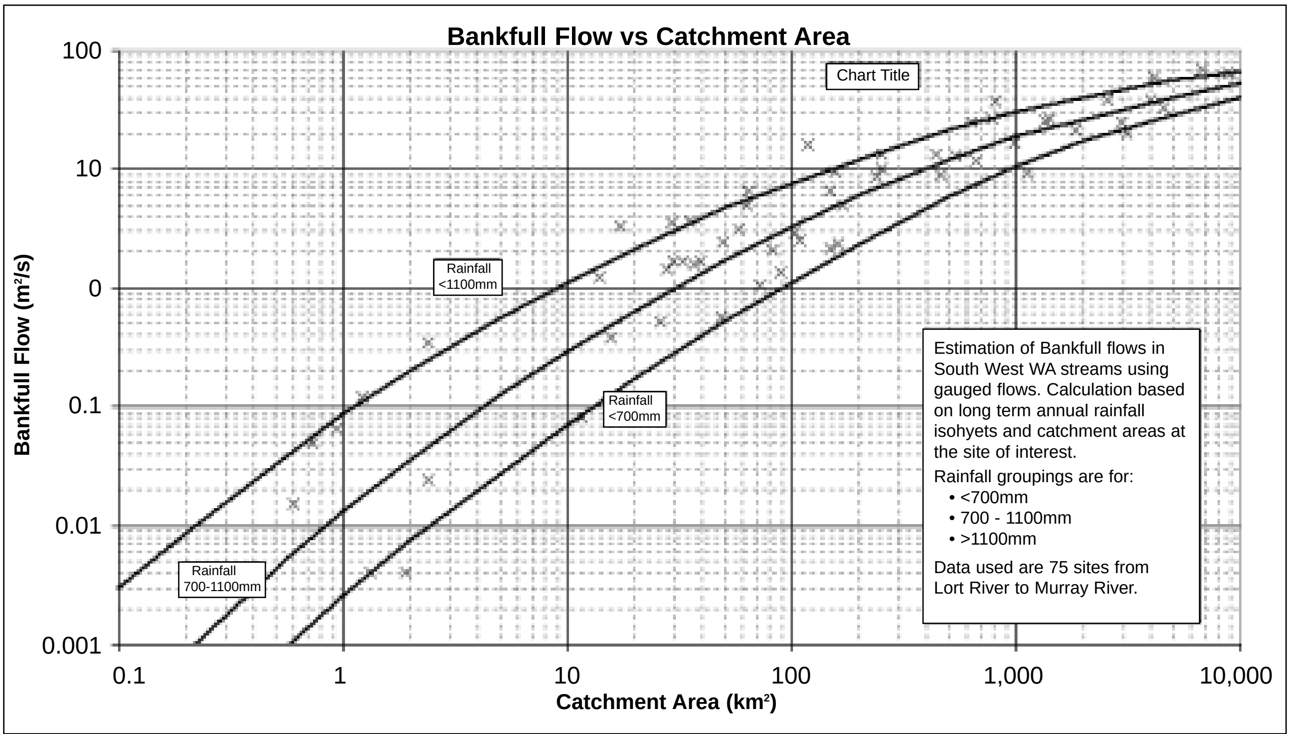


Figure 2.2: The relationship between catchment area and channel forming flows (bankfull flows) for streams of the south-west of Western Australia, divided into three rainfall zones.

2.3. Examining the flow record

Flow records may exist for the reach in which you are interested, or at least for some reach close to it. These can be obtained from the Water and Rivers Commission[7]. The record will enable you to determine the maximum discharge (in m^3/s) recorded for the reach in each of a number of years. Maximum discharge is also called *peak discharge*. An example is provided in Table 2.1 for the Canning River at MacKenzie Grove gauging station in Kelmscott. Should you be unable to gain a flow record for your reach, but have one for a comparable area or upstream or downstream of the reach, simply convert the flow figures by the ratio of the catchment area for the point at which the record was taken with that of the catchment area of your reach.

For example, if the gauging station at which the flows were recorded exists is well upstream of your reach, it must have a smaller catchment. If this area is only 80% of your estimated catchment (from Section 2.1), and your catchment is thus 1.25 times larger, multiply the flood figures by 1.25 to get an estimate of the flows at your reach.

Note that this provides only a rough guide to flood flows at your reach, as flood flows generally decrease, in proportion to catchment area, as catchment area increases. This is because the channel has a large storage capacity. That is the flood is stretched out along the channel as it moves downstream, attenuating peak flow in the downstream direction. In other words small catchments produce larger floods than large catchments when considered in proportion to their land area.

Exercise: Familiarise yourself with the flow record. Note the longer the flow record the more comprehensive it is in expressing flow variability. How many years of flow record do you have? How do the flows compare with the estimates of channel forming discharge obtained in Section 2.2?

2.4 Determining the channel forming flow from the flow records

As mentioned above channel forming flows are thought to occur once in every 1-2 years on average. That is a flood occurs at this frequency that fills the channel at the bankfull level.

We can estimate this bankfull flood or discharge (m^3/s) from the flow record. We do this by listing the annual peak flows from the highest to the lowest (see Table 2.1). This is called ranking.

Now that we have the ranked order, the probability of exceedence (PE) can be determined. The PE is the probability, from year to year, that a particular discharge and therefore flood level will be exceeded. Take for example the peak flow record. It shows that at least some flow was recorded in each year. Therefore the probability that zero discharge will be exceeded is 100%. Take the highest flow in our example. It is one of 25 records, which is 4% of the record (100/25 = 4%), but since we are interested in the probability of exceeding both zero and the 25th rank we add 1 to 25, to obtain 3.8%[8]. So between each rank and below zero and above rank 25 there is a net difference of 3.8%. Therefore the probability of exceeding the rank 1 discharge, the next annual peak flow rank above zero, is 100-3.8 = 96.2%. In other words in any year there is a 96.2% probability that a rank 1 flood flow will be exceeded. Rank 2 has a probability of exceedence of 96.2-3.8 = 92.4%; and so on. Put simply, in any year there is a high probability that a little flood will occur and a low probability of a big flood. Probability decreases as flood size increases.

At some point we will reach the probability of exceedence of the channel-forming flood. Since we accept it occurs about every 1.5 years, or twice in every three years, we know the probability of exceedence is about 67% (2/3 = 0.67) (Newbury and Gaboury, 1993). Look up this exceedence level to estimate the channel forming discharge (see Table 2.1). An estimate of channel forming flow improves with increasing number years of record, providing that the climate or catchment have not changed significantly over this time.

7 If you have access to the Internet the Water Resources Catalogue can be found at http://www.wrc.wa.gov.au/waterinf/wric/wric.asp.

8 Think of probability increments as the spaces between the 25 records. Another way of looking at it is as ‘slices’ of probability. For example, if you made 25 equidistant cuts in a sausage 100 cm long you would have 26 slices of sausage each of 3.8 cm in length.

Table 2.1: Annual Flow Peaks - Canning River, Mackenzie Grove Station 616027, 1974 - 1998

Year	Rank	Annual max discharge (m^3/s)	% Probability of Exceedence
1987	1	53.495	3.8
1992	2	43.071	7.7
1974	3	40.380	11.5
1988	4	19.055	15.4
1997	5	17.900	19.2
1978	6	17.497	23.1
1993	7	11.671	26.9
1976	8	10.680	30.8
1998	9	9.959	34.6
1983	10	9.3133	8.5
1984	11	9.226	42.3
1986	12	7.833	46.2
1979	13	7.150	50.0
1977	14	7.009	53.8
1994	15	6.787	57.7
1991	16	6.752	61.5
1985	17	6.396	65.4
1975	18	6.243	69.2
1980	19	6.064	73.1
1996	20	5.280	76.9
1989	21	5.122	80.8
1990	22	4.640	84.6
1995	23	4.477	88.5
1981	24	4.436	92.3
1982	25	3.576	96.2

A more accurate alternative is to plot the information, using linear/logarithmic graph paper as shown in Figure 2.3; fit a straight line to the data (as shown) and use the point of intersection on the line as the estimate of maximum annual flow at 67% exceedence. Draw a vertical line from the 67% PE and read off the maximum annual discharge where it intersects the line of best fit.

Canning River Annual Flow Peaks 1974 - 1998 Station 616027 MacKenzie Grove

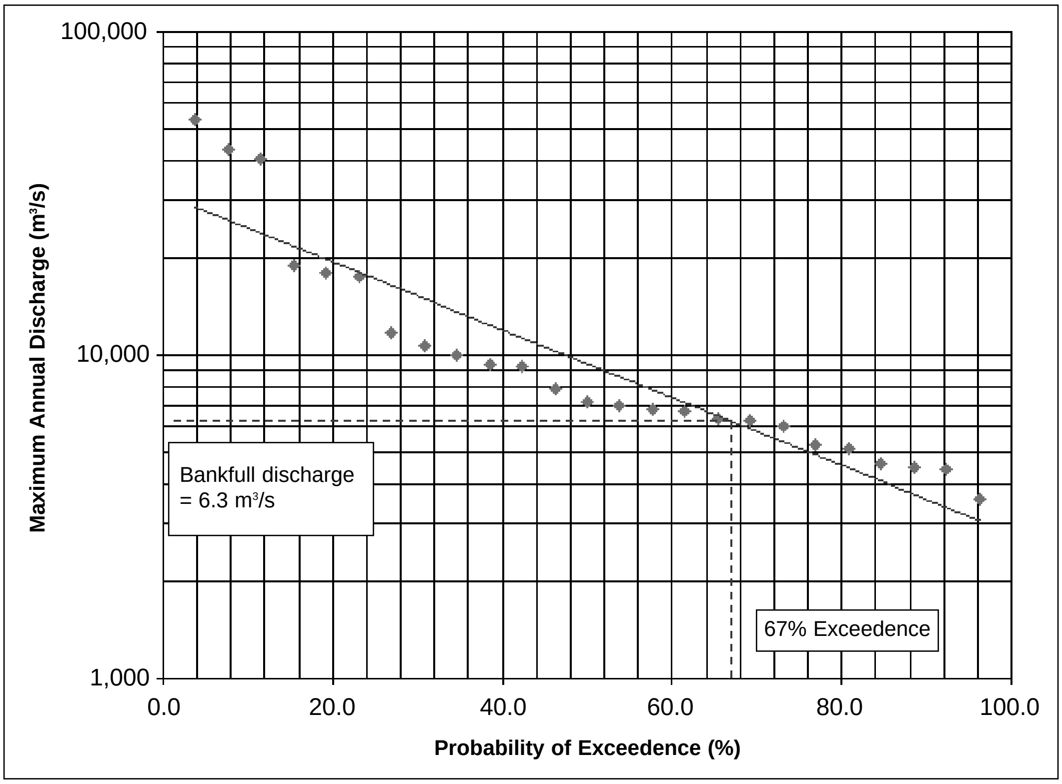


Figure 2.3: Graph of annual peak discharge vs probability of exceedence

Taking catchment change into account

A long flood record is very useful information, but if the catchment has changed over the time of the record, say from naturally vegetated to rural and then to urban, the flood history will be less of a reflection of the present catchment. Generally flood intensity and frequency increases with clearing and then again with urban development. Conversely a former broad-acre farmland catchment planted out to blue gums or horticultural species will show a decline in flood intensity. Knowing something about the history of the catchment allows the selection of the part of the recent flow record that is most relevant to the current catchment. For very long records, climate change may also be a factor that needs to be taken into account. For example, a 20% reduction in average rainfall since 1910 has resulted in a 45% reduction in stream runoff in the Perth hill's catchments (Schofield 1990). Once again the most relevant portion of the recent record should be used. Yet another factor is damming, which has the effect of reducing flood magnitude, and especially channel forming flows if they are not consciously maintained through planned releases. Once again use that portion of the record since damming became significant in the catchment.

Exercise: Rank the flood flows for your reach from lowest to highest.

Calculate the probability of exceedence (PE) level for each rank.

PE = (rank of annual peak flow/n+1) x 100

where PE = probability of exceedence (%)
n = number of records

Look up the 67% exceedence level for the channel forming flow and then correct for difference in catchment area between the site where the record was obtained and the reach.

2.5 Longitudinal survey of river channel from a map

You should be familiar with the slope of the reach in which you are working in relation to the wider river system. You need to know whether the slope is typical or atypical and how your reach relates to the underlying geology (eg the Swan-Avon passes over the Yilgarn Plateau, Darling Scarp and Swan Coastal Plain and the slope and channel form changes accordingly). Knowing the rough slope is also needed to identify comparable *reference reaches* (see Section 3.6).

