Development of a National River Classification System

Final Report

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Environment Australia, and the
Land and Water Resources Research &
Development Corporation**

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Executive Summary

The Environmental Flows Decision Support Program, a partnership between the Murray Darling Basin Commission and the National River Health Program (established by Environment Australia and the Land & Water Resources Research & Development Corporation), was established to develop a range of science-based products to help predict the likely effects of a wide range of actions and policies on Australian riverine environments. The Environmental Flows Decision Support Program includes the development of a computer based decision support system, an ecology-flows handbook, an environmental floodplain mapping methodology, and a national physically-based system of river classification.

PPK Environment & Infrastructure, in association with Dr Wayne Erskine and Mr Bob Junor, were commissioned by the Murray-Darling Basin Commission and Environment Australia to develop a National River Classification System.

The specific objectives of the project were:

1. *to review and evaluate river classification methodologies and approaches relevant to flow, natural resource planning and management of riverine environments;*
2. *to develop a practical, management-orientated, hierarchical framework for the classification of Australian rivers and their associated riverine environments to:*
    - *assist environmental flow allocation and management; and*
    - *facilitate the development and application of the Environmental Flows Decision Support System and Ecology-Flows Handbook; and*
3. *to indicate how the framework relates to, and is comparable with, existing river classification systems in use within Australia.*

It is intended that the outcome of the project will facilitate the structuring of ecology-flow information on a channel-type basis so that managers can apply this information generically for similar river systems.

The approach taken to meet the project objectives involved the review of proposed and existing river classification methodologies in use in Australia and overseas, the convening of a workshop to discuss the outcomes of the review and identify the key characteristics and most appropriate methodologies for the classification system, and finally the development of a practical, management-orientated, hierarchical framework for the classification of Australian rivers.

A literature review of proposed and existing classification systems identified a wide range of methodologies and approaches relevant to river flows, natural resource planning and river management. These methodologies differ in their purpose and management application, framework, and classification criteria. These features of the key classification systems were identified and their potential for application to environmental flow allocation assessed as part of the project. The literature list of systems reviewed and the evaluation of key methodologies is provided in Appendix A.

There is no existing river classification scheme that is capable of being applied to, or that would accommodate, all Australian rivers. Rivers change greatly in character from their source to the ocean, or to a terminal lake or floodout. The diversity of Australian rivers is so great that any *regionally-based scheme will always experience shortcomings when applied to an area outside that for which it was developed. This is well recognised in the river classification literature (Kondolf and Downs, 1996). Many schemes have been developed which either only focus on rivers (Brierley, 1999) or lakes (Timms, 1992) or estuaries (Roy, 1984) or some aspect of the condition of a river, lake and/or estuary (Department of Land and Water Conservation's stressed rivers assessment reports; Brierley, 1999). There is no existing scheme that meaningfully attempts to cover all water bodies. This deficiency was one of the reasons that this project was commissioned.*

The key elements of a management-based National River Classification System were discussed at the project workshop convened on 20 July 1998. Based on the outcomes of the workshop, the role, framework and classification criteria were further developed by the project team.

There was general agreement at the workshop that the framework for river classification needs to be hierarchical. A hierarchical structure allows for consideration of rivers at national, regional, local and site specific scales. It was agreed also that the National River Classification System should be based on physical characteristics, specifically climate and geomorphology. It was proposed that the open-ended structure should be capable of being expanded to include biological characteristics at various levels in the hierarchy.

The adopted approach is an original nested hierarchical scheme based on the channel network, which, to varying degrees, draws on the earlier work of Kellerhals et al. (1976), Mosley (1982), Riley et al. (1984), Roy (1984), Frissell et al. (1986), Hawkins et al. (1993), Rosgen (1985; 1994; 1996a), Bisson and Montgomery (1996), Brierley et al. (1996), Thorne (1998), Erskine et al. (1999a), Webb and Erskine (2000) and Brierley (1999).

At the highest level of the classification, broad characteristics of catchments and sub-catchments are defined based on existing inventories of climate and landform at a scale of 1:1,000,000, and on the degree of flow regulation and water extraction. However, the catchment level was intended for use with biogeoclimatic regions (Frissell et al., 1986) that have not been defined for Australia as yet. These biogeoclimatic regions can be added at a later date when they have been developed to the stage where they can be implemented nationally.

During the project workshop it was agreed that the scale most relevant to water allocation and management of environmental flows is the reach. River reaches are homogeneous lengths of channel within which hydrological, geological, and adjacent catchment surface conditions are sufficiently constant that a uniform river morphology is produced (Kellerhals et al., 1976) or a consistent pattern of alternating river morphologies is produced (Erskine et al., 2001). The proposed classification system is intended for application to rivers from their headwaters to the ocean or to a terminal lake or floodout. As a result, it covers rivers, gullies, lakes, estuaries and artificial water bodies. No other scheme currently in use in Australia has attempted to cover whole river systems.

While classification at reach level is considered the appropriate scale for the primary purpose of the proposed classification system, the bedform/habitat scale is appropriate to river ecology and is included in the proposed system for completeness.

The proposed National River Classification System has been applied to the Snowy River below Jindabyne Dam (in Chapter 6) to demonstrate its use. The Snowy River example clearly demonstrates the suitability of the proposed classification system to regulated as well as national rivers. Trialing of the system on some rivers in other regions of Australia is recommended.

1. Background and Objectives

River regulation and the large scale abstraction of water has modified flow regimes and resulted in degradation of many Australian Rivers (Walker, 1985; Erskine, 1985; Erskine et al., 1999a; 1999b). In order to manage rivers sustainably, the demand for water from rivers for agriculture, industry, and human consumption must be balanced against in-stream water requirements for river health (Erskine et al., 1999a; 1999b). We need to understand the water volumes and flow regimes required to conserve biological diversity and maintain habitat and good water quality.

The Environmental Flows Decision Support Program, a partnership between the Murray Darling Basin Commission and the National River Health Program (established by Environment Australia and the Land & Water Resources Research & Development Corporation), was established to develop a range of science-based products to help predict the likely effects of a wide range of actions and policies on Australian riverine environments. The Environmental Flows Decision Support Program includes the development of a computer based decision support system, an ecology-flows handbook, an environmental floodplain mapping methodology, and a national physically-based system of river classification.

PPK Environment & Infrastructure in association with Dr Wayne Erskine and Mr Bob Junor were commissioned by the Murray-Darling Basin Commission and Environment Australia to develop a National River Classification System.

The specific objectives of the project were:

1. to review and evaluate river classification methodologies and approaches relevant to flow, natural resource planning and management of riverine environments;
2. to develop a practical, management-orientated, hierarchical framework for the classification of Australian rivers and their associated riverine environments to:
   - assist environmental flow allocation and management; and
   - facilitate the development of and application of the Environmental Flows Decision Support System and Ecology-Flows Handbook; and
3. to indicate how the framework relates to, and is comparable with, existing river classification systems in use within Australia.

The outcome of the project will facilitate the structuring of ecology-flow information on a channel-type basis so that managers can apply this information generically for similar river systems.

2. Approach

The approach taken to meet the project objectives involved the review of proposed and existing river classification methodologies in use in Australia and overseas, the convening of a workshop to discuss the outcomes of the review and identify the key characteristics and most appropriate methodologies for the classification system, and finally the development of a practical, management-orientated, hierarchical framework for the classification of Australian Rivers.

The review of proposed and existing river classification methodologies is discussed in *Section 3* and summarised in *Appendix A*. Each of the reviewed systems is summarised in relation to the following characteristics:

- framework (hierarchical similarity);
- use;
- classification basis;
- management application;
- potential for application to environmental flow allocation and management; and
- success as a management tool.

The workshop held on 20 July 1998 comprised geomorphologists, natural resource managers and river classification experts from Australia and New Zealand. The workshop agenda and list of participants is provided in *Appendix B*. The outcomes of the workshop in terms of identifying the key characteristics and most suitable methodologies for the classification system are discussed in *Section 4*.

The proposal National River Classification System is presented in *Section 5* and applied to the Snowy River in *Section 6*. A comparison of the proposed system with existing river classification systems in Australia is presented in *Section 7*.

3. Existing River Classification Methodologies

River classification is important for many research and management purposes and is used, to varying degrees, in catchment and river management, river rehabilitation, geomorphology, sedimentology, stream ecology, environmental flows and environmental planning. Various schemes have been proposed for particular disciplines and purposes. Schumm's (1963a; 1963b; 1968; 1981; 1985) pioneering work has been widely used by earth scientists. However, there is no universally accepted river classification scheme because any classification will require modification to suit rivers different to those used to derive the scheme (Kondolf and Downs, 1996; Bisson and Montgomery, 1996; Erskine and Webb, 1999). Therefore, classificatory schemes should be continuously revised and updated (Erskine and Webb, 1999; Webb and Erskine, 2000; Erskine et al., 2001).

A literature review of proposed and existing classification systems identified a wide range of methodologies and approaches relevant to river flows, natural resource planning and river management. These methodologies differ in their purpose and management application, framework, and classification criteria. These features of the key classification systems were identified and their potential for application to environmental flow allocation assessed as part of the project. The literature list of systems reviewed and evaluation of key methodologies is provided in *Appendix A*.

In a previous review of river classification, O'Keeffee et al. (1994), notes that while several river classification systems have been developed world wide, few of them are non-controversial and none are universally applicable (Kondolf and Downs, 1996; Bisson and Montgomery, 1996; Erskine and Webb, 1999).

Within Australia, a number of classification systems have been proposed or established for river morphology and aquatic ecology purposes. Our evaluation of these systems is also presented in *Appendix A*.

4. Key Elements of a National River Classification System

The key elements of a management-based National River Classification System were discussed at the project workshop convened on 20 July 1998. Based on the outcomes of this workshop, the role, framework and classification criteria were further developed by the project team. The result of this work is presented below.