Exercise: Use a piece of string or fine chain on a topographical map to measure the distances upstream from the mouth of your river to each contour line intersection (with the river). Do this for the longest arm of the river, generally through the middle of the catchment. Using the distance and respective contour level, plot out the longitudinal profile of the channel. This is the full profile of the river, between its confluence and its headwaters.

Do not use the same scale on the y axis (height above mean sea level) as with the x axis (distance). You want to achieve an exaggeration of the slope. In other words if the lowest contour is 85 m and the highest is 135 m, then the lowest level on the y axis should read 80 m and the highest 140 m.

Look for the section of uniform slope running across the subject reach. We will use this section to calculate the overall slope of the reach. Divide the difference in height (say 9 m) by the length of the section (say 5000m) to get the slope (0.0018). Note that the slope here is calculated as a ratio and can also be expressed as 1:550 for example.

Understanding and visualising slope is one of the critical skills in river restoration work. Whilst the mathematical formulae require the absolute number (ie 0.0018), this is extremely difficult to visualise. However, if the slope is expressed as a ratio, ie a 1 metre fall over a distance of 550 metres, then you have familiar measures of fall and distance. Just remember to always keep your vertical and horizontal units the same, usually metres.

3. Getting to know the river channel – field measurement

In this part of the analysis the river keeper gets into the stream valley and 'reads' the river channel and its ecosystem, looking at slope, cross sectional areas and the nature of the bed and banks of the channel.

3.1 Longitudinal survey of the channel

A level survey is conducted along the invert (lowest line of the channel) using a dumpy level, staff and measuring tape (Note that the low flow channel runs along the invert). Ideally enough points should be included to record the significant rises and falls, humps and hollows, along the streambed and determine the overall longitudinal profile of the stream. A good profile will be needed later for design of restoration works. Both the high and low points of the invert need to be measured and recorded. The current water level, bankfull level, and top of the banks should also be surveyed at a number of points. These are levels are taken at exact right angles to where the invert reading is taken.

In the course only sufficient points are surveyed along the invert to determine the overall slope, which is the major factor in determining velocity (m/s) of flow.

At a number of points the water level must be surveyed to determine water level slope (needed later to calculate stream power as *tractive force*). Again this will be an average water level, as it will vary with channel slope and obstructions which impound water.

Exercise: Locate the dumpy level where a good view along the river channel can be obtained from the point of start, the **backsight**, as far as the change point (the last point that will be surveyed from the current position of the level). This point is the **foresight**.

When placing the dumpy level take care to make allowance for any obstructions in the line of sight as a clear view is needed to read the staff. Make sure that the legs are firmly located on the ground and level the dumpy level using the bubble. Check the bubble before making each reading.

Place pegs along the invert at intermediate locations between the start and change point to characterise the path of the stream channel.

Measure the distances between the pegs along the invert (as the 'fish swims') using the tape measure. This can be done as an exercise in itself or as part of the level survey when the staff is being moved.

Start the survey in the channel at the peg from which the horizontal distances will be measured. Place the staff on the bed just in front of the peg. Make sure the staff is vertical and face-on to the dumpy level so that accurate readings can be made. Have someone else check and confirm the reading or double check yourself (see Figure 3.1). Do not press against the level when making readings, as this may put it out of kilter.

The person making the recordings in the note book should be aware that the survey is moving upstream or downstream. Therefore readings off the staff, in respect to channel location (invert, water level, bankfull and bank top) are generally falling (if going upstream) or rising (if going downstream) respectively. This is an easy check for correct readings, but note that channel level will vary greatly[9].

As mentioned earlier level readings should also be taken at the water's edge (water surface), bankfull level and top of bank (both sides or if one side is very high at the lower or floodplain level). These points should be at right angles to the centre line of the channel.

The staff is then moved to the next peg and the same readings are made. The distance between the last and next peg may also be measured at this time.

This process continues until the last peg, at which all the readings at the various levels are made. The last reading in the channel or a reading from some other 'hard' point will become the new backsite, when the dumpy level is moved to the next 'clear vision' position on the river, ie the last sight is known as the foresight and once the level is moved it becomes the new backsight. **When the level is on the move the staff must stay put**, as we have just

[9] Note that the basic function of a dumpy level is to enable a circular view which is along an exactly level plain, by using the middle horizontal cross hair (Figure 3.1).

determined the height of this point from the dumpy level's old position, and must now use it as our new backsight of known height to be able to relate to the next lot of readings. This leap frogging survey continues along the river (Figure 3.2). The golden rule is when the staff is being moved the level stays put and when the level is on the move the staff stays put.

In the classroom the levels will be reduced to points of known height (as shown in Appendix 1) and the data graphed using the distance measurements. Appendix 1 also provides a simple description of the principles of level surveying using a dumpy level.

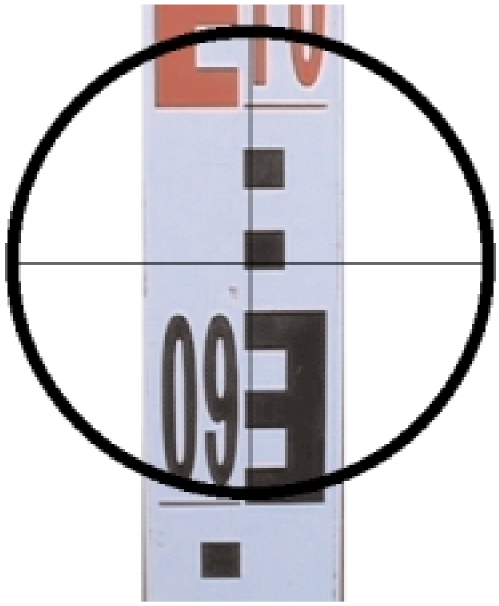


Figure 3.1: Survey Staff Viewed through Dumpy Level.

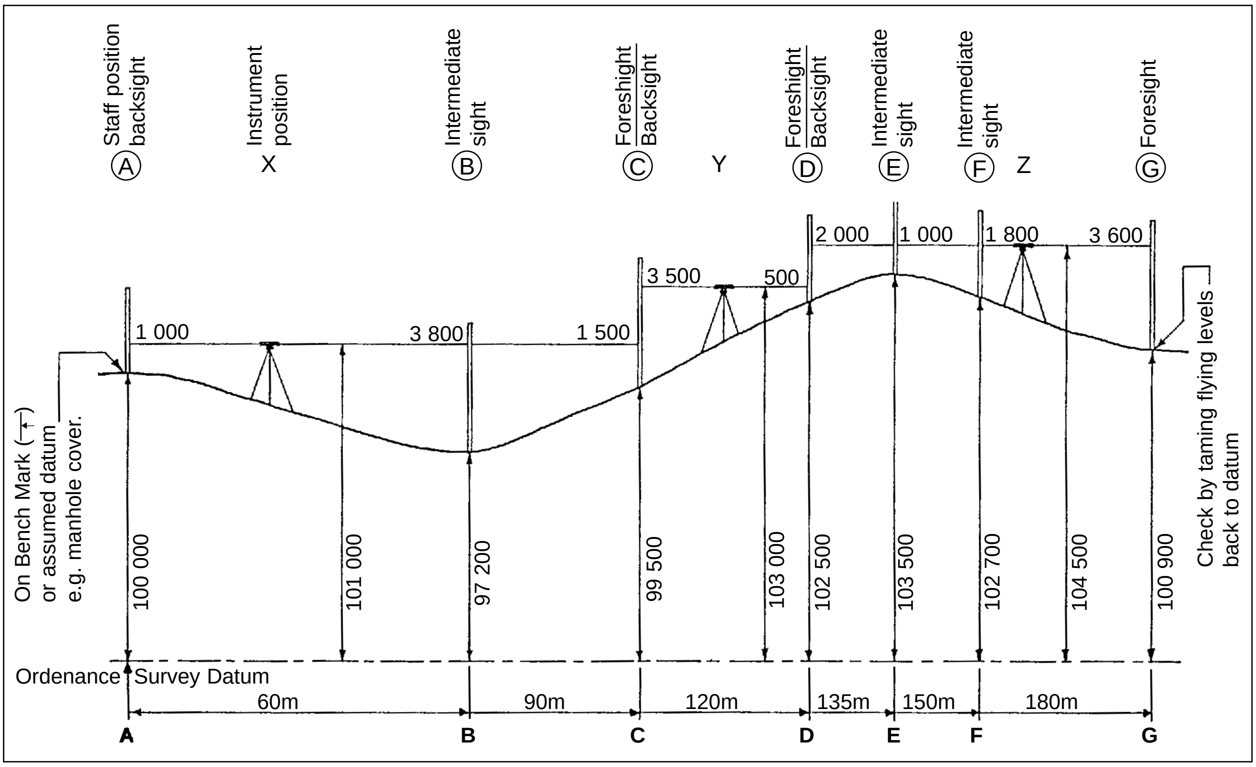


Figure 3.2: Levelling Survey showing movements of Dumpy Level.

3.2 Recognising bankfull level

Bankfull level is the level on the bank of the stream that flow reaches during a 1:1.5 year flood. This is referred to as the channel forming flow. This flow level is reached or exceeded often enough to be meaningful to the channel. That is, it shapes the channel and leaves its mark. This level may be at the top of the bank or some point below it, particularly if the channel is incising (deepening). The marks or clues include the following:

* upper edge of generally exposed soil;

* lowest extent of lichens;

* lowest extent of annual grasses;

* grooves in the bank; and

* upper edge of water stains on the bank

Note: If the catchment is producing more water than in the past (eg it has gone from rural to urban), the channel may be growing in size. Conversely, if it is well supported with vegetation, channel-forming flows may have yet to form a new channel and may at the present time be spilling over the bank. Look for sediment and debris deposits to give an indication of present-day bankfull level.

3.3 Cross sectional areas

Bankfull cross section

To be able to estimate bankfull discharge (m^3/s), that is the amount of water flowing in the channel when the water level is at bankfull, we need channel slope and cross sectional area. Slope, which is the main factor determining velocity, will be derived from the longitudinal survey. Cross sections need to be measured directly. Channel roughness, which slows the water, is covered in Section 4.4.

We need to measure, at least six different cross sections along the reach to calculate an average cross sectional area. You should choose cross sections that are very different in shape.

Exercise: For each of six very different sites, stretch out a tape measure from the bankfull level on one bank to the bankfull level on the other bank. While keeping the tape measure stretched out, take the staff and measure the vertical drop from the tape to the bed at sufficient points to plot the ups and downs of the bed perimeter. Also measure the vertical drop to the water's surface. This is most easily done at the existing water's edge. At each point call out the drop and the distance along the tape measure. The procedure is illustrated in Plate 3.1 and Figure 3.3.

This data will be used to graph-up each cross section and calculate cross sectional area.

Plate 3.1: Measuring cross-section at Bankfull Level using tape and staff.

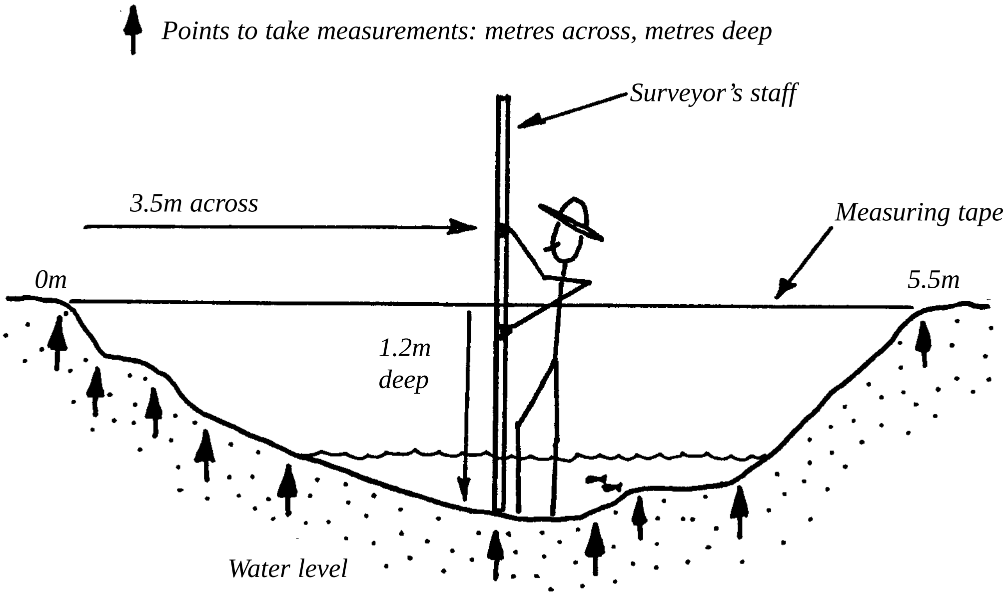


Figure 3.3: Measuring stream channel cross-section.