4.1 Role and Application

A clear definition of the role of the proposed classification system, including who will use the system and for what purpose, needs to be established before the system can be developed. During the project workshop, a number of potential roles for a national river classification system were identified. The identified roles generally fell into one or more of the following categories:

- to facilitate research;
- to provide a basis for extrapolation of information;
- to assist in prioritisation for resource management;
- to provide a consistent reference for monitoring and reporting; or
- to facilitate community understanding.

These roles were identified in addition to the defined project role: to classify rivers and their associated floodplains nation-wide, specifically for the purpose of environmental flow allocation and management.

It is clear that one national river classification system cannot satisfy all potential users. The limitations of any classification system need to be recognised. Clearly, every river is different in some ways from another. However, a classification system that ends up with each river in an individual group will not be a useful management tool. The use of classification is not to identify all distinguishing features of a river but rather to establish their similarities.

O'Keeffee et al. (1994) proposes that classification is ultimately an exercise in data organisation, the creation of groups which can be an invaluable help in making judgements and decisions. Importantly, any predictions, extrapolations, judgements and decisions made on the basis of these groupings are supplementary extensions of the classification exercise, not part of it.

With this understanding, the project team determined that the primary role of the proposed National River Classification System is to aid the transfer and application of scientific information on rivers, particularly information relating to the allocation and management of environmental flows. The immediate users of the classification system are likely to be community-based river managers. In this role, the potential applications of the classification system include:

- to enable managers, scientists and the community to communicate river types in much the same way we talk about soil types and vegetation communities;
- to provide the ability to extrapolate from data-rich rivers to data-poor systems and thus assist managers to make decisions about water usage with relatively little background information; and
- to predict the effects of a proposed water allocation on one river by comparison with a similar river already under this management regime.

4.2 Framework

4.2.1 Hierarchy

During the project workshop there was general agreement that the framework for river classification needs to be hierarchical. A hierarchical structure allows for consideration of rivers at national, regional, local and site specific scales. The hierarchical framework proposed at the workshop is outlined in *Table 1*.

Table 1: Hierarchical Framework for a National River Classification System

Classification Level	Scale (River Length)*		Essential Features
	Small	Large	
Catchment	$>10\ m^3$	>1,000 km	Catchment/sub-catchment scale boundary conditions
Valley Segment	$>10\ m^2$	100 - 1,000 km	Length of valley with essentially constant form and external conditions
Reach Type	>10 m	10 - 100 km	Length of river exhibiting relatively homogeneous channel characteristics or a consistent pattern of repetitive/alternating characteristics
Habitat/Bedform	$>10^0 m$	0.1 - 10 km	Areas of relatively homogeneous bed material, flow velocity and depth
Micro Habitat	$10^{-1} m$	<0.1 km	Patch of similar flow velocity, substrate and cover

* Scale is indicative only, it must be appropriate to catchment size.

This river classification approach is an original nested hierarchical scheme based on the channel network, which, to varying degrees, draws on the earlier work of Kellerhals et al. (1976), Mosley (1982), Riley et al. (1984), Roy (1984), Frissell et al. (1986), Hawkins et al. (1993), Rosgen (1985; 1994; 1996a), Hart (1996), Bisson and Montgomery (1996), Brierley et al. (1996), Thorne (1998), Erskine et al. (1999a), Webb and Erskine (2000) and Brierley (1999). Frissell et al. (1986) clearly illustrate the relationship between these classification levels, each forming the environment of its sub-system at lower levels (*Figure 1*).

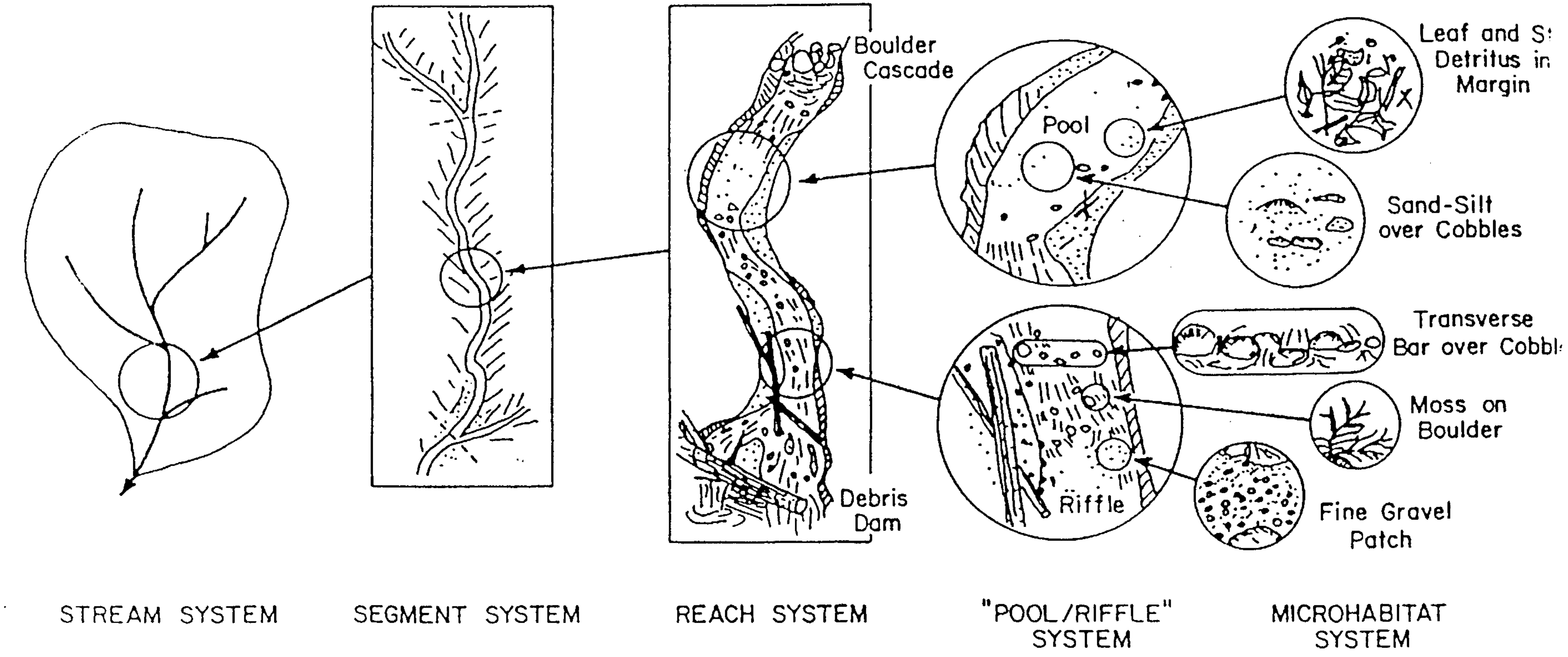


FIGURE 1: **Frissell et al. (1996) Hierarchy of a River System**

There are similarities between this hierarchy and the classification levels of Frissell et al. (1986) but there are some significant differences in the meaning of each level of the hierarchy. The smallest linear spatial scale has been taken from Frissell et al. (1986) who concentrated on small mountainous forested streams. The size of each level increases with catchment area and run-off.

The advantages of the hierarchical structure for classification include:

- it allows the manager to select the level of resolution in relation to the management objectives;
- it provides for integration of data from different scales and from a variety of sources; and
- it enables the classification system to be open-ended and capable of being expanded and periodically revised.

An important distinction is made between river characterisation and classification (Mosley, 1987). Reaches result from classification and may be used for characterisation (*top down approach*). That is, in the proposed framework, a reach is classified based on an understanding of its catchment, segment and reach features (*top down approach*). Characterisation can also be used as the basis for defining channel reaches (*bottom up approach*) (Bisson and Montgomery, 1996; Brierley, 1999). The proposed classification scheme is a top down approach because of the recommended data sources used to define channel reaches, the most useful scale for management.

4.2.2 Reaches

During the project workshop it was agreed that the scale most relevant to water allocation and management of environmental flows is the reach. River reaches are homogeneous lengths of channel within which hydrological, geological, and adjacent catchment surface conditions are sufficiently constant that a uniform river morphology is produced (Kellerhals et al., 1976) or a consistent pattern of alternating river morphologies is produced (Erskine et al., 2001). This scheme is intended for application to rivers from their headwaters to the ocean or to a terminal lake or floodout. As a result, it covers rivers, gullies, lakes, estuaries and artificial water bodies. No other scheme currently in use in Australia has attempted to cover whole river systems.

4.3 Classifying Criteria

During the project workshop it was agreed that the National River Classification System should be based on physical characteristics, specifically climate and geomorphology. It was also proposed that the open-ended structure should be capable of being expanded to include biological characteristics at various levels in the hierarchy.

The classification systems in the literature (*Appendix A*) identify many physical criteria which could be used for river classification. These include:

- Catchment Characteristics:
    - catchment lithology;
    - slope;
    - catchment relief;
    - catchment area;
    - floodplain area;
    - soil moisture storage;
    - soil erodibility and stability;
    - solar radiation; and
    - terrestrial litter;
- Section Morphology:
    - erosion;
    - transport and deposition;
    - flow velocity - annual, monthly, peak and low flow;
    - must be done over short distances;
    - bed material;
    - bed-form pattern;
    - roughness of bed section;
    - sediment storage capabilities;
    - pool spacing;
    - suspended sediment characteristics;
    - channel morphology – sinuosity, braiding;
    - width/depth ratios;
    - gradient of channel;
    - flood peaks;
    - organic debris; and
    - flow regime;
- Water Chemistry:
    - electrical conductivity;
    - dissolved oxygen concentration;
    - pH;
    - inorganic ions;
    - nitrate;
    - sulfide;
    - turbidity;
    - temperature;

  - salinity; and
  - phosphate; and
- Ecological:
  - channel vegetation;
  - riparian vegetation;
  - ratio of photosynthesis to respiration;
  - populations;
  - diversity; and
  - other indicators.