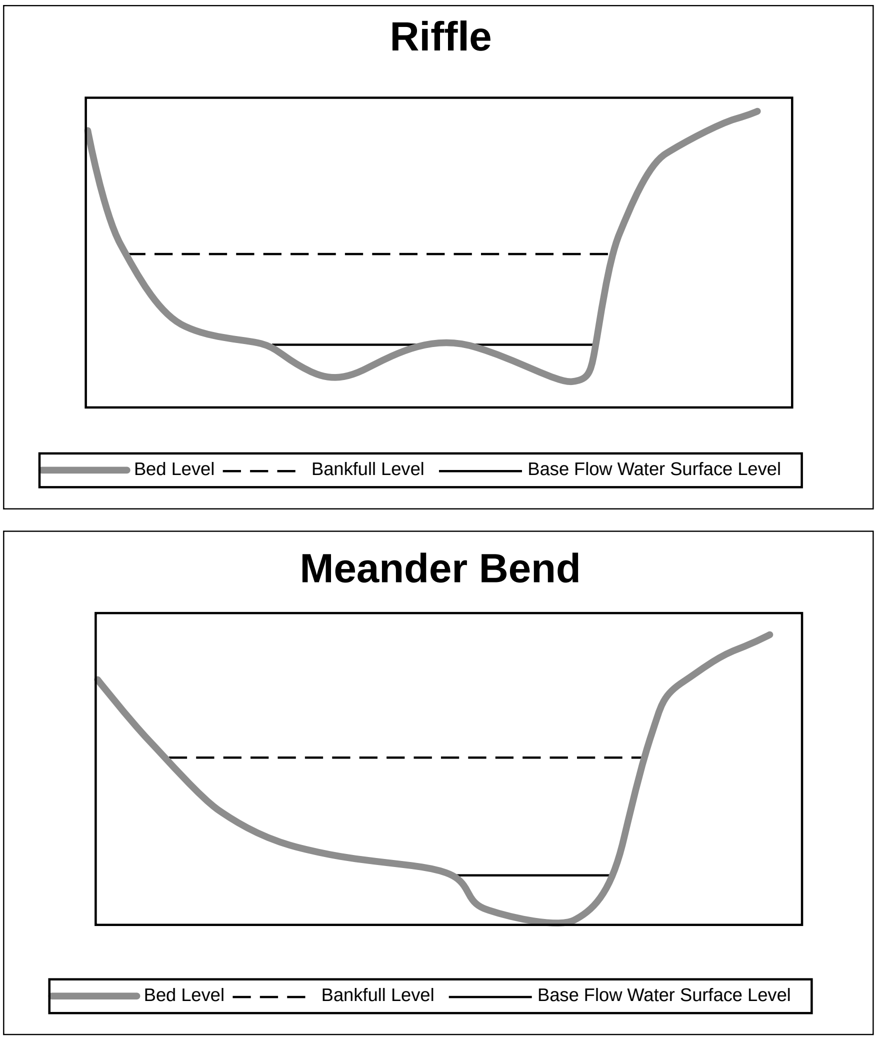


Figure 3.4: Typical channel cross-sections.

Existing flow cross section

If the reach in which you are working is currently carrying a flow of water, then there is an opportunity to compare this flow, which you will measure, with that which you can predict. The prediction is done using standard formulas and measurements of cross sectional area of that flow, channel slope and estimates of channel roughness (See Sections 4.1 and 4.4).

Since we wish to measure the existing discharge (m^3/s), so that we may compare it with a predicted flow for the existing flow level, it is necessary to obtain a cross sectional area for the existing water level. We do this using a cross section where flow is relatively uniform and steady (see Section 3.4).

Exercise: Measure the cross section of the existing flow at a point on the channel where the existing flow can be measured easily (see Plate 3.1).

Larger channel cross section

The bankfull level may be much lower than the upper level of the entire channel. Floods rising to this level may occur less frequently than 1 in every 1 to 2 years. Larger floods would spill out over the floodplain. Thus the upper level of the bank determines the maximum flood flow that passes along the channel and it is this flow that subjects the channel to the greatest stream power. For this reason it is useful to determine the cross section of the larger (floodplain level) channel. Where the channel has been denuded of protective vegetation and is prone to erosion, measurements to the floodplain level are necessary and should be taken at all cross sections.

Determining the cross section of the larger channel will help provide estimates of the discharge that would fill this channel and of the stream power that will be exerted (see Sections 5.2 and 6.1). The power of this flood could do a great deal of damage to the channel, particularly if it is denuded of protective fringing vegetation and passes through non-cohesive soils. Any protective structures, such as rock bedding or rip-rap, would have to withstand this stream power.

Another interesting exercise is to compare the predicted discharge that would fill the larger channel with the actual annual peak flow records (see Section 2.3). It may be that the predicted full channel discharge is far greater than the largest flood discharge ever recorded. This is indeed the case for the greatly incised and widened Serpentine River on the Swan Coastal Plain. Here, only the lower portion of the incised channel would be filled by the larger flood flows.

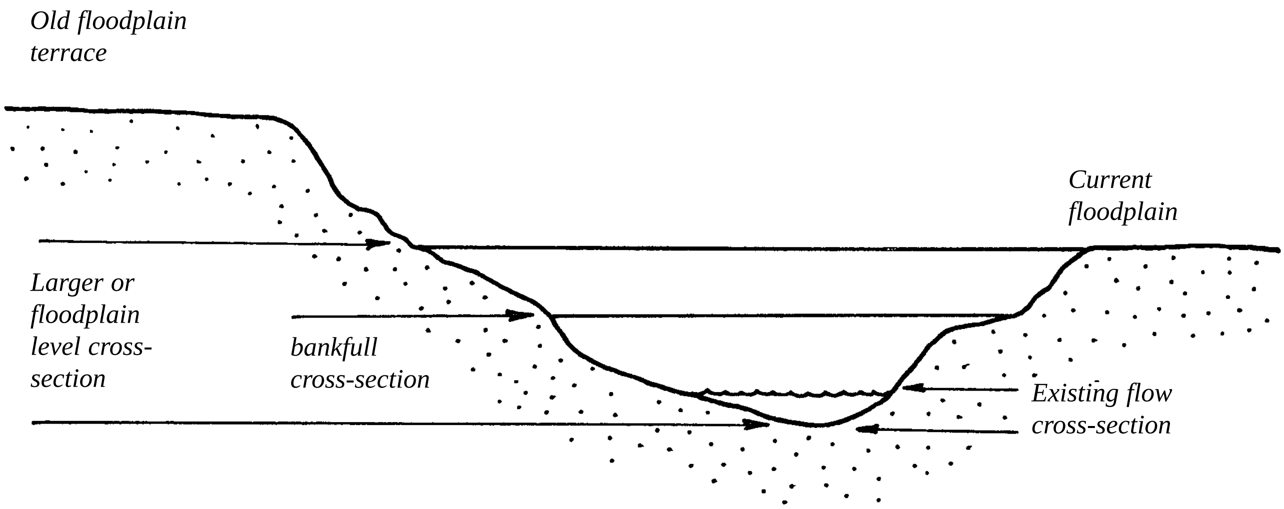


Figure 3.5: Cross sections of existing flow, bankfull and larger (floodplain level) channel.

Exercise: Measure the cross section of the larger channel as for the bankfull cross sections, and do this at one of the existing bankfull measurement sites. If the channel is very large, it may be difficult to read the staff. The dumpy level can be used as a telescope to read the staff. Remember that you should ideally do about 5 or 6 cross sections over 200-300 m to get a good 'average' appreciation of the channel.

3.4 Existing flow velocity

Estimating the existing flow velocity in the reach at the time of your survey is necessary to be able to determine the existing discharge.

Exercise: Mark out a straight line distance using pegs, say about 10 to 20 metres apart, where the existing flow cross sectional area was measured. Then using a honky nut, rolled ball of grass or peeled orange, to measure the time it takes for the honky nut, or whatever, to float this distance. Do this five or six times and then average the values. The result should be in metres per second (m/s).

3.5 Bed material assessment and measurements

It is necessary to gain an appreciation of the material, other than vegetation, that comprises the stream bed, whether it be clay, sand, stone, woody debris, etc. Simple notes should be taken and estimates made of the width and length of woody debris (eg 5-20 cm diameter and 2-5 m long) and the height above the bed to which material would project into the water column. Observe what material appears to be free standing and mobile versus that which is rigid (eg very large logs, buried logs and rocks, basement rock, etc). These features should be recorded.

For stony bed streams it is also necessary to get some idea of the size range and median size of free standing pebbles, cobbles and boulders as these will only be moved during flood flows. We need to know what size material will be transported during bankfull or channel forming flows. Later we can relate this information to estimates of stream power. The information may be useful for an assessment of channel roughness.

Exercise: Take notes as above:

- bed material - clay, sand, stone (base rock, pebbles, cobbles, boulders
- vegetation in the channel (trees, shrubs, sedges and rushes; grasses and weeds; submergent, floating, emergent aquatic species; algae)
- woody debris and other debris (eg shopping trolleys) with approximate dimensions
- partially buried material (eg boulders, logs, car bodies)
- average height of channel material projecting into flow

Take a random sample of 25-35 freestanding stones (eg pebbles, cobbles and boulders) on the surface of the stream bed and measure the length, width and depth of each. [This information will be used to determine median bed paving size later].

3.6 Channel sketch map

The best way to get to know the river channel is to draw a sketch map. This map should be approximately to scale. It can be used as a basis of a planning diagram, illustrating remedial actions. The sketch map should include the following information:

- general distribution and cover of vegetation, particularly noting the amount of shade;
- sites of erosion and bank failure, including undercutting, slumping, gullying;
- sediment deposits, especially large plumes in the channel, on point bars and filling pools;
- pools and riffles;
- rock, laterite (ironstone), clay or coffee rock bars;
- islands and bars;
- meander bends;
- velocity of existing flow as arrows, the longer the arrow the faster the flow;
- points of eddying and turbulent flow;
- woody debris, including fallen logs and log jams;
- accumulations of leaf litter;
- evidence of animals (tracks, scats, nests, sightings, etc) and particularly of breeding;
- weed list (of major aquatic, woody and climbing species);
- list of dominant native species of upper, middle and lower stories;
- observations of native species regeneration;
- rubbish, vandalism and poaching (eg dug out plants and marron pots);
- recent fire (blackened trucks); and
- feral animals - rabbits, foxes, cats.

Exercise: Have one surveyor draw up a sketch map of the reach, noting the more relevant points given above.