In selecting criteria for classification, the most important consideration is the end use (role and application) of the system. Other features of preferred criteria include:

- low cost and ease of data collection;
- high level of understanding among classification system users;
- uniformity in interpretation among users; and
- key determinants of the behaviour of the river.

According to O'Keeffee et al. (1994), classifications should as far as possible use criteria that do not reflect human modifications to the river system. This is problematic as few Australia rivers are not modified in some way, and in many systems, degradation is now a key factor determining aquatic ecology. Therefore, in the hierarchical system, it is proposed that such modifications could be included at the finer levels of the classification. Mixing the two types of data at higher levels of the classification could result in arbitrary groupings that do not reflect natural affinities or levels of degradation.

Classification of rivers based on natural criteria enables the manager to identify similar river reaches at different levels of degradation. We can then predict the effects of an impoundment or change in river flow on a relatively pristine river by observing the effects on another river, which has already been dammed or subjected to an altered flow regime.

The classification scheme proposed in the following section uses geomorphic criteria for reach identification for the following reasons. Firstly, geomorphic criteria can be collected and applied at scales of 1:250,000 to 1:4,000 from topographic maps, orthophoto maps, vertical air photographs, air photograph mosaics and geology, soil, vegetation and land systems maps. These sources of information are available for either all or many parts of Australia. Secondly, geomorphology forms the physical template or habitat for ecological communities. The presence or absence of species or communities is usually interpreted from the type of habitat. Therefore, habitat should be considered directly. Thirdly, sections of river exhibiting similar morphology are subject to similar biophysical processes that can be altered to varying degrees by many human activities, such as flow regulation, land use, extraction and mining, channelisation and inter-basin water transfers. Similar changes to fluvial processes should induce similar river responses within the same channel reach. Abiotic factors such as physical form are also being increasingly recognised as the key targets for river restoration rather than biotic factors (Brookes and Shields, 1996). Fourthly, field data cannot be used as the basis of a national classification scheme because of the cost and time involved in collecting the base data. Topographic maps, vertical air photographs, aerial reconnaissance and selective field checking are the most efficient data sources for a national river classification scheme.

5. Proposed National River Classification System

A proposed National River Classification System is developed in this section based on the role and key elements identified in the previous chapter.

The framework of the National River Classification System is illustrated in *Table 2*, and each level of the hierarchy is discussed in detail below.

Table 2: Appropriate Geomorphic Criteria for the Identification of Channel Reaches on Australian Rivers

Geomorphic Criterion	Suggested Method of Measurement
1. Channel Pattern	▪ Sinuosity* (Schumm, 1963b; Rosgen, 1994) ▪ Number, size and character of channels* (Schumm, 1981; 1985) ▪ Visual comparison with standard patterns (Mollard, 1973; Kellerhals et al., 1976; Mosley, 1982; Thorne, 1998) ▪ Meander wavelength (Thorne, 1998) ▪ Meander belt width (Rosgen, 1994)
2. Slope	▪ Map determined bed slope* (Rosgen, 1994; Bisson and Montgomery, 1996) ▪ Field survey of water surface slope* (Rosgen, 1994; Bisson and Montgomery, 1996)
3. Cross Sectional Form and Geometry	▪ Width/depth ratio* (Schumm, 1963b; Rosgen, 1994) ▪ Bankfull and/or benchfull width* (Riley, 1972; Warner et al., 1975; Erskine and Livingstone, 1999) ▪ Hydraulic geometry (Rosgen, 1994) ▪ Spatial variations in channel width (Schumm, 1981)
4. Lateral Bedrock Confinement	▪ Ratio of valley floor width to channel width* (Bisson and Montgomery, 1996). Additional categories will be required. ▪ Channel pattern distortion (Lewin and Brindle, 1977)
5. Vertical Bedrock Confinement	▪ Entrenchment ratio* (Rosgen, 1994). Rosgen's (1994) values need checking for Australian rivers.
6. Channel Bars	▪ Kellerhals et al. (1976)*; Mosley, 1982; Thorne (1998)
7. Channel Islands	▪ Kellerhals et al. (1976)
8. Macrobedforms	▪ Brush et al. (1966)*, Keller and Melhorn (1978)* and Grant et al. (1990)*
9. Bed-material Size	▪ Sediment size scale (such as Wentworth) for mean/median size and/or for percentage of various sediment size fractions for particular bedforms*. ▪ Sedimentary structures for bed surface features, particularly armour and sub-armour layers.
10. Type of Floodplain, Sediments and Stream Power	▪ Nanson and Croke (1992)*

Geomorphic Criterion	Suggested Method of Measurement
11. Anabranches and Distributaries	▪ As for Channel Pattern and Cross Sectional Form and Geometry ▪ Character of channels (Schumm, 1981; 1985)
12. Lateral channel activity	▪ Kellerhals et al. (1976)*
13. Linkages in sediment movement within and between channel reaches	▪ Sediment source, transfer and/or storage zones (Pickup, 1988)*
14. Tidal influence	▪ Tidal range and type and persistence of salt stratification, salinity*
15. Estuarine Morphodynamics	▪ Estuarine landforms, sediments and processes (Roy, 1984; Woodroffe et al., 1989)*
16. Lake Formation	▪ Geomorphic processes of lake formation (Timms, 1992)*
17. Artificial Feature	▪ Features, functions and construction materials (Erskine, 1999a)*

* Recommended methods.

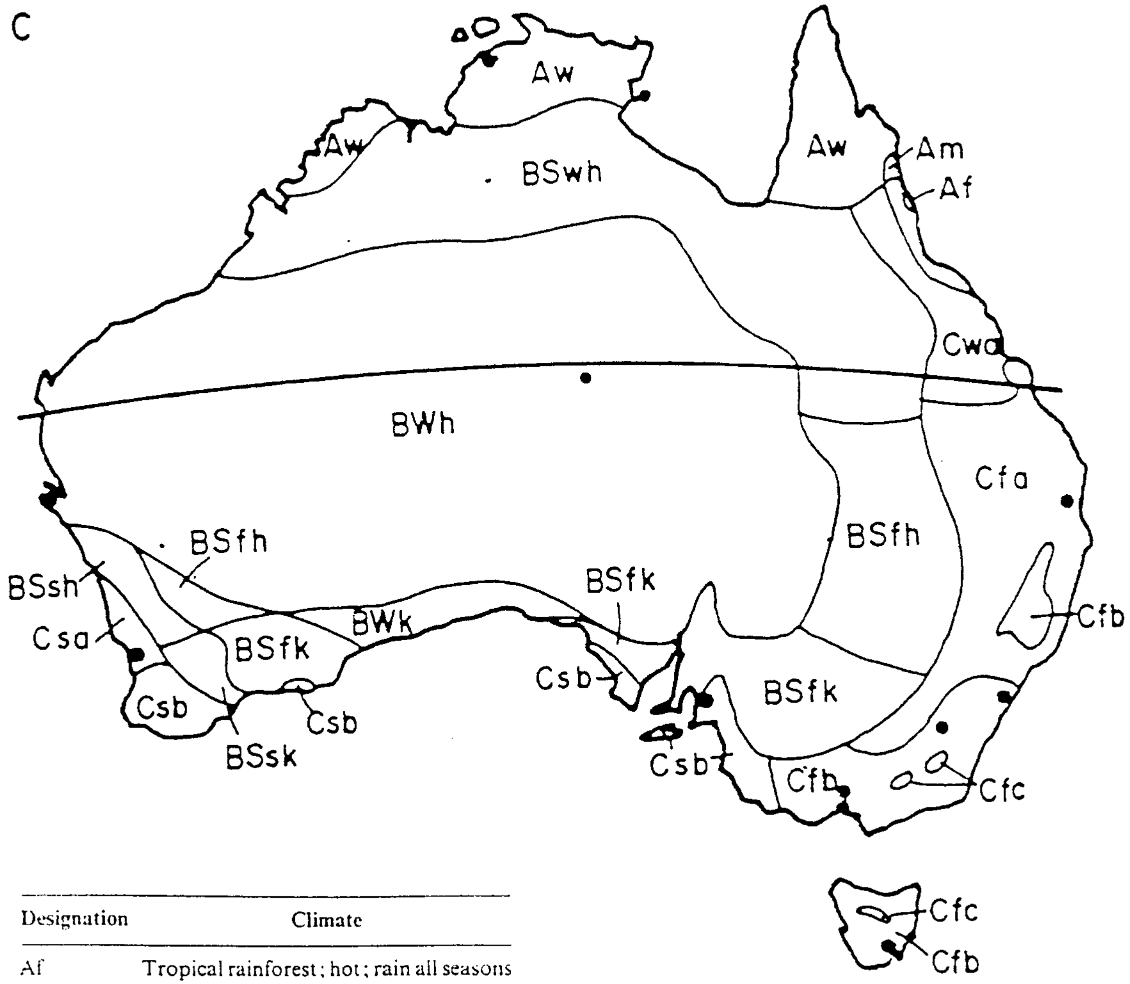
The application of the proposed classification system to the Snowy River downstream of Jindabyne Dam is illustrated in *Section* 6.

5.1 Catchment Definition

At the highest level of the classification, broad characteristics of catchments and sub-catchments are defined based on existing inventories of climate and landform at a scale of 1:1,000,000, and on the degree of flow regulation and water extraction. However, the catchment level was intended for use with biogeoclimatic regions (Frissell et al., 1986) that have not been defined for Australia as yet. These biogeoclimatic regions can be added at a later date when they have been developed to the stage where they can be implemented nationally.