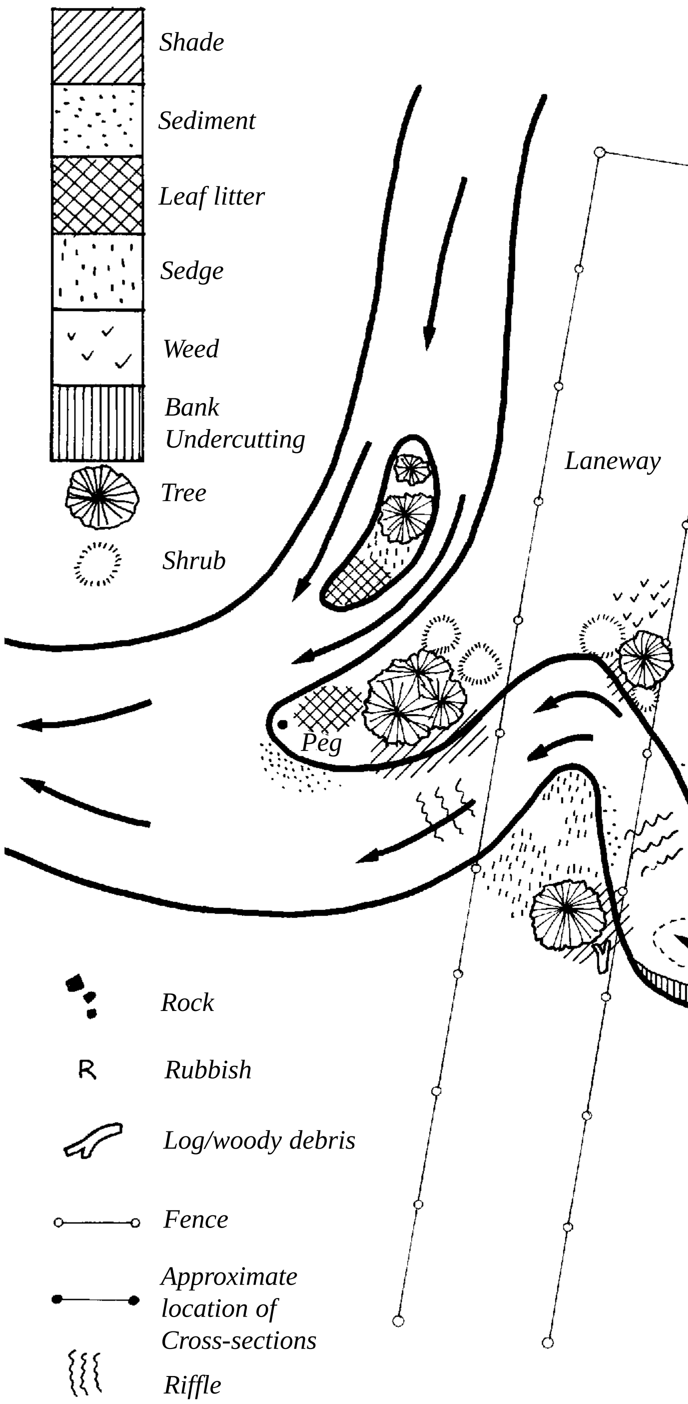
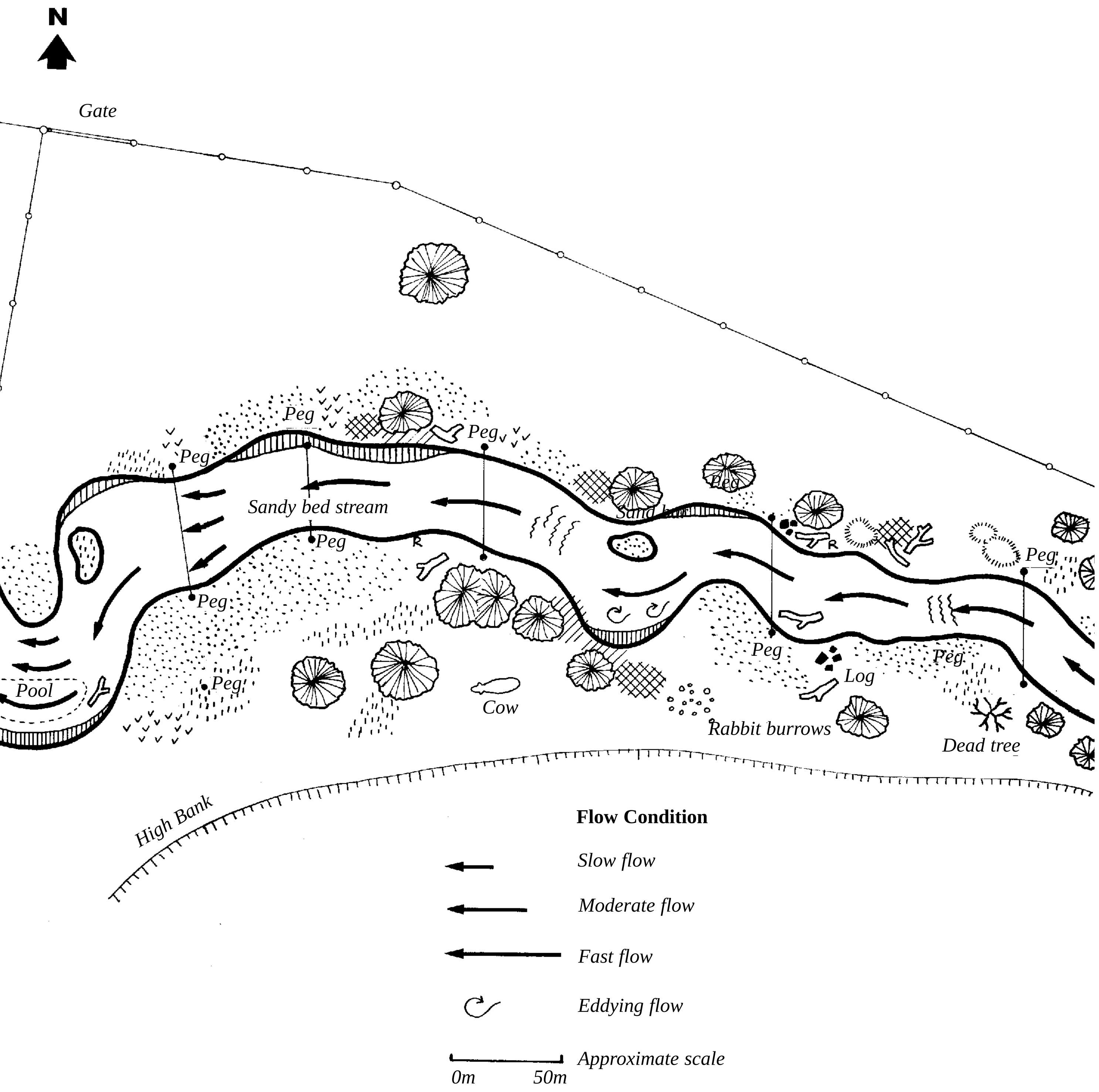


Figure 3.6: Example of a sketch map


N
Gate
Peg
Peg
Peg
Peg
Peg
Peg
Peg
Peg
Peg
Peg
Sandy bed stream
Pool
Cow
Log
Rabbit burrows
Dead tree
High Bank
Flow Condition
Slow flow
Moderate flow
Fast flow
Eddying flow
Approximate scale
0m
50m

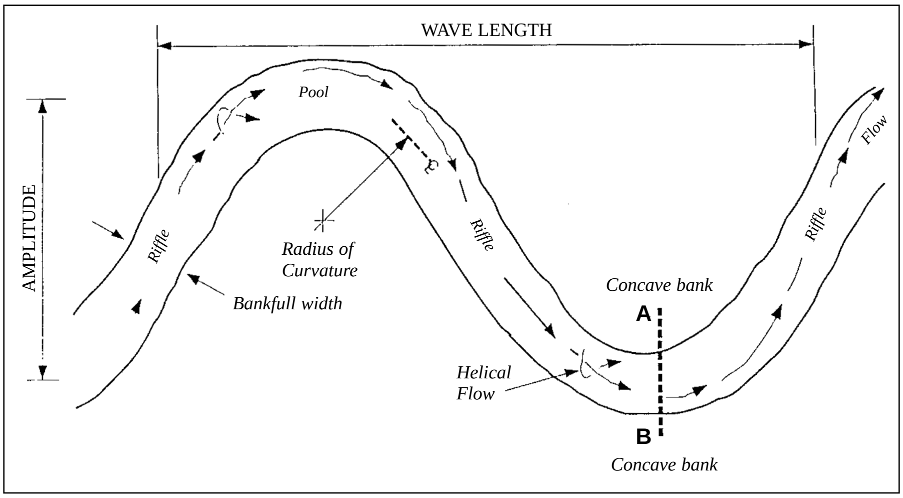
Reference reach survey

In seeking to restore the natural habitat to a section of stream, it is useful to have survey information from a comparable reach in its natural state. This reach would have the same stream order and may be located upstream or downstream on the same stream or in another part of the catchment. A reference reach may be located in another catchment of the same biogeographical region.

In a reference reach survey essentially the same information is collected and measurements are made as for the reach you are seeking to manage. However, this time the survey concentrates on the natural components of the system, such as variations in water movement, woody debris, vegetative cover, etc, and where these elements are located in relation to channel form. Getting to know what natural habitat elements need to be restored is particularly important where the aim is to recover biodiversity or create habitat for a particular species, such as marron or freshwater cobbler.

Meandering form and pool-riffle sequence

Streams move in a meandering or sinuous pattern. One consequence of this is to lengthen the channel between two points, reduce slope and thus the velocity and hence stream power. A second consequence is that water tumbles in a helical or spiral pattern as it moves around a meander bend, often forming and maintaining a pool. As the flow straightens out prior to the next meander bend, it may form and maintain a shallow riffle. On a worldwide basis meander bend radius is on average 2.3 times the width of the bankfull channel. Pool-riffle sequence (one pool and one riffle) is generally 5-7 times the width of the bankfull channel (Leopold et al 1964; Gregory et al 1994). However, a better understanding of the particular meandering form and pool-riffle sequence of the subject reach can be obtained by survey. This will also identify other localised influences on stream form, such as dolerite dykes forming rocky riffles or a constriction in the river valley causing the acceleration of flood flows which excavate and maintain a river pool.



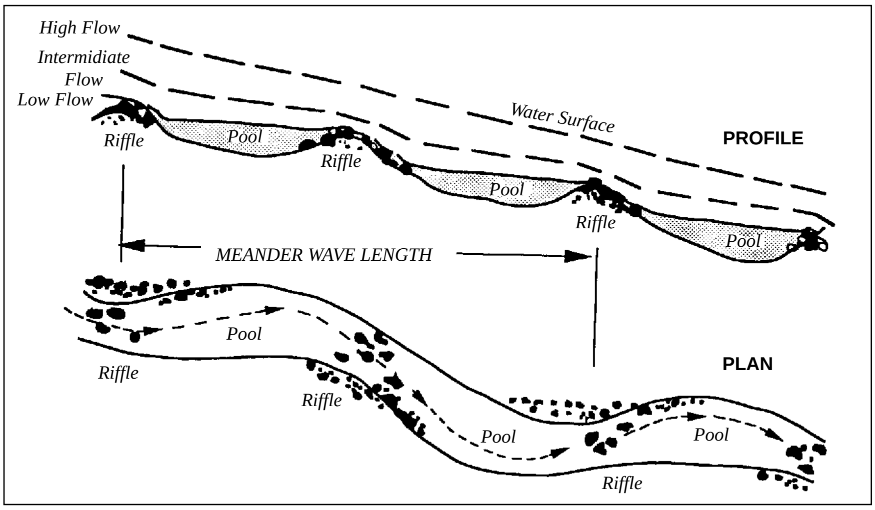


Figure 3.7: Meandering form and pool-riffle sequence.

If the subject reach has become badly eroded or sedimented or greatly altered through river training, then a reference reach (see above) should be used to gain an understanding of meander pattern and pool-riffle sequence. This is essential where river restoration seeks to replace natural sinuosity to bring back a full range of habitats or to control erosion.

3.7 Foreshore and habitat assessment

Foreshore and habitat assessments are undertaken along rivers and creeks to collect standardised information. This information is collated to present the condition of the stream over long distances, and thus identify what sections are in need of management and to prioritise work (eg attend to sections which are degrading quickest).

Standard methods and forms are available to undertake foreshore and habitat assessment in south-west farming areas and in urban and semi-rural areas. These are described in booklets RR2 and RR3 in the Planning and Management Section of this Manual.

Exercise: Have someone conduct a foreshore survey appropriate to the area in which the subject reach is located.

4. Getting to know the river channel – plotting, tabulating and calculations

In this part of the analysis the information gained in the field is used to determine the nature of flow within the channel, principally for bankfull level, but also for other levels.

4.1 Channel slope - from the longitudinal survey

The main factor determining the velocity of flow is channel slope. We derive the slope from a plot of bed longitudinal profile.

Exercise: Reduce the levels (as shown in Appendix 1) and graph the data using the distance measurements. Although the stream was obviously meandering, the graph will be as if for a straight channel. Four lines may be produced, one for the bed profile (invert level), one for the estimated bankfull level, one for the floodplain level and one for the current water level.

Using the plot of longitudinal bed profile (taken at the invert level), draw a straight line that best fits the peaks of the profile. This should be a sloping line, angled downwards in the downstream direction. Use this line to estimate slope. If you observe a drop of 30 cm over 300 m, the slope is 0.30/300 = 0.001 or a 0.1% slope.

Note: Because the landscape of the south-west is often flat it may be difficult to detect a slope over a short distance of say 200-300 m, especially if the channel is highly irregular in longitudinal profile (eg lots of pools and riffles, woody debris, bars, sediment plumes, etc). If this is the case take the water surface slope from points where the water was moving freely and not impounded by a fallen log for example.

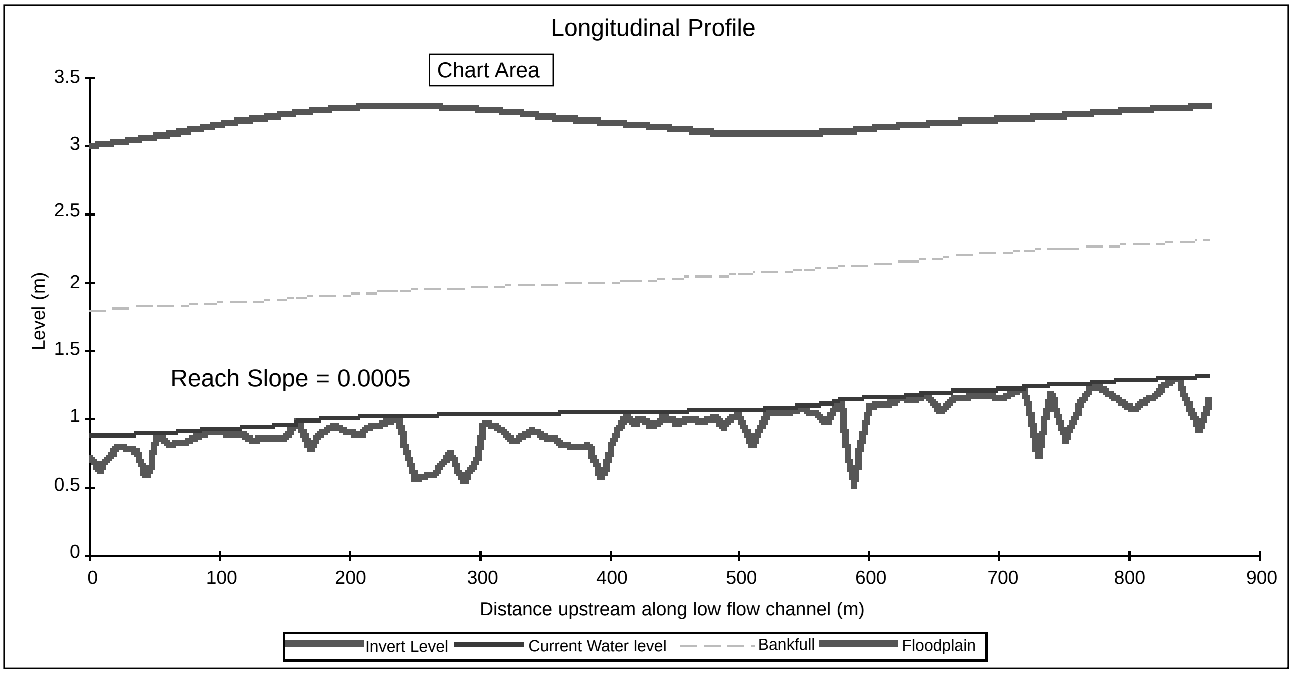
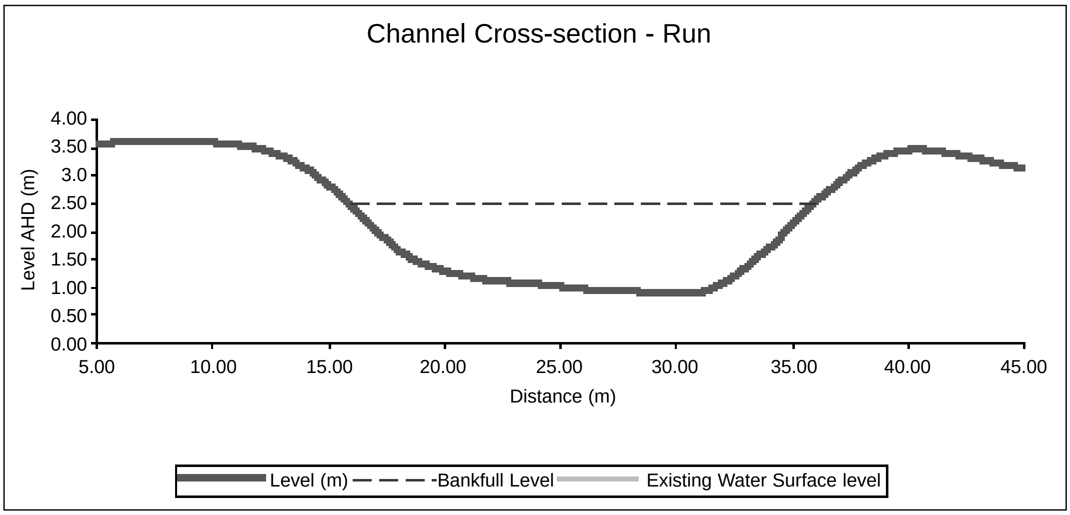


Figure 4.1: Longitudinal profile of surveyed reach.

4.2 Average bankfull cross section

Slope largely determines the velocity of flow. The cross section of the channel determines the quantity of water contained within the channel and hence together with slope how much and how fast the water is flowing, the discharge (in m^3/s). We have the overall slope that determines flow velocity and now we need the average cross section to determine the average bankfull discharge.

Exercise: Graph each cross section. Estimate cross sectional areas by breaking up each cross section into rectangular or triangular panels and summing the areas. Then obtain the average for all six cross sections. Note that the vertical and horizontal scale need to be the same for easy measurement and indeed also for wetted perimeter (see below).



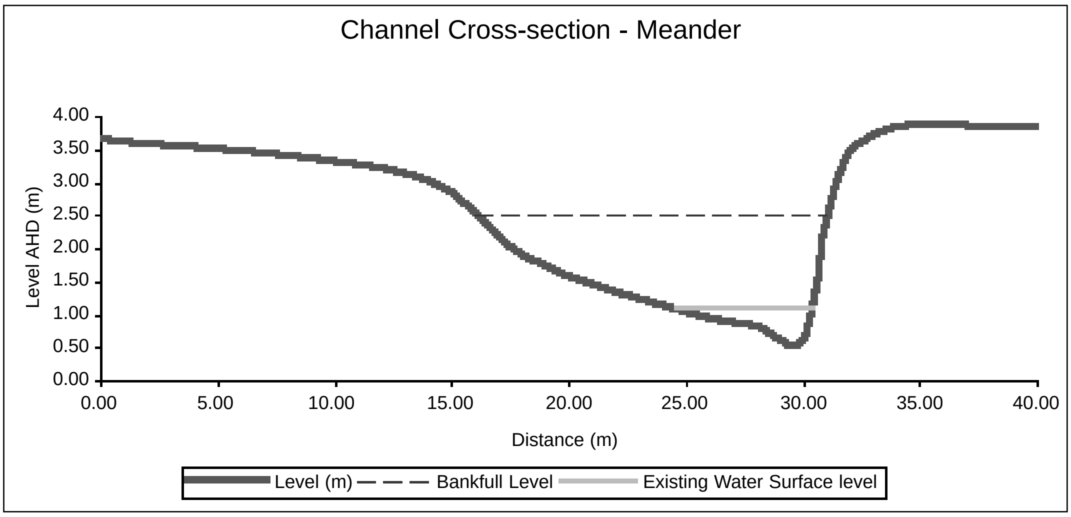


Figure 4.2: Plotted Cross-sections.

4.3 Wetted perimeter

Wetted perimeter is that part of the bed cross-section which is in contact with the flow, hence is wet, and is measured as that part of the flow cross section in contact with the channel bed. We need this to estimate hydraulic radius (see below), which in turn is needed to calculate flow velocity, which in turn is needed to predict discharge (Section 5).

Exercise: Once again using a piece of string, measure the wetted perimeter for all six bankfull cross sections and then average. Do this for the cross section for existing flow. Note again that you must use plots where vertical and horizontal scales are the same.

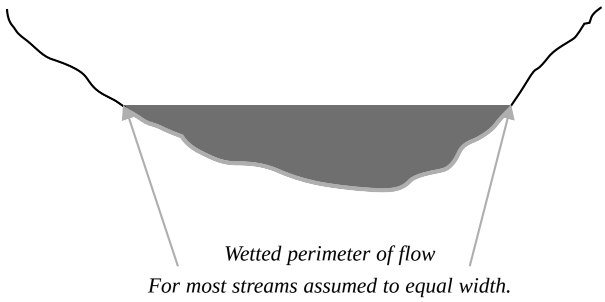


Figure 4.3: Wetted Perimeter of Flow

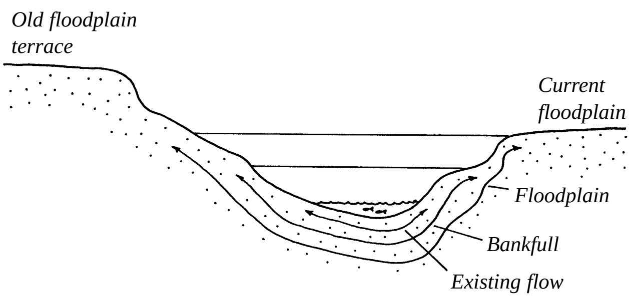


Figure 4.4: Wetted perimeter of existing flow, bankfull stage and larger (floodplain level) channel.

4.4 Channel roughness - Manning's 'n'

Slope and cross section are not the only two factors determining discharge. The roughness of the channel is also important, because it determines the frictional effect of the channel in slowing the flow. The rougher the channel the greater the frictional effect.

The roughness effect can be described by a number, known as *Manning's ' n'*, after the person who worked out how to quantify the effect. There is no simple way to determine this number. Mannings 'n' values are obtained by empirical methods. For a particular channel section, measurements of discharge, cross sectional area and slope can be used to calculate an 'n' value. As with most channel parameters an average value is obtained from many sites with similar configurations.

We can obtain Manning's 'n' from standard tables (see Table 4.1) and call it the assumed Manning's 'n'.

Exercise: From the notes and sketch map of the reach use the standard table to obtain an estimate of Manning's 'n' for the entire reach up to bankfull level.

It is also useful to obtain an estimate for that section in which flow velocity of the existing flow was measured and also for the entire reach up to the top of the banks. Manning's 'n' may change with increasing flow (see Figure 4.5).

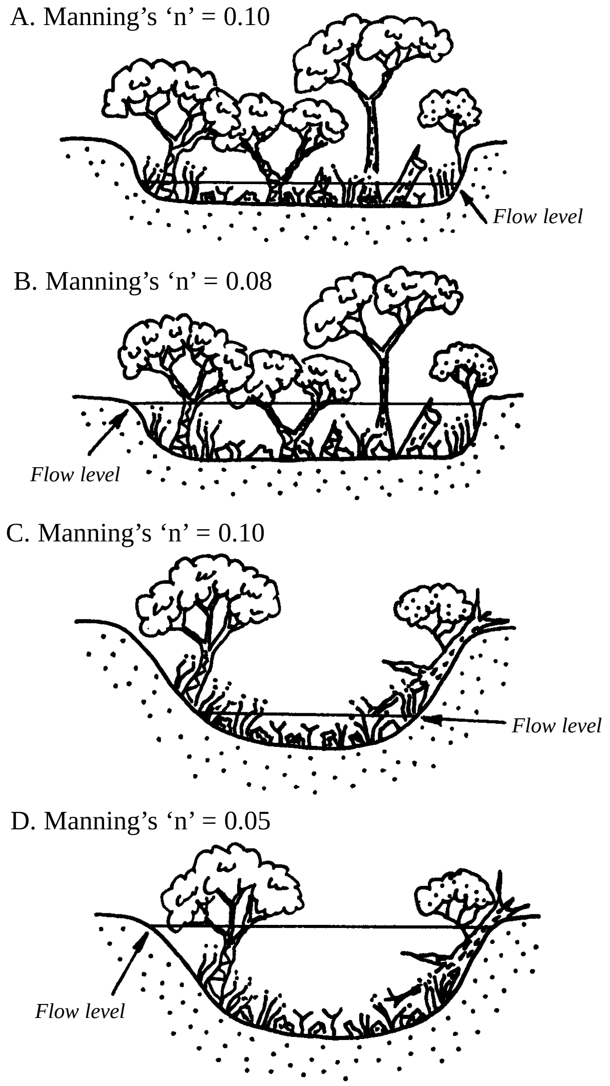


Figure 4.5: Changes in Manning's 'n' at different flow levels and different shaped channels.