5.1.1 Climatic Regions

The first criterion is based on climate, which provides an indicator of the natural hydrology of the river. Linacre and Hobbs (1977) and Gentilli (1986) identified 13 climatic regions (Koeppen-Gieger system) in Australia based on rainfall, temperature, evaporation, and their seasonality. The climatic regions are identified in *Figure* 2 and described in the associated table. The climatic types Af (Tropical rainforest) and Am (Tropical monsoon) have been combined for the purposes of this classification system due to their small area and similarities in terms of their impact on river flows.



Designation	Climate
Af	Tropical rainforest; hot; rain all seasons
Am	Tropical monsoon; hot; seasonally excessive rainfall
Aw	Tropical savanna; hot; seasonally dry, usually winter
BSh	Tropical steppe; semi-arid; hot
BSk	Mid-latitude steppe; semi-arid; cool or cold
BWh	Tropical desert; arid; hot
BWk	Mid-latitude desert; arid; cool or cold
Cfa	Humid sub-tropical; mild winter; moist all seasons; long hot summer
Cfb	Marine; mild winter; moist all seasons; warm summer
Cfc	Marine; mild winter; moist all seasons; short cool summer
Csa	Interior Mediterranean; mild winter; dry summer; hot summer
Csb	Coastal Mediterranean; mild winter; dry winter; short warm summer
Cwa	Sub-tropical monsoon; mild winter; dry winter; hot summer

FIGURE 2: Linacre and Hobbs, 1977 Climatic Regions of Australia

5.1.2 Geomorphological Regions

The second criterion is based on geomorphology. Broad landform regions, chosen to represent the landscapes through which the river flows, are an important determinant of flow regime, stream power, sediment supply, sediment calibre and sediment transport. The landform regions are defined as follows based on the 227 physiographic regions of Australia defined by Jennings and Mabbutt (1986):

Uplands:	Areas of high ground of subdued crestal outlines and limited internal relief. Uplands include areas commonly referred to as plateaux or tableland and are characteristic of many of Australia's highland catchments.
Lowlands:	Areas of low altitude with modest internal relief.
Ranges:	An area of dissected linear crests, also referred to as ridges and hills.
Slopes/Falls:	An area of gradual or stepped decline from uplands to lowlands or plains.
Plains:	Relatively flat landscapes irrespective of altitude.

Jennings and Mabbutt (1986) proposed a threefold hierarchy of geomorphic regions for Australia involving three major divisions, 23 provinces and 227 sections. The appropriate level of this hierarchy can be used for this classification scheme.

5.1.3 Flow Regimes

The third criterion is based on the degree of flow regulation and water extraction because this classification scheme will be applied by natural resource managers to environmental flows. Five indicators are proposed based on an assessment of the impact of flow regulation on the total flow regime. A single measure of regulation-induced changes in flow regime can never indicate the full range of documented changes (Erskine, 1985; 1996a; Erskine et al., 1999a; Sherrard and Erskine, 1991; Benn and Erskine, 1994; Tilleard et al., 1994; Sammut and Erskine, 1995).

First Indicator

The first indicator is the change in *mean annual flow* at a river gauging station on the regulated stream before and after the commencement of upstream impoundment, inter-basin water transfers and/or flow diversion standardised against changes in mean annual flow for an unregulated control river for the same time periods. This can be expressed by:

$$P_c = \left\{\left(R_2/R_1 / C_2/C_1\right) - 1\right\} \times 100$$

where P_c is the standardised percentage change in mean annual flow before and after flow regulation;

R_1 and R_2 are the mean annual flows for the regulated river for the pre-and post-regulation periods, respectively; and

C_1 and C_2 are the mean annual flows for the unregulated, control river for the pre-and post-regulation periods, respectively.

The use of the above indicator is dependent on the existence of an appropriate control station. This standardisation is essential because of well documented changes in mean annual rainfall and run-off over large areas of Australia during the twentieth century (Pittock, 1975; Cornish, 1977; Bell and Erskine, 1981; Erskine and Bell, 1982; Erskine, 1986a). Where there is no such control station, a comparison of measured regulated annual flow with estimated natural annual flow is usually possible because dam management authorities often estimate natural dam inflows (Erskine, 1996a).

Second Indicator

To assess regulation-induced changes in flow seasonality, a second indicator, the standardised percentage change in *mean monthly flow* for each month before and after flow regulation, should be used. Equation 1 is simply changed to use mean monthly flow. In the Mediterranean climates of southern Australia, dams with large storage capacities (that is, the dam storage capacity is much greater than the mean annual flow) can totally reverse the natural seasonal flow pattern (Erskine, 1996a). In summer rainfall areas, winter flows are greatly reduced to conserve storage for irrigation releases during the summer crop growth period (Erskine, 1985). Again where there is no appropriate control station, a comparison of measured regulated annual flow with estimated natural annual flow is often possible (Erskine, 1996a).

Third Indicator

Flow duration curves depict the cumulative frequency distribution of *mean daily flows* at a gauging station and hence cover the full range of flows needed to determine an environmental flow regime. Equation 1 has been used to determine a third indicator, regulation-induced changes in daily flows for the whole flow duration curve by calculating P_c for a range of flow durations (Erskine, 1985; Sherrard and Erskine, 1991; Benn and Erskine, 1994; Erskine et al., 1999a). It is recommended that P_c be calculated for mean daily flow for durations of at least 1, 5, 10, 20, 50, 80, 90 and 95 percent. High flows are often stored by dams to enable subsequent releases during dry periods (Erskine, 1985; Sammut and Erskine, 1995; Erskine, 1996a). Low flows are also often reduced by storage (Sammut and Erskine, 1995; Erskine, 1996a).

Fourth Indicator

Major downstream flood suppression is often caused by dams (Erskine, 1985; Sherrard and Erskine, 1991; Benn and Erskine, 1994; Tilleard et al., 1994; Sammut and Erskine, 1995; Erskine, 1996a; Erskine et al., 1999a). Equation 1 can also be applied to the results of flood frequency analysis for a fourth indicator, which measures the magnitude of change in *flood peak discharge* for a range of recurrence intervals following flow regulation. The type of flood series used (annual maximum, annual exceedance, peak over threshold series or partial duration series) depends on the quality and length of the gauging record. Qualified personnel must undertake such analyses. Again a range of recurrence intervals should be used to adequately cover the flood frequency distribution from small to large floods. The adopted recurrence intervals will vary depending on which flood series is used and the length of available record. The published literature should be consulted to select appropriate recurrence intervals for the particular river and flood series (see Erskine, 1985; Sherrard and Erskine, 1991; Benn and Erskine, 1994; Sammut and Erskine, 1995; Erskine, 1996a; Erskine et al., 1999a).

Fifth Indicator

The fifth indicator is the *volume of water licensed for extraction* from a length of stream. The actual extracted volumes should be used instead if the data are available.

5.2 Valley Segment Classification

Following Bisson and Montgomery (1996), the valley segment refers to the valley form based on the dominant types of sediment input and transport processes. *Figure 3* outlines the classes for valley segments and is a greatly expanded version of Bisson and Montgomery (1996) to allow for the range of Australian conditions. Each class is briefly described below.

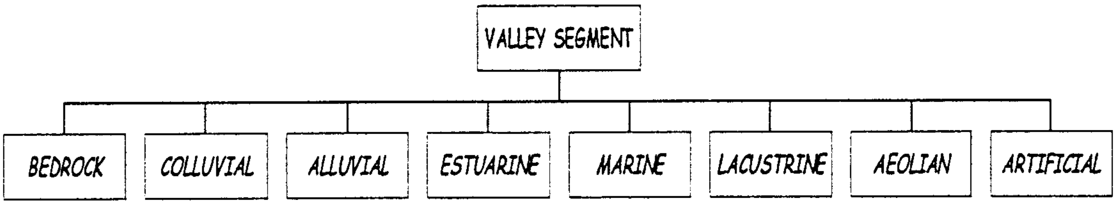


FIGURE 3: **Classification of Valley Segments**

5.2.1 Bedrock Valley Segments

Bedrock valleys have high sediment transport capacities because of steep slopes and close lateral and vertical bedrock confinement. As a result, long sections of channel are excavated in bedrock and exhibit isolated large boulders and boulder bars. Catastrophic floods are often responsible for forming the morphology of bedrock channels (Baker and Pickup, 1987; Wohl, 1992a; 1992b; 1993). While debris flows can be important for exposing bedrock, this process is restricted to steep mountainous areas subject to intense rainfall in Australia (Rutherfurd et al., 1994). Localised slackwater deposits of sand and silt are laid down at protected sites in bedrock valleys (Baker and Pickup, 1987; Wohl, 1992a; 1992b; 1993; Saynor and Erskine, 1993). These valleys are common on rivers draining various granitoid batholiths (Erskine, 1993; Erskine and White, 1996; Erskine et al., 1999), resistant volcanic rocks (Wohl, 1992a; 1992b) and Mesozoic and Paleozoic quartz sandstones in Australia (Wohl, 1993; Erskine, 1998; 1999; Erskine and Saynor, 2000).

5.2.2 Colluvial Valley Segments

Colluvial valleys are partly filled with poorly sorted sediment supplied from the surrounding hillslopes. Shallow overland flows and mass movements supply the sediment to the valley floor and the stored sediments are often episodically eroded. These sediments are commonly deeply weathered and have been extensively removed by gully erosion over the last two hundred years in south eastern Australia (Pickup, 1986). The "zero-order" basins of Dietrich et al. (1987) and the CBDs (colluvium-filled bedrock depressions) of Crozier et al. (1990) are examples of low order colluvial valleys. Similar features exist in forested landscapes throughout eastern Australia.