Manning's 'n' and changing depth

Channel roughness in relation to flow generally decreases with increasing depth of flow. You can visualise low flows having to negotiate their way through and around the material of the bed, which protrudes into the majority of the depth of flow. Here Manning's 'n' assumes a high value. In contrast visualise a flood flow where the majority of the water column is well above the material of the bed. Here Manning's 'n' assumes a relatively low value.

For the situation in which bed material protrudes into less than a third of the depth of flow, which may occur during floods or virtually always for smooth bed streams, an equation does exist to enable an empirical estimate of Manning's 'n'. You can use your measurements of bed material (see Sections 3.5 and 4.6) in this equation which was derived by Strickler (1923).

$n = .04 \times d^{1/6}$ (where depth of flow is 3x median bed material)

Where: n = Manning's 'n'
d = median bed paving size (m)

Table 4.1: Range of values of the roughness coefficient 'n' for a selection of natural channels. (Extracted from "Open-Channel Hydraulics" by Ven Te Chow, Ph.D).

Type and Description of Channel	Minimum	Normal	Maximum
A. Minor Streams (top width at flood stage > 30m)			
(a) Streams on plains:			
(1) Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
(2) Same as above, but more stones and weeds	0.030	0.035	0.040
(3) Clean, winding, some pools and shoals	0.033	0.040	0.045
(4) Same as above, but some weeds and stones	0.035	0.045	0.050
(5) Same as above, lower stages, more ineffective slopes and sections.	0.040	0.048	0.055
(6) Same as 4, but more stones	0.045	0.050	0.060
(7) Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
(8) Very weedy reaches, deep pools or floodways and heavy stand of timber and underbrush	0.075	0.100	0.150
(b) Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages:			
(1) Bottom: gravels, cobbles, and few boulders.	0.030	0.040	0.050
(2) Bottom: Cobbles with large boulders	0.040	0.050	0.070
B. Flood Plains			
(a) Pasture, no brush:			
(1) Short Grass	0.025	0.030	0.035
(2) High Grass	0.030	0.035	0.050

Type and Description of Channel	Minimum	Normal	Maximum
(b) Cultivated areas:			
(1) No Crop	0.020	0.030	0.040
(2) Mature row crops	0.025	0.035	0.045
(3) Mature field crops	0.030	0.040	0.050
(c) Brush:			
(1) Scattered brush, heavy weeds	0.035	0.050	0.070
(2) Light brush and trees, in winter	0.035	0.050	0.060
(3) Light brush and trees, in summer	0.040	0.060	0.080
(4) Medium to dense brush, in winter	0.045	0.070	0.110
(5) Medium to dense brush, in summer	0.070	0.100	0.160
(d) Trees:			
(1) Dense willows, summer, straight	0.110	0.150	0.200
(2) Cleared lands with tree stumps, no sprouts	0.030	0.040	0.050
(3) Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
(4) Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
(5) Same as above, but with flood stage reaching branches	0.100	0.120	0.160

4.5 Hydraulic radius

Now having told you that slope determines velocity and together with cross sectional area determines discharge, in the ideal channel; and that in the absence of such a channel, roughness reduces velocity and hence reduces discharge, we need to consider two more factors, depth and shape of the cross section. Generally the deeper the water the faster it flows. In channels of the same shape, water will flow faster in the deeper ones, because less of the water is in contact with the bed. For this reason shape is also important. For example, shallow broad channels and very deep narrow channels (like a slot) place more water in contact with the bed, increasing the frictional effect. There is then an ideal cross section, not too narrow and too wide which places the least water in contact with the bed, ie least wetted perimeter[10]. This shape is roughly semi-circular. Note also that velocity of flow is not uniform in the cross section, and increases with increasing distance from the bed.

We express both the depth and shape factors in determining overall flow velocity by hydraulic radius (R). Put simply it is the cross sectional area (A), divided by the wetted perimeter (P).

$$R = A/P$$

Where R = hydraulic radius (m)
A = cross sectional area (m^2)
P = wetted perimeter (m)

Exercise: Calculate R for the average bankfull cross section.

Calculate R for the existing flow cross section and the larger channel cross section.

[10] Think of the ideal pipe cross section to minimise contact with the water (wetted perimeter). It is, not surprisingly, round.

4.6 Median bed paving

For stony bed streams the median size of the bed material is needed to compare with estimates of stream power and how this relates to the size of material the stream is able to mobilise in times of flood.

Exercise: Obtain the average dimension of each of the stones measured above (Section 3.5) and place these averages in order from the largest to the smallest stone. Take the middle ranked stone as your estimate of median bed paving.

Table 4.2: Bed paving measurements showing middle rank

X	Y	Z	$Ø_m$	rank	%freq.
50	50	35	**45**	3	**9**
15	10	10	**12**	19	**78**
35	20	20	**25**	9	**35**
18	15	8	**14**	16	**65**
15	10	15	**13**	17	**70**
45	20	25	**30**	6	**22**
24	11	8	**14**	15	**61**
60	70	130	**87**	1	**0**
75	55	35	**55**	2	**4**
25	35	40	**33**	4	**13**
20	20	12	**17**	12	**48**
5	8	10	**8**	21	**91**
10	20	20	**17**	13	**52**
5	10	10	**8**	21	**87**
20	25	35	**27**	8	**30**
5	10	15	**10**	20	**83**
30	25	15	**23**	10	**39**
20	15	10	**15**	14	**57**
4	7	10	**7**	23	**96**
7	4	8	**6**	24	**100**
15	15	9	**13**	18	**74**
20	35	40	**32**	5	**17**
20	20	25	**22**	11	**43**
40	25	20	**28**	7	**26**

4.7 Existing flow

The existing flow in the reach at the time of your survey is an expression of the slope, cross sectional shape of the channel up to the flow level (expressed as hydraulic radius) and channel roughness (Manning's 'n'). It is important to understand that these factors will be operating at a smaller scale than for higher flows, such as the bankfull flow.

Note also that, though you will estimate discharge at only one point along the reach, it will be the same at any other point. Flow velocity and cross sectional area may vary with changes in channel form, slope, roughness and bed material (mineral and vegetable), but net discharge will remain the same. This is why we need only take measurements for existing flow at one point. But to estimate bankfull flow in the absence of actual flow at this level needs an average of conditions. This is why we take six cross-sections.

Exercise: Multiply the measured cross sectional area (A) of the channel at the existing flow level by the measured velocity (v) to obtain the existing discharge (Q).

$$Q = A \times v$$

Where: Q = discharge (m^3/s)
A = area of cross section (m^2)
v = velocity (m/s)

5. Predicting and comparing flow velocity and discharge

Now that all the channel measurements have been made we are in a position to estimate or predict the average velocity of flow (m/s), the flow or discharge (m^3/s) and the average stream power of the reach.

Although the discharge remains constant, it is important to understand that the velocity of flow and stream power are not uniform along the reach nor at any particular cross section. As we have seen velocity is determined by depth and channel shape (the shape of the cross section). Channel roughness also varies constantly. The equations that we will use to calculate the above parameters provide average figures and come from the discipline of *fluid mechanics*. Here engineers seek to understand the motion of fluid as an average of what is happening overall. For example, there are simple equations to determine the flow of water in a pipe, which will be given as cubic metres per second, but we know that the flow will be fastest at the centre of the pipe and least right up against the edge of the pipe. Even the smoothest of pipes, like channels, will impose some resistance to flow. In other words they have their Manning's 'n' also. These equations express empirical relationships between the channel and the motion of water as observed in the laboratory and the field.

We will be using the simplest of equations to estimate flow characteristics in our channel. More complicated equations exist that give better estimates, but they require a more accurate understanding of channel characteristics and more accurate measurements. We will compare our simple estimates with actual measurements to demonstrate that simple estimates are much better than educated guesses.

5.1 Predicting flow velocity

The velocity of flow is determined by slope (S) in relation to the depth and cross section shape, combined as hydraulic radius (R), and channel roughness, Manning's 'n' (n). The relationship of these parameters is expressed mathematically as:

$v = (R^{2/3} \times S^{1/2})/n$

Where: v = velocity of flow (m/s)

R = hydraulic radius of flow (m)

S = channel slope (as a ratio, eg 0.001)

n = Manning's n (no units)

Note that this equation has no time parameter on the right side of the equals sign! Where then does the 'per second' come from? The simple answer is that the equation expresses an observed empirical relationship between the channel and the motion of water within it, and is not a deterministic expression of the forces at work to produce that flow. In fact time is embedded within the 'n' value.

Exercise: Using your measurements of average hydraulic radius, slope and Manning's n of the bankfull channel, calculate the bankfull velocity. The result is called the *predicted bankfull velocity*.

Do the same using the measurements of the existing flow cross section and for the larger channel cross section.

5.2 Predicting discharge

As before discharge (Q) can be calculated using the following equation:

$$Q = A \times v$$

Where: Q = discharge (m^3/s)

A = area of cross section (m^2)

v = predicted velocity (m/s)

Exercise: Using your measurements of average bankfull cross section and predicted velocity calculate the bankfull discharge. The result is called the *predicted bankfull discharge*.

Do the same for the existing flow cross section and for the larger channel.

5.3 Comparing predicted discharge with actual measurements

The predicted bankfull discharge can be compared with the 60-70% exceedence flood determined from the annual peak flow (flood) record (see Section 2.4). The predicted existing flow level discharge can be compared with your actual measurement of existing discharge. These comparisons will give you an idea of how well you have assessed and measured the channel. Expect differences in the predicted and actual discharge if you are not confident of your slope measurements or assessment of Manning's 'n'; or if the flood record is brief or no longer a good reflection of the catchment, because of clearing and development (Section 2.4). Also, in the case of bankfull discharge your recognition of bankfull level may be inaccurate, which is mostly a problem for highly eroded channels and where flooding has changed due to changes in the catchment.

Where predicted and actual measurements comply, more or less, you can be confident that you understand the channel and can begin planning rehabilitation works that are consistent with channel form and reinforced by channel forming flows.

6. Predicting stream power

Managing a stream ecosystem involves an understanding of the energy of moving water and the forces it exerts within and upon the channel. The capacity of moving water to erode the channel bed and to move objects within the channel is expressed as *tractive force*. It can be understood as a moving, pressing down force upon the channel bed (also known as *shear stress*), similar to the force of truck wheels upon the road surface or train wheels on the railroad tracks. Just as trucks and trains can transport material, so can a stream of water. We need to know how powerful our stream is, and convert this power to a maximum size particle that can be moved. We would then choose particles larger than this size for any relatively permanent restorative works, such as rock riffles.

6.1 Estimating tractive force

Tractive force (t) as a measure of stream power can be obtained empirically using the following relationship:

$$t = 1000 \times d \times s$$

Where: t = tractive force (kg/m^2)

d = depth of flow (m)

s = slope of water surface

Note that this equation gives tractive force for the particular depth of flow you are interested in. Depth of flow will vary along the reach longitudinally and across the cross section laterally. Note also that the slope is for the slope of the water surface, not the bed.

Exercise: Use the above relationship to estimate tractive force for the average bankfull depth. Compare this with the tractive force for the existing flow and for the larger channel by substituting the deepest point of the existing and larger cross section, respectively.

6.2 Tractive force vs bed paving

For the construction of canals and the repair of rivers, much work has been done to relate tractive force to bed paving material. Charts have been produced to enable the sizing of bed material in relation to tractive force (see Lane, 1955; Magalhaes and Chau 1983). This is the size material that you would use in restoration works as it would be resistant to mobilisation by typical bankfull flows.

Exercise: Use the chart provided to determine the appropriate bed material size for restorative works in your reach. Use your estimate of bankfull tractive force.

Do the same, but this time use your estimate of tractive force exerted by the larger channel when completely flooded.

Compare the bed material of your reach, and especially median bed material size (if you have it), with the size of material suggested by the charts.

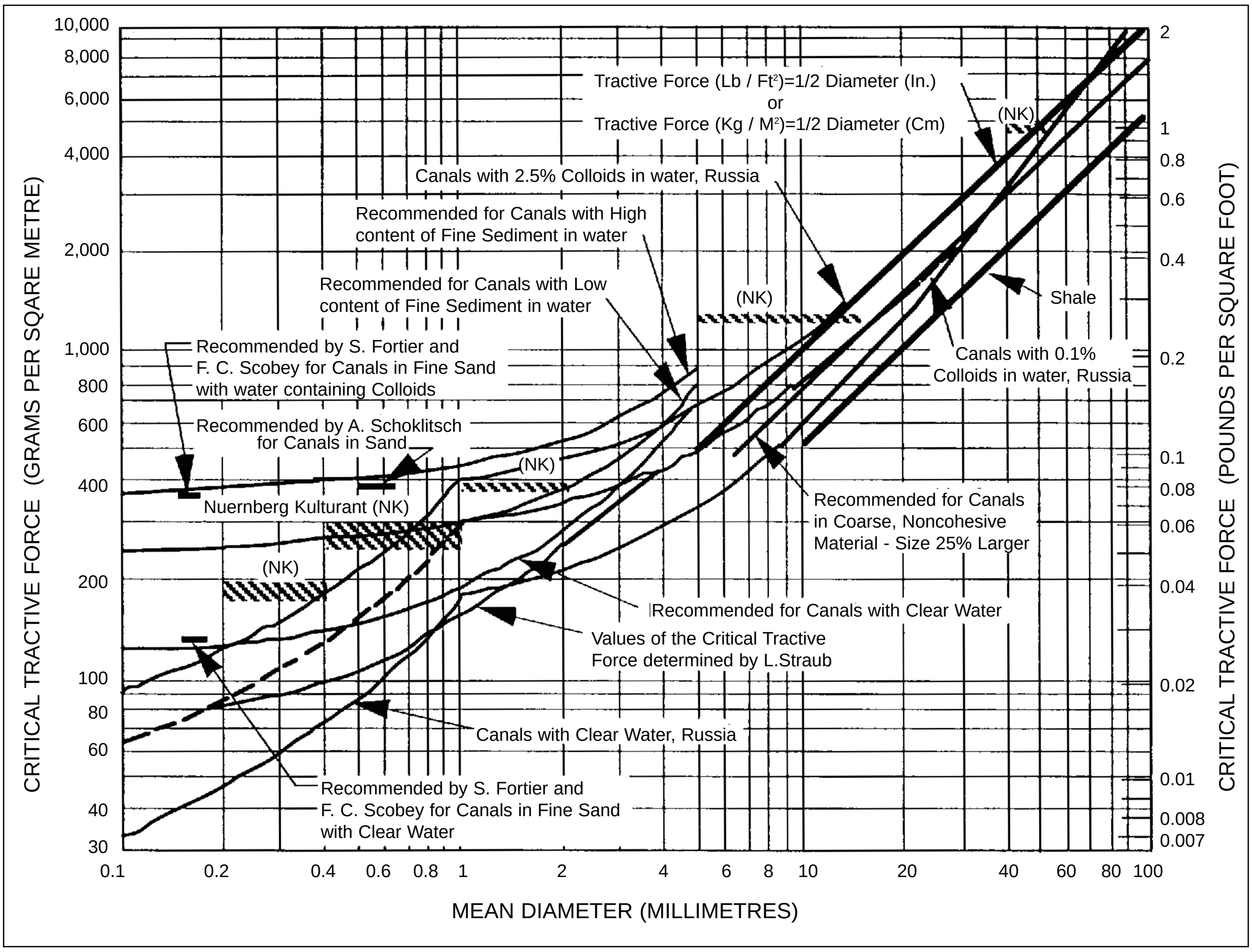


Figure 6.1:Relationships between tractive forces on the streambed and size of bed material that will erode (Lane, 1955, Magalhaes and Chau, 1983)

7. Understanding critical flow

The concept of critical flow is not an easy one to impart, but some understanding of it is necessary to understand the full range of flow conditions that may exist in a reach. We start by understanding that water has appreciable internal cohesion. As water accelerates, that is it moves away from water flowing more slowly behind it, it does not initially separate, but rather stretches, as the forces of cohesion, including gravity and viscosity, are being overcome by the increasing movement of the water (see Figure 7.1). This can be seen as water passes over a weir or approaches a constriction in the channel (eg a flume). The water falling over the crest of the weir is accelerating and indeed may break up, but as it does so its store of kinetic energy increases until it is released in a chaotic explosion of activity. This increase in kinetic energy can be seen by a noticeable dip in the water surface just upstream of the crest of the weir. Prior to this dip the velocity of water is said to be sub-critical; at the dip it is critical and below the dip, it is super-critical[11].

Stream flow cannot go on accelerating in the natural river environment. At some stage their needs to be a resolution of super-critical flow, as deceleration occurs and the water assumes the same velocity as the water in front of it (sub-critical velocity). It does so by means of a *hydraulic jump*, where the super-critical flow, on reaching the slow moving water at the base of the weir, riffle, set of rapids, or individual rock or log, is swept upwards and falls back on itself, like a crashing wave, but falling in the upstream direction (Figure 7.1). Here the water decelerates and returns to its subcritical state, to join the slower, placid, steadily moving downstream flow, unless of course there is yet another fall to be negotiated. Over the course of the hydraulic jump undissipated kinetic energy is explosively converted into turbulence and potential energy (see RR6) which lifts the water level after the jump (Figure 7.1).

Whether a section of channel will yield a change in (critical) flow, from sub-critical to super-critical, can be assessed by calculating the Froude number. This is done using the following equation:

$$F = v/(g \text{ x } d)^{1/2}$$

Where F = Froude number of flow

v = velocity of flow (m/s)

g = gravitational acceleration (9.8 m/s)

d = depth of flow (m)

Essentially the Froude number compares the velocity of flow with what is called the critical velocity for the reach - the point at which water appears to stretch out. A value of one is the point of critical velocity, which itself is simply the square root of the product of acceleration due to gravity multiplied by the depth of the reach ($(g \text{ x } d)^{1/2}$). Depth and gravity are the key factors in determining critical flow.

Where the Froude number is less than 1 the water flow has no opportunity to accelerate beyond the critical velocity. It is hindered by the bulk of water immediately downstream. The flow is considered sub-critical. Turbulence can and does exist but local velocities are not sufficient to overcome the internal viscous character of the water. At a Froude number greater than 1 the water flow has been able to accelerate (over a hydraulic drop) and has now exceeded the critical velocity ($(g \text{ x } d)^{1/2}$). Its energy state is unstable and its flow is considered super-critical. The sudden enforcement of sub-critical conditions on this flow as it re-encounters the inertia of the water downstream, results in a release of internal kinetic energy, some of which overcomes the cohesive forces holding the water molecules together foaming the water and tossing it about as can be seen in rapids[12].

Exercise: Calculate the Froude number of the bankfull flow in the subject reach. It should be less than one.

[11] The'dip' or stretching out effect is also evident in water flowing slowly from a tap in the way the stream becomes thinner before it breaks-up into droplets.

[12] Turbulence is not specifically an effect of gravity. Imagine water being pumped along a pipe in outer space. It will have turbulence due to impartations from the pump, its internal viscosity and due to the roughness of the pipe walls. If it then emerges into a broad unrestricted space. What will happen? The confines of the pipe, like gravity holding water in a channel, are gone and the internal velocities overcome the molecular cohesive forces. The result is that the water will go sailing off as globules. In other words the stream channel is the bottom half of the pipe and gravity effectively creates the top half. In so doing it produces an internal pressure or head (the pump), a factor in the energy store that relates to depth.

The significance of super critical flow

Super critical flow conditions have both ecological and hydrological implications of great significance to stream management.

For the stream ecosystem the hydraulic jump is a very significant component. Firstly it entrains air into the water column, oxygenating the stream ecosystem. Secondly, it provides a 'launch pad' for fish seeking to leap obstructions in their efforts to move upstream. For jumps that have a chute form, water may also swirl upstream either side of the fall of water, again assisting aquatic organisms to move upstream. Thirdly, the hydraulic jump is the only time that the pure movement of water makes sound (the babbling of brooks and the roaring of rapids), through the bursting of bubbles, as the entrained air rises to the surface. And fourthly, the super-critical flow conditions are primary habitat for certain aquatic organisms.

For modified or human-made channels supercritical flow has advantages and disadvantages. It is not uncommon for engineers to create channels with sufficient depth, smoothness and slope to create super critical flow; in order to move water faster through a small narrow channel, and thus free-up land for development or reduce the amount of land that needs to be purchased. Such channels however are inherently dangerous and must be fenced-off. They must also be made of concrete or stone to prevent erosion from the powerful flows.

Super critical flow, with its high velocity and turbulent motion, often with standing waves and occurring on a slippery surface, presents a considerable hazard to people and other terrestrial fauna. Water, only a foot or two deep, but moving at a super critical velocity can sweep a person or animal downstream and hold them under water, as canoeists well know.

The creation of super critical flow is not always intended. Channel modifications that result in a shorter than natural channel, such as meander cut-offs or channel straightening, can create a channel of very steep slope sufficient to cause super critical flow. The effect is enhanced when the new channel is made particularly smooth by desnagging or vegetation clearance. Needless to say, should the channel be formed in non-cohesive material, serious erosion will result.

An interesting way of observing super-critical flow is by throwing a stone into flowing water and observing the ripples. If the ripples move upstream from the point of emanation then the flow is sub-critical, but if the ripples are swept downstream, then the flow is super-critical. Even better compare the rippling effect of objects projecting above the water at points upstream and downstream of critical flow. No ripples will travel upstream of the latter (Figure 7.2).

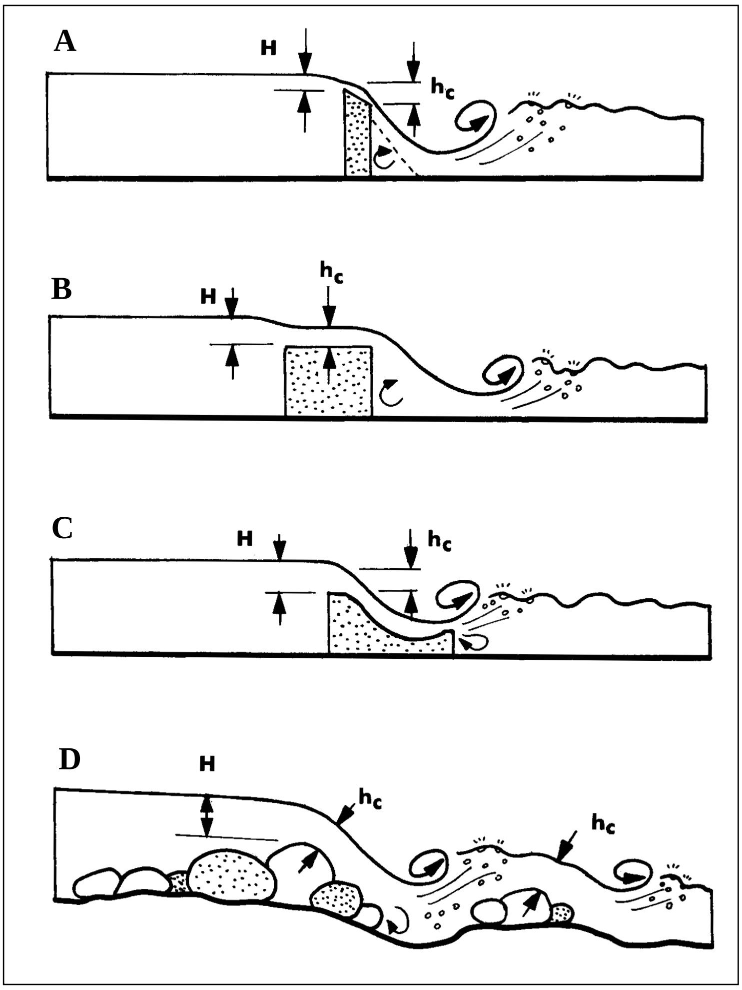


Figure 7.1: Demonstrating flow conditions above and below critical flow, for (A) sharp-crested weir, (B) broad crested weir, (C) Ogee spillway and (D) natural rocky riffle. It is the head or depth above the obstruction (at sub-critical flow); hc is the critical depth, being equal to 2/3H (point of critical flow just above the fall where super-critical flow occurs). Sub-critical flow returns at a below the hydraulic jump.