5.2.3 Alluvial Valley Segments

Alluvial valleys are partly filled with sediments deposited by the present or former river and by overbank flows (Nanson and Croke, 1992). A range of channel patterns develop on alluvial plains (Schumm, 1963b; 1981; 1985) and some may lack contiguous channels for thousands of years (Melville and Erskine, 1986). Chain of ponds (Eyles, 1977a; 1977b) were often present on unchanneled alluvial valleys in south eastern Australia at the time of first European settlement. Many have now been gullied. Alluvial valleys may be partly confined by materials of limited erodibility, resulting in distorted channel patterns (Lewin and Brindle, 1977). Much geomorphological, sedimentological and ecological research has been conducted on alluvial streams.

5.2.4 Estuarine Valley Segments

Estuarine valleys are included because this classification scheme will be applied to rivers from their source to the ocean or to an inland floodout or terminal lake. Estuaries exhibit a range of different morphologies, as has been demonstrated for mesotidal to intermittently tidal estuaries in NSW (Roy, 1984) and for macrotidal estuaries in the Northern Territory (Woodroffe et al., 1989). Large amounts of fluvial sediment are often trapped in the fluvial delta, channel bed and sub-tidal point bars, mangrove and reed swamps, floodplain and mud basins of estuaries. Pyritic estuarine sediments also oxidise to produce sulfuric acid, which has caused fish kills and outbreaks of mycotic diseases in fish (Sammut et al., 1995). Many Australian estuaries are major sediment sinks (Roy, 1977).

5.2.5 Marine Valley Segments

Marine valleys are found at the mouth of some Australian estuaries where coastal plains of cheniers, beach ridges, marine deltas and sand barriers have been constructed or where the post-glacial marine transgression has drowned an embayed coastline.

5.2.6 Lacustrine Valley Segments

Lacustrine valleys refer to those superimposed on lake sediments. Some Australian rivers discharge into terminal lakes, such as Lake George, Lake Eyre and Lake Frome and flow for some distance over the exposed lake bed. The length of such valleys varies with lake level, which has been highly variable during the late Quaternary (Coventry, 1976; Nanson et al., 1998).

5.2.7 Aeolian Valley Segments

Aeolian valleys are those where various inland rivers cut through or are dissipated in sand dunes. These valleys are only activated at irregular intervals following large floods (Williams, 1971; Tooth, 1999). They act as sinks for water, sediment and solutes where rivers floodout in the dune fields. The fluvial sediments are often subsequently reworked by wind when they dry.

5.2.8 Artificial Valley Segments

Artificial valleys are those created by construction activities such as urbanisation, drainage, flood mitigation, irrigation and the like (Erskine, 1999a). The natural valley is often buried with fill of various types or a new valley is created by excavation. These segments are particularly common in urban and irrigation areas.

5.3 Reach Identification

River reaches are homogeneous lengths of channel within which hydrological, geological, and adjacent catchment surface conditions are sufficiently constant so that uniform river morphology is produced (Kellerhals et al., 1976) or a consistent pattern of alternating river morphologies is produced (Erskine et al., 2001). Bisson and Montgomery (1996) proposed that channel reaches consist of relatively homogeneous associations of landforms and habitat types, which distinguish them from adjoining reaches. The river styles of Brierley et al. (1996) and Brierley (1999) correspond to reaches but introduce a new, specialised terminology based on only three criteria. More criteria are required for a national classificatory scheme (see below). Furthermore, river styles are a bottom up approach based on the expensive and time-consuming collection of lower level information. This has to be done before the river can be classified and is a significant limitation for a national scheme. Furthermore, estuaries and lakes are ignored.

Reaches are typically 10 to 100 km in length. While the core length of a reach is relatively easy to identify, it is often more difficult to define precisely the boundaries of the reach due to the transitional nature of most boundaries (Erskine, 1996b). Bisson and Montgomery (1996) proposed that provisional reach boundaries could be identified from topographic maps, vertical air photographs, geology maps, soil survey maps, etc. and then the bedforms or habitat characteristics could be determined from selective field surveys. Any method based on field surveys will be costly and time consuming. There is also a problem in determining how to spatially interpolate from the sample site to the reach when the whole river is not sampled. Furthermore, a lot of site-specific measurements often do not meaningfully define reach boundaries (Webb and Erskine, 2000).

There is no universal agreement as to which geomorphic criteria should be used for the classification of river reaches. The schemes of Neill and Galay (1967), Galay et al.

(1973), Mollard (1973), Kellerhals et al. (1976), Schumm (1981; 1985), Mosley (1982; 1987), Rosgen (1985; 1994; 1996a) and Thorne (1998) used up to 25 criteria.

Webb and Erskine (2000) used ten geomorphic criteria to formally define nine channel reaches on the Snowy River below Jindabyne Dam. Erskine (1996b) used four geomorphic criteria to informally define three channel reaches on Congewai Creek and Wollombi Brook in the Hunter Valley. Erskine et al. (1995) used five geomorphic criteria to informally define nine channel reaches on the Wingecarribee River downstream of Wingecarribee Dam.

River reaches can also be defined on management criteria, such as river lengths between particular regulatory structures, which do not correlate with natural features. This is appropriate for the provision of environmental flows on many highly regulated rivers. However, the lengths of river defined on this basis will not necessarily exhibit homogeneous characteristics and will not respond to flow regulation in the same manner, to the same degree or at the same rate.

Reach identification is an iterative process based on cross checking between map and air photograph patterns and the bedforms/habitat types observed in the field. Therefore, periodic revisions of reaches should be expected as more data are collected.

For the application of this classification, it is recommended that at least five geomorphic criteria should be used. These criteria should be selected carefully on the basis of what is most relevant to the river, gully, estuary, lake and/or artificial channel of interest but the first eight criteria in *Table 2* are recommended as a starting point for rivers. *Table 2* lists the most useful criteria for the range of Australian rivers, gullies, estuaries, lakes and artificial water bodies investigated by the authors as well as appropriate methods for their measurement.

Where appropriate, the reaches should be given a formal name usually comprising three terms. The first term should be based on a geographic name for a location within or near the reach; the second should be a geomorphic descriptor for one of the dominant geomorphic characteristics of the reach; and the third, when needed, is the term "reach" or "zone". For example, the *Willis sand zone* on the Snowy River is 93.5 km long and was named after Willis (the area at the NSW/Victorian border on the Snowy River, which is located within the reach) and the extensive sand storage that occurs in the long, relatively flat parts of this reach that are sandwiched between shorter, steeper bedrock sections (Erskine et al., 1999a; Webb and Erskine, 2000; Erskine et al., 2001).

Channel reaches are placed into one of 50 reach types (*Figure 4*). These are based on the work of Rosgen (1985; 1994; 1996a), Erskine (1999a), Schumm (1968; 1981; 1985), Roy (1984), Melville and Erskine (1986), Nanson (1986), Woodroffe et al. (1989), Nanson and Croke (1992) and Hart (1996). After identifying and naming channel reaches, each should then be allocated to one reach type for each valley segment. Each reach type is given a simple descriptive name based on its geomorphic characteristics. This is more meaningful than the alphabetical naming system of Rosgen (1994; 1996a). Correlations between rivers should be based on reach type. Furthermore, river response to flow regulation or environmental flows is only predictable when considered for specific reach types. The following reach types are provisional until extensively field tested by applying the scheme to a number of Australian rivers.