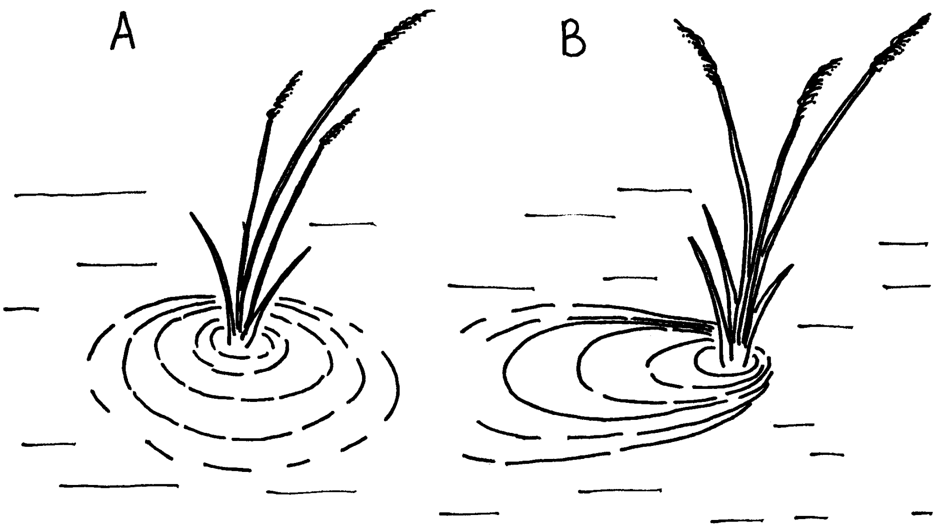


Figure 7.2: Rippling effect on flowing water with respect to sub-critical flow (A) and super critical flows (B).

8. References

Gregory, K. J. Gurnell, A. M. Hill, C. T. and Tooth, S. (1994), *Stability of the pool-riffle sequence in changing river channels*. Regulated Rivers: Research and Management 9: 35-43.

Lane, E. W. (1955), *Design of stable channels*. American Society of Civil Engineers Transactions 120: 1234-1279.

Leopold, L. B. Wolman, M. G. and Miller, J. P. (1964), *Fluvial Processes in Geomorphology*. W. H. Freeman & Co., San Francisco.

Magalhaes, L. and Chau, T. S. (1983), *Initiation of motion condition for shale sediments*. Canadian Journal of Civil Engineering 10: 549-554.

Newbury, R. W. and Gaboury, M. N. (1993), *Stream Analysis and Fish Habitat Design, A Field Manual*. Newbury Hydraulics Ltd, Manitoba Habitat Heritage Corporation and Manitoba Fisheries Branch.

Schofield, N. J. (1990), *Water Interactions with Land Use and Climate in South-west Australia*. Western Australian Water Authority Report No. 60.

Strickler, A. (1923), *Some contributions to the problem of velocity formula and roughness factors for rivers, canals and closed conduit*. Mitteilungen des eidgenossischen Amies fur Wasserwirtschaft, Bern, Switzerland. No. 16.

9. Appendix 1

Appendix 1: The principles of conducting a level survey using a dumpy level.

The basic principle of the level survey is to determine the height of a point or a number of points using a point of known height. All that is needed is a clear view from the telescope of the dumpy level to the various points along a line to which the staff can be read. The most difficult aspects of conducting a level survey are 'leveling' the level and reading the staff.

The staff is placed on the point of known height and viewed from the dumpy level. A reading is taken where the central horizontal cross hair passes across the face of the staff (see Figure A). The actual level of the telescope is unimportant and only placed with respect to the comfort of the person who is to read the staff through the telescope of the dumpy level. Once levelled, care must be taken not to accidentally 'unlevel' the dumpy, by for example leaning against it.

The dumpy level scribes out a circular plain of equal level in all directions. If I read 0.98 m on the staff sitting on a firm point of know height, say 100 m above sea level, I know I am reading a level 100.98 metres. It I then view the staff at a different point and it reads 2.15 m, I know that I am reading at a higher level on the staff, which means that the staff must be placed at a lower position than the point of known height? Because the staff has gone down, I am reading it higher up on its length. The difference between the two points will be 0.98 - 2.15 m or -1.17 m. In other words a **fall** of 1.17 metres. The actual level is then 100 - 1.17 m or 98.83 m. This is called a **reduced level** (see Table A).

In a level survey readings are taken at various points along a line. The distances between the points are measured (ie using a tape measure).

The first reading of the survey is taken from the point of known height, and is called the **backsight**. The last reading is taken at a point known as the **foresight.** Points surveyed between these two are called **intermediates** (see Figure B). If the survey is to continue (eg on down the river) the dumpy level is moved to a new point where it can see the previous foresight position and all the new points to be surveyed.

At this new position of the dumpy level the previous foresight is at a point of known height, since we just measured it, and as a result we call it the backsight for this new position of the dumpy level. A point at which a foresight and a backsight are read is known as a **change point**.

Back to the survey. Having read the first 'intermediate' as 2.15 m, we then read the second as 1.80 m. As we are now reading lower on the staff the ground must have risen. By how much? The answer is 2.15-1.80 m or + 0.35 m. Thus I have a rise of 0.35 m. Added to the previous reduced level this gives me a reduced level of the second intermediate point of 98.83 + 0.35 or 99.18 m. The survey continues in this way, adding rises and subtracting falls from the previous reduced level, until we come to the last position at which the staff can be read accurately. The reading is taken at this foresight and while the staff stays put the level moves to its new position and we begin over. At each point along the way notes should be taken (see Table A).

Backsight and foresight points are the most important points and the most care should be taken to do the readings correctly. For this reason backsight and foresight points should be located on a solid object on which to place the staff. This is so the staff can be safely swivelled around to enable an accurate reading from the dumpy level placed in a new position. The solid point may be a peg placed in the ground, the pinnacle of a rock, tip of a log or root, corner of a concrete block, a nail hammered into bitumen, etc. It is not necessary for the back and foresight positions to be part of the actual survey (ie within the stream channel). Note that if backsight points are incorrectly read all the intermediate points will be in error also.

In a proper survey the first backsight position is a standard height datum, accurately surveyed in by the Department of Land Administration (DOLA). These are located about the landscape and are numbered. DOLA can be contacted to obtain the height above mean sea level for a datum that has been found nearby and they can also provide the location and heights nearest the survey area.

For a survey at which the relative levels only are needed an ‘assumed height’, say 100 m, can be used for the first backsight. If the true heights are needed at a later stage the original backsight can be surveyed in, providing that it is well defined and can be found at a later date.

An example of a level survey is provided in Table A. To check the accuracy of a channel survey, the survey should be ‘closed’. This means that having reached the last point to be surveyed, the survey team then works its way back to the original backsight position, to actually determine the height of the position coming from a different direction. This can be done by taking the quickest route back to the original backsight (ie across the paddock rather than back along the channel). Since the survey in closing has moved up and/or down by equal amounts the rises and falls should give equal totals. That is the total of the falls equals the total of the rises. An accurate survey should have an error of no more than 10 mm vertical for every 1000 m horizontal distance surveyed.

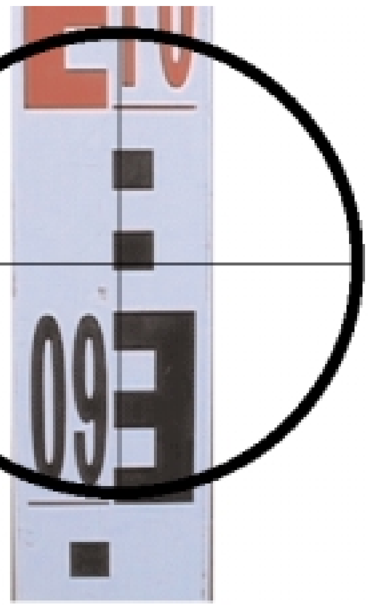


Figure A: Survey Staff Viewed through Dumpy Level. It reads 0.962 metres.

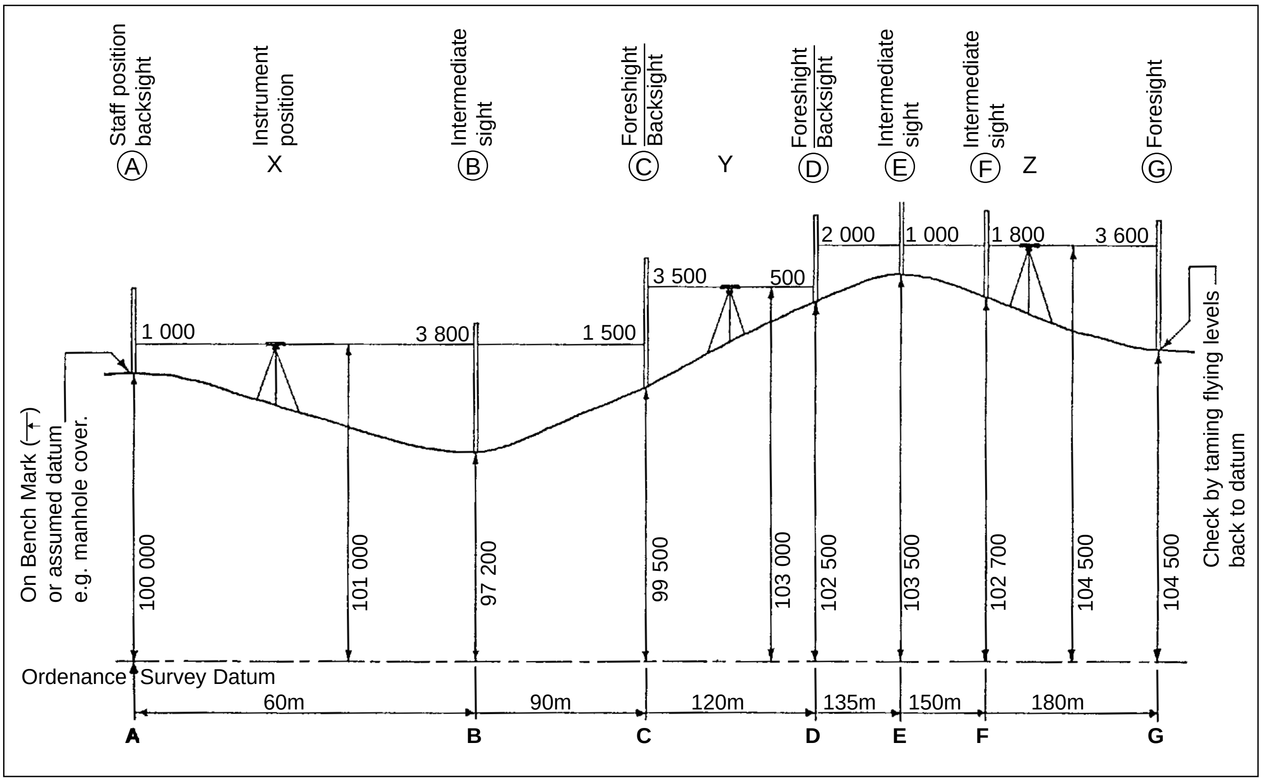


Figure B: Levelling Survey showing movements of Dumpy Level.

Table A: Survey field book calculation exercise.

Back Sight	Inter-mediate	Fore Sight	Rise	Fall	Reduced Level	Distance	Remarks
0.98					100.00		Temporary Bench Mark
	2.15			1.17	98.83	0	River invert - centre of channel
	1.80		0.35		99.18	0	Water surface (x sect 1)
	1.19		0.61		99.79	0	Observed Bankfull level - left bank
	1.97			0.78	99.01	42	Invert - top of riffle (x sect 2)
	1.76		0.21		99.22	42	Water surface
	1.14		0.62		99.84	42	Observed Bankfull level - left bank
1.77		1.04	0.10		99.94	50	Change Point - Rock on right bank
	2.88			1.11	98.83	73	Invert in pool (x sect 3)
	2.46		0.42		99.25	73	Water surface
	1.84		0.62		99.87	73	Observed Bankfull level - left bank
	2.76			0.92	98.95	105	Invert (x sect 4)
	2.42		0.34		99.29	105	Water surface
1.90		1.80	0.62		99.91	105	Change Point - Bankfull level - left bank
	2.73			0.83	99.08	150	Invert (x sect 5)
	2.48		0.25		99.33	150	Water surface
	1.95		0.53		99.86	150	Bankfull level - left bank
1.58		1.74	0.21		100.07		Change Point - Protruding tree root
		1.65		0.07	100.00		Temporary Bench Mark
6.23		**6.23**	**4.88**	**4.88**			

Rises and Falls are calculated by subtracting the reading for a point from the previous reading.

If the result is negative it is recorded in the Fall column. Increasing staff reading indicates a fall.

If the result is positive it is recorded in the Rise column. Decreasing staff reading indicates a rise.

Once all Rises and Falls are calculated check the arithmetic by adding the total of both columns. Both columns should be equal.

Reduced Levels are calculated by subtracting falls and adding rises sequentially commencing from the assumed datum of the temporary bench mark..

The calculated reduced level of the TBM at the last reading should be the same as the first reading.

If not there has been an arithmetic error in filling in this column.