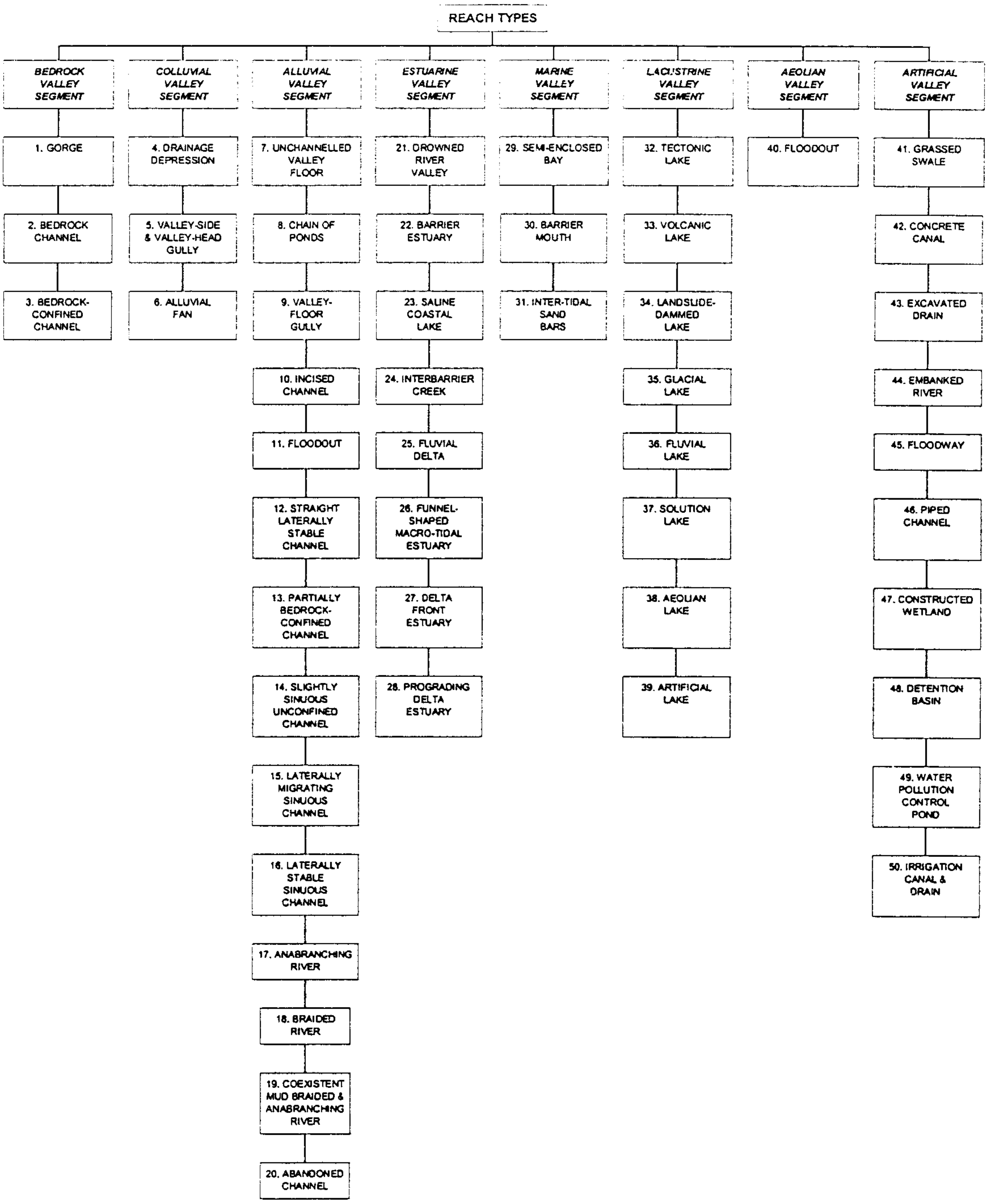


FIGURE 4: **Classification of Reach Types**

5.3.1 Bedrock Valley Segments

1. Gorge

Gorges have boundaries cut almost entirely in the underlying rock and are common in, but by no means restricted to, quartz sandstone, and resistant volcanic and granitoid rocks (*Figure 5*). Vertical and lateral bedrock confinement dominate channel morphology. Slopes are steep to very steep (>4 percent), entrenchment ratios (ratio of floodplain width to bankfull width) are less than 1.4 and bankfull channel width is essentially equivalent to valley floor width (Rosgen, 1985; 1994; 1996a). Channel pattern is usually joint and/or fault controlled but is essentially straight (sinuosity of ~1 which corresponds to the ratio of channel length to valley length). Macrobedforms (see next section) consist of pools, riffles, bedrock rapids and steps, transverse ribs, boulder clogs and various types of bars (Pickup, 1986; Baker and Pickup, 1987; Wohl, 1992a; 1992b; 1993). Bedrock channels form by incision due to base level lowering, uplift or climatically induced changes in water and sediment fluxes. Waterfalls with deep downstream plunge pools are often present either within, or at the upstream limit of, the gorge, with Jim Jim and Twin Falls on the edge of the Arnhem Land escarpment in the Northern Territory being well known examples. Similarly, very deep scour pools often develop at sites of extreme turbulence, such as at abrupt angle bends (for example, Nortons and Horseshoe Basins in the Fairlight Gorge of the Nepean River; Erskine, 1999a). These channels are similar to the Aa+ and bedrock A stream types of Rosgen (1994; 1996a).

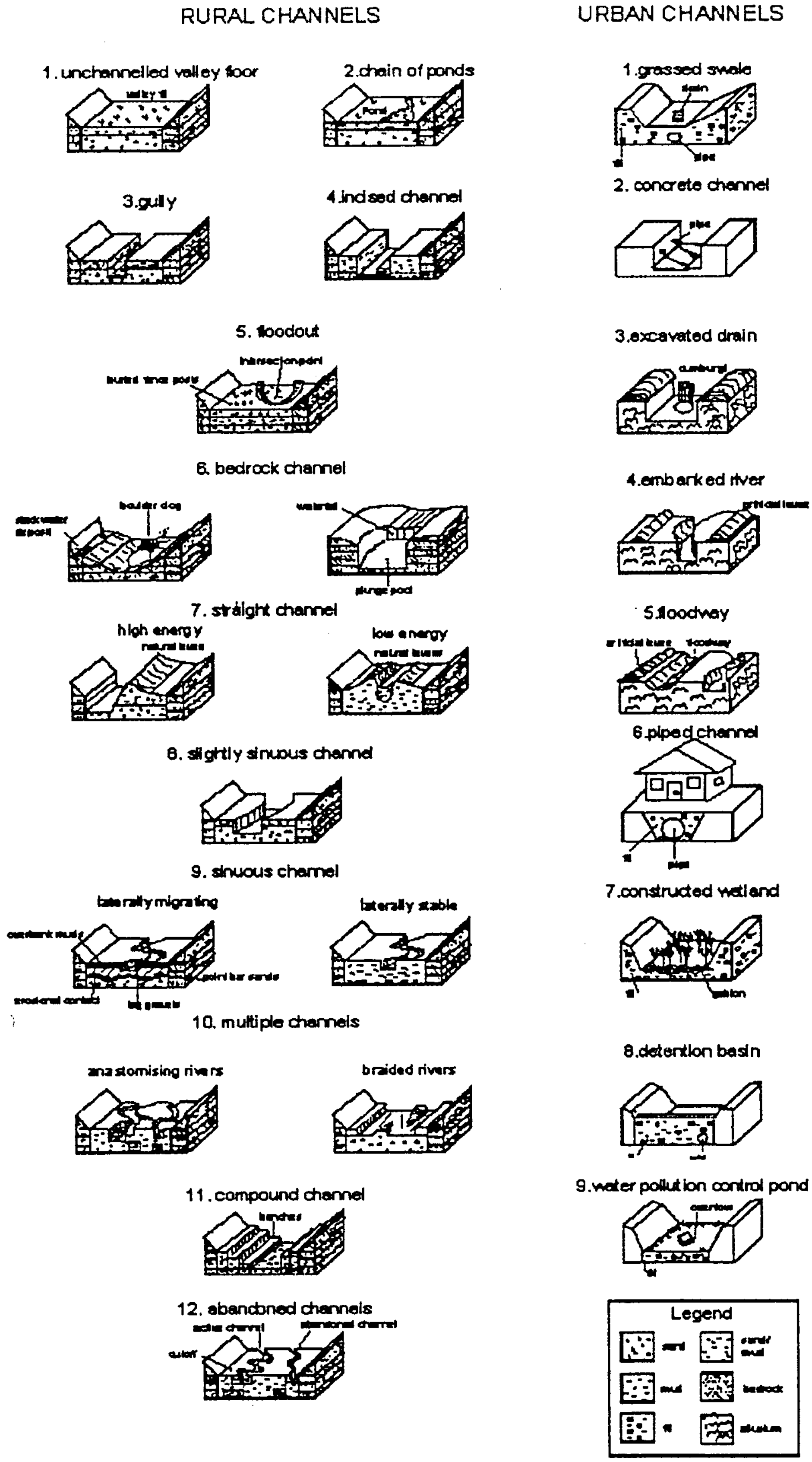


FIGURE 5: **Erskine's (1999a) classification of channel types found in the Hawkesbury-Nepean River catchment**

Slackwater deposits are typically fine-grained sand and silt, which accumulate rapidly from suspension during major floods in protected areas of bedrock gorges where current velocities are locally reduced. They blanket bedrock or terrace sediments or floor caves (Saynor and Erskine, 1993) and can be used to reconstruct palaeoflood histories (Baker, 1987). Riley et al. (1989) and Saynor and Erskine (1993) found slackwater deposits in the Fairlight Gorge of the Nepean River and demonstrated that at least one late Holocene flood greatly exceeded the largest historical flood of 1867. This event was so large that it would have destroyed the original Warragamba Dam.

Well known examples of gorges are the Bents Basin and Fairlight Gorges on the Nepean River near Sydney (Saynor and Erskine, 1993; Erskine, 1998; 1999a), the Katherine Gorge in Nitmiluk National Park in the Northern Territory (Baker and Pickup, 1987) and the Herbert Gorge in far north Queensland (Wohl, 1992a).

2. *Bedrock Channel*

Bedrock channels are not incised, but are cut into bedrock. As a result, they are steep, vertically confined channels but are not closely laterally confined by bedrock. The entrenchment ratio is usually greater than 1.4 and the channel pattern is structurally controlled. Macrobedforms include falls, cascades, rapids, slots, sheets, runs, plunge pools and step pools (see next section). They are found either in upland settings above waterfalls, such as on the Arnhem Land Plateau in Kakadu National Park or on localised outcrops of bedrock.

3. *Bedrock-Confined Channel*

Bedrock-confined channels (*Figure 5*) have a sinuosity approaching one (Schumm, 1963b) and are so laterally confined by bedrock and resistant river terrace and other types of sediments that they essentially follow the valley in which they are constrained (Erskine and Melville, 1983a; Erskine, 1986a; Nanson, 1986; Nanson and Erskine, 1988; Nanson and Croke, 1992; Erskine and Livingstone, 1999). The confining valley, which is structurally controlled, may be sinuous but alluvial meanders do not develop. Entrenchment ratios are less than 1.4, slopes are moderately steep and the valley floor width is less than about twice channel width. This type has relatively high stream power but has a wider valley than bedrock gorges. They are transitional between bedrock and alluvial valley segments. As a result, localised, in-channel benches (Erskine and Livingstone, 1999) and spatially disjunct pockets of floodplain with well-developed natural levees are constructed in the valley expansions. The benches and floodplain are episodically destroyed by catastrophic floods or a series of large floods in rapid succession and then reform on top of the eroded stump (Nanson, 1986; Nanson and Erskine, 1988; Erskine, 1994a; Flack and Erskine, 1996; Erskine and Livingstone, 1999). Bed-material can be highly variable, ranging from gravel, to mixed sand and gravel to sand. Examples of high energy, bedrock-confined straight channels are common in sandstone valleys in the Hunter Valley (Erskine, 1996b) and the East Alligator River in Arnhem Land.

5.3.2 Colluvial Valley Segments

4. *Drainage Depression*

These are very small headwater valley segments lacking stream channels and are common in many forested catchments in New South Wales. They are infilled with colluvium of highly variable texture supplied from the adjacent hillslopes (*Figure 5*). Concentrated water flow occurs episodically but they have limited aquatic habitat. Similar landforms overseas are called "zero-order" basins (Dietrich et al., 1987) and colluvium-filled bedrock depressions (Crozier et al., 1990). Rosgen's (1985; 1994; 1996a) and Brierley's (1999) classification schemes ignore such low order valley segments. Drainage depressions accumulate sediment for varying periods of time before being eroded by debris flows or gullies. This is a cyclic process about which little is known of the characteristic time scales involved in Australia. Further work is required to better define this reach type.

5. *Valley-side and Valley-head Gully*

According to Schumm et al. (1984), gullies are relatively deep, recently formed, eroded channels that are cut into unconsolidated material where no well-defined channel previously existed (*Figure 5*). Brice (1966) maintained that they have steep sides, a width >0.3 m, a depth >0.6 m and terminate at an upstream headscarp or knickpoint. Gullies can be located in many topographic positions and those included here correspond to Schumm et al. (1984) valley-side and valley-head gullies (*Figure 5*). Such gullies can be formed by fluvial processes when the erosivity of flows exceeds the erodibility of the boundary sediments (Cooke and Reeves, 1976; Schumm et al., 1984). However, debris flows can also be responsible for excavating the bulk of the colluvial sediment (Dietrich et al., 1987; Crozier et al., 1990). Gullying can then proceed to modify the debris flow scar. Although the October 1993 flood in north eastern Victoria initiated a lot of debris flows, little is known of the frequency of occurrence and the controlling mechanisms of such events (Rutherfurd et al., 1994). Further work is also required to better define this reach type. However, the reach types for colluvial valley segments apply mainly to low order valleys to which river classification may be rarely applied (for example, see Brierley et al., 1996; Brierley, 1999).

6. *Alluvial Fan*

Alluvial fans are conical shaped bodies of clastic sediments deposited where channels debouche from closely bedrock-confined valleys onto a piedmont or into a higher order channel (*Figure 5*). They are significant sediment storages that are often eroded by fanhead trenching, gullying and drainage rejuvenation (Schumm et al., 1987; Scott and Erskine, 1994). Debris flows are important for fan formation in many dry environments (Wasson, 1977; 1978) but many fans in well vegetated environments are composed entirely of fluviatile sediments (Erskine and Melville, 1983b; Scott and Erskine, 1994). Fans store sediment in transit from hillslopes to high order channels for variable periods of time. The size of fans is highly variable. Large events are important for fan development (Wasson, 1974; Scott and Erskine, 1994). The present classification schemes do not recognise fans and the characteristics of channels on fans are so variable that no attempt is made to define them here. Rather fans are identified by their shape, location and sediments.

Scott and Erskine (1994) documented the evolutionary development of fan-head trenches in the sandstone valleys to the north of Sydney. They demonstrated that progressive aggradation led to the development of a locally overstepped segment of the fanhead which then failed to produce a scour pool or knickpoint which migrated upstream. The eroded channel often extended downstream. Fans were found upstream of unchannelled valleys (see below).

5.3.3 Alluvial Valley Segments

7. Unchannelled Valley Floor

Many valley floors where the catchment area ranged between about 1 and 100 km^2 were swampy depressions at the time of first European settlement in south-eastern Australia (for example, Erskine and Melville, 1983b; Erskine, 1986b; Melville and Erskine, 1986; Prosser, 1987; Prosser et al., 1994; Brierley and Fryirs, 1998). These unchannelled valley floors (*Figure 5*) occur downstream of drainage depressions and many still exist today. However, many have also been gullied over the last 200 years (Erskine and Melville, 1983b; Erskine, 1986b; Melville and Erskine, 1986). Valley floors containing no channel have been variously called unchannelled valley floors (Erskine, 1986b; Melville and Erskine, 1986), swampy meadows (Prosser, 1987; Prosser et al., 1994), non-incised valley networks (Day, 1980), unincised valley floors (Prosser and Slade, 1994) and ungullied valleys (Gillespie et al., 1992). Unchannelled valley floors often extend up-slope into alluvial fans (Erskine and Melville, 1983b; Scott and Erskine, 1994) or into drainage depressions, hillslope hollows or percolines. They are usually well vegetated by wetland species and have high water tables, at least during wet periods.

Mud sediments are usually deposited in unchannelled valley floors over relatively long periods of time until they are partially or completely destroyed by gullying (Erskine and Melville, 1983a; Melville and Erskine, 1986; Prosser et al., 1994). Unchannelled valley floors are found in upland, valley and plains settings and are *not* restricted to particular lithologies or physiographic regions. Gullying is initiated by the development of knickpoints via sediment storage producing locally steeper valley floor segments, by disturbance of valley floor vegetation and/or by various physical disturbances associated with road works, drainage, mining, extraction, etc. (Erskine and Melville, 1983a; Melville and Erskine, 1986; Prosser and Slade, 1994; Scott and Erskine, 1994). Nanson and Croke (1992) included all of the first five alluvial valley segments in their cut and fill floodplain category. While experience may indicate that this is meaningful, they are separated for initial application of this classification scheme.

8. *Chain of Ponds*

Chain of ponds are a significant and distinctive drainage form (*Figure 5*) that were common at the time of first European settlement throughout south eastern Australia (Eyles, 1977a; 1977b; Erskine, 1994b; Erskine et al., 1995). Eyles (1977a; 1977b) poorly defined these landforms which are referred to repeatedly in the historical literature. Although Gallagher (1984) maintained that chains of ponds consisted of discrete ponds **not** connected by a river channel, it is apparent from the historical literature and from surviving examples that many ponds were also connected by small capacity, often ill-defined depressions (Eyles, 1977a; Erskine, 1986b; 1994b). Each pond is relatively large and usually oval to round in shape with concentrically arranged zones of aquatic vegetation on the littoral margins (Eyles, 1977a; 1977b). Although ponds convey surface run-off, they are always windows in the floodplain water table and are relatively permanent sources of water. Many ponds were made water reserves at the time of land subdivision to enable settlers access to permanent water.

Many chain of ponds have been destroyed by incision and channelisation over the last 200 years by the same processes as outlined above for unchannelled valley floors (Eyles, 1977a; 1977b; Gallagher, 1984; Erskine, 1986b; Melville and Erskine, 1986; Bannerman, 1987). Chain of ponds have been recorded in similar geomorphic settings and areas to unchannelled valley floors. Gallagher's (1984) conclusion that ponds should not occur in sandstone landscapes is wrong (Erskine, 1986b). She also repeated Eyles' (1977b) finding that ponds are only found in areas with dispersible subsoils. Erskine (1994b) found that chain of ponds produce a relatively deep alluvial fill consisting of thin, fine-grained sheet deposits with minimal prairie soils. Channel sediments are poorly developed to absent although distinct, organic-enriched pond-infills are sometimes present (Erskine, 1986b). Dispersible subsoils are not always found where there are chains of ponds (Erskine, 1986b; Erskine, 1994b).

9. *Valley-floor Gully*

Post-European settlement gullying has destroyed many unchannelled valley floors, generating large volumes of sediment in the process (Melville and Erskine, 1986; Brierley and Fryirs, 1998). The rate of gully erosion is most rapid immediately after the gully has been initiated and then declines exponentially over time (Graf, 1977). Gullies extend the drainage network by eroding upstream via the migration of a single or a number of vertical headcuts (Erskine and Melville, 1983a; Melville and Erskine, 1986). Following the passage of the primary headcut, the gully sidewalls are eroded by a number of processes which widen the initial trench. Sediment storage may occur in the gully when it becomes overwide or the new channel starts to laterally migrate (Erskine and Melville, 1983a; Melville and Erskine, 1986). Gullies seem to erode for about 100 years before they self-stabilise. Most of the gullies initiated following first European settlement are now relatively stable. Active gullies are those that were initiated in the later part of the 20th century. It must be emphasised that gully erosion will continue in the future because there are still unchannelled valley floors and because many gullies are now recovering from the erosion phase.

Gullies are started when the erosion potential of valley floor flows exceed the resistance of valley-floor materials (Cooke and Reeves, 1976). There are many mechanisms whereby gully cutting can be initiated (Cooke and Reeves, 1976; Schumm et al., 1984). It is unusual for a single cause to operate throughout a large area (Cooke and Reeves, 1976; Erskine, 1986b). While the disturbance of valley-floor vegetation is undoubtedly an important cause of gully cutting (Prosser and Slade, 1994), it is not the only one responsible for post-European gullying in south-eastern Australia (Melville and Erskine, 1986).

10. Incised Channel

According to Schumm et al. (1984), incised channels are a deep trench resulting from erosion of an existing channel (*Figure 5*). The distinction between gullies and incised channels is based on the pre-erosion channel form. Many chain of ponds and sinuous channels (see below) have been converted to incised channels in Australia since European settlement (Erskine, 1999b). Once erosion is initiated, gullies and incised channels behave similarly, with incised channels usually being larger versions of gullies. Channel erosion produces high sediment yields that result in significant downstream deposition (Erskine and White, 1996; Erskine, 1999b). Incised channels progress through many stages following initial incision and may recover to the pre-incision state (Schumm et al., 1984; Simon and Hupp, 1986; Erskine, 1999b). Incision can occur in situ or during and following channel avulsion (see below and Erskine, 1999b; Schumm et al., 1996).

Incised channels are characterised by bankfull mean stream power of about 70 W/m^2, low sinuosities (<1.2), low large woody debris loadings, large channel capacities and infrequent overbank flow (Erskine, 1999b). They can be cut into a range of different sediments and only become vegetated when recovering from the initial incision (Schumm et al., 1984; Simon and Hupp, 1986). While incised channels are significant sediment sources, they can also store large volumes of sediment in benches and floodplains.

11. Floodout

A floodout is a form of channel failure where substantial sediment storage occurs because the bed load is not transported by all flows (Melville and Erskine, 1986) (*Figure 5*). An intersection point (the point of extinction of the channel because the bed and bank profiles coalesce) is usually present in a floodout (Erskine and Melville, 1983a; Erskine, 1986a; Melville and Erskine, 1986), as shown in *Figure 5*. Schumm (1961) identified similar features on ephemeral channels in the USA which he called depositional or aggradational zones. Floodouts in the semi-arid and arid zones refer to the zone where rivers spill out across the adjacent plain loosing all definition of a channel (Tooth, 1999). Melville and Erskine (1986) constructed a detailed sediment budget for the post-European settlement phase of gullying to show that floodouts have a very high sediment trap efficiency for the inflowing sediment. They found that 53 percent of the gully-eroded sediment was deposited in the floodout and that a farther 37 percent was deposited in the upstream gully in a floodplain. Therefore, 90 percent of the sediment remobilised by post-European gullying was stored immediately downstream. Neil and Fogarty (1991) found that as much as 60 percent of the material eroded from discontinuous gullies in south-eastern Australia was deposited solely in the downstream floodout and hence was not transport out of the basin.

Tooth (1999) recognised intermediate and terminal floodouts on arid rivers. Those associated with gullies and incised channels are intermediate floodouts because channels reform downstream (Tooth, 1999). Melville and Erskine (1986) demonstrated that floodouts form by rapid localised reductions in channel capacity and in-channel stream power, causing displacement of flow overbank. This, in turn causes deposition. Floodouts require an active sediment source immediately upstream. In extreme cases, floodouts can store that much sediment that telegraph poles are buried. They consist of the coarsest sediment (usually sand) generated by upstream erosion and are best developed in sandstone and granite areas. Re-incision of the sediment deposited in the floodout is common when gully erosion rates decline over time. This reach type is not recognised by Rosgen (1985; 1994; 1996a).

12. Straight Laterally Stable Channel

Laterally stable straight channels have a sinuosity of ~1 (Schumm, 1963b) and are flanked by broad floodplains (*Figure 5*). They occur in very low energy environments where there are very low valley slopes (Schumm and Khan, 1971; 1972; Smith and Smith, 1980; Nanson and Croke, 1992). Where sediment is supplied to these channels, fine-grained, low, marginal levees develop (Flack and Erskine, 1996) but where sediment yields are very low, no levees form (Erskine et al., 1995). Examples of low energy straight channels are found in relatively broad upland valleys downstream of extensive swamps (Erskine et al., 1995). Bed material is usually sand although mud examples probably exist. These channels are not included in the Rosgen (1994; 1996a) scheme.

13. Partially Bedrock-Confined Channel

Partially bedrock-confined channels have a sinuosity of about 1.2 and exhibit some alluvial bends, unlike straight channels (*Figure 5*). They develop in valleys where the floodplain is wider than for bedrock-confined straight channels (reach type 3) and also exhibit relatively high stream powers. The ratio of valley floor width to channel width ranges between two and five. These channels are often unstable and exhibit rapid bank erosion and channel enlargement during large floods, particularly on bends. As a result, marked localised channel expansions often occur on bends and in-channel benches (Erskine and Livingstone, 1999) are usually present. These channels are found in association with straight bedrock-confined channels. Bed-material can be highly variable, ranging from gravel, to mixed sand and gravel to sand. Splays of sand and gravel are deposited on the spatially disjunct pockets of floodplain by large floods. Flood chutes are often found either on bends or in straight reaches (Warner, 1988; 1997).

14. Slightly Sinuous Unconfined Channel

This reach type is a higher energy version of a laterally migrating channel (reach type 15). The channels are found on steeper valley slopes but are not laterally and vertically confined by bedrock. Entrenchment ratios are greater than 1.4 and the ratio of valley width to channel width is greater than four. Sinuosity is usually about 1.2 but is often spatially variable. Bed material can be highly variable ranging from gravel to mixed sand and gravel to sand.

15. Laterally Migrating Sinuous Channel

According to Leopold and Wolman (1957), sinuous or meandering channels have a sinuosity of at least 1.5. They exhibit well developed alluvial bends, rhythmically spaced, pool-riffle sequences and a channel capacity ranging between the modal and mean annual flood (Leopold and Wolman, 1957; Wolman and Leopold, 1957; Page, 1988). These channels are **not** vertically and laterally confined by bedrock and hence entrenchment ratios are usually greater than 2.2, the valley floor width is usually greater than 10 times the channel width and slopes are moderate. The classic laterally migrating, meandering stream (Leopold and Wolman, 1957; 1960; Wolman and Leopold, 1957) is one where:

- the channel pattern approximates a sine-generated curve;
- cut bank erosion occurs on the outside of the bend and is concentrated downstream of the bend axis;
- the whole platform migrates downstream;
- a point bar is deposited in the void on the inside of bends; and
- a floodplain forms dominantly by point bar deposition (that is, lateral accretion).

Many laterally migrating sinuous channels are **not** type examples. The rate of lateral migration is often very slow. Cohesive, fine-grained bank sediments (Riley, 1967; Pickup, 1976) and a thick root mat along the base of the bank reduces migration rates. Bed material can be highly variable ranging from gravel to mixed sand and gravel to sand. Mud bed sinuous channels usually belong to reach type 16.

16. Laterally Stable Sinuous Channel

These channels have fine-grained bank sediments and often exhibit a well vegetated mud bed (*Figure 5*). Bankfull channel capacity is very low and these streams are very stable over time spans of centuries because of low stream powers (Erskine, 1986b). Ferguson (1981) explained the absence of lateral migration on some sinuous streams in Britain by a combination of low stream power and high bank resistance. The same explanation applies here also. However, the development of a sinuous pattern on a non-migrating channel requires investigation. It seems likely that the sinuous pattern was inherited from a formerly laterally migrating sinuous channel which become stabilised by an influx of fine-grained sediment and/or vegetation. The channels have low slopes, entrenchment ratios greater than 2.2 and ratios of valley floor width to channel width of greater than six.

17. Anabranching River

Anabranching or anastomosing rivers are a system of multiple channels separated by islands which are usually excised from the floodplain and which are large relative to the size of the channel (Knighton and Nanson, 1993). They serve to concentrate stream flow and maximise bed load transport in areas where there is little or no opportunity to increase hydraulic gradient (Nanson and Knighton, 1996). There is a wide range of anabranching channels from the ridge form of Wende and Nanson (1998) to the sand island form of Nanson et al. (1993) to the floodplain form of Schumm et al. (1996). Some anabranching rivers (floodplain form) have multiple channels which can vary markedly in channel morphology and age (*Figure 5*) (Schumm et al., 1996). Young channels have large bankfull flows, low sinuosity, large meander wavelength, steep gradients and are unstable (*Figure 5*). On the other hand, old channels have small bankfull flows, high sinuosity, small meander wavelength, low slope and are relatively stable, although they often laterally migrate within a restricted meander belt (*Figure 5*). The multiple channels develop by repeated avulsions (*Figure 6*). As individual channels become older and more sinuous, they also become more hydraulically inefficient. Thus, increasing proportions of flood discharge are displaced overbank which concentrate in relatively straight floodplain depressions. A new channel develops by both up and downstream progressing degradation. Downstream progressing degradation is initiated at outflow points and upstream degradation at inflow points. With time, the degrading channels coalesce to form a new anabranch of the anabranching network (Erskine et al., 1990; Schumm et al., 1996).

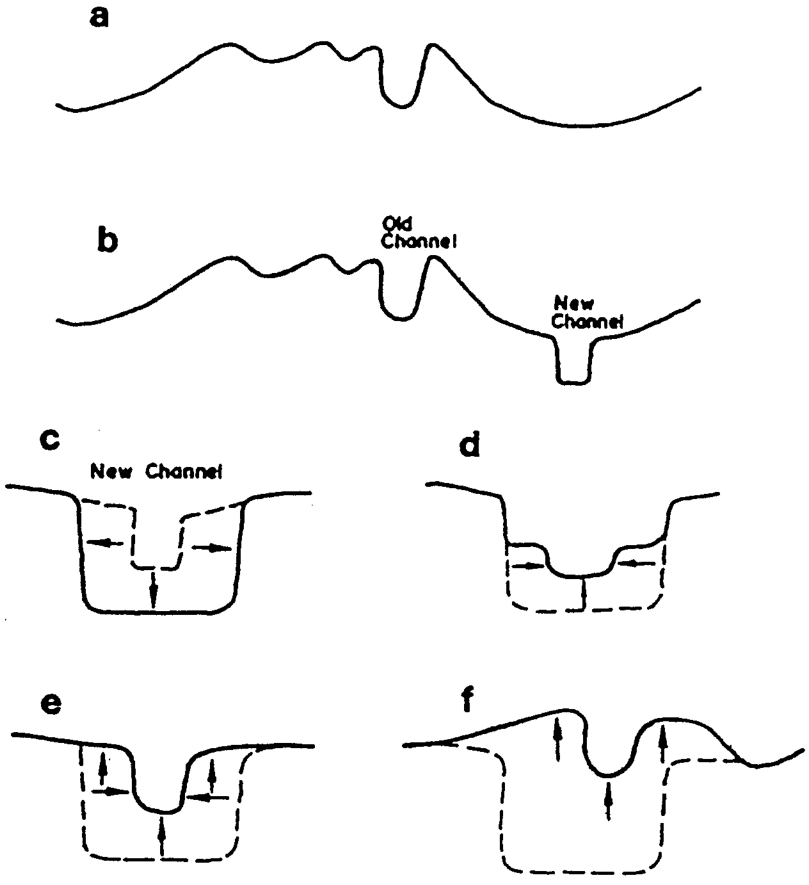


FIGURE 6: **Six Stage Model of Avulsed Channel Evolution.** Stage a is the original channel which is abandoned by avulsion. Stages b to f, inclusive represent the progressive development of the new channel. At any one time, the anabranching network is composed of multiple channels of different ages and hence different morphologies (Source: Erskine et al., 1990; Schumm et al., 1996).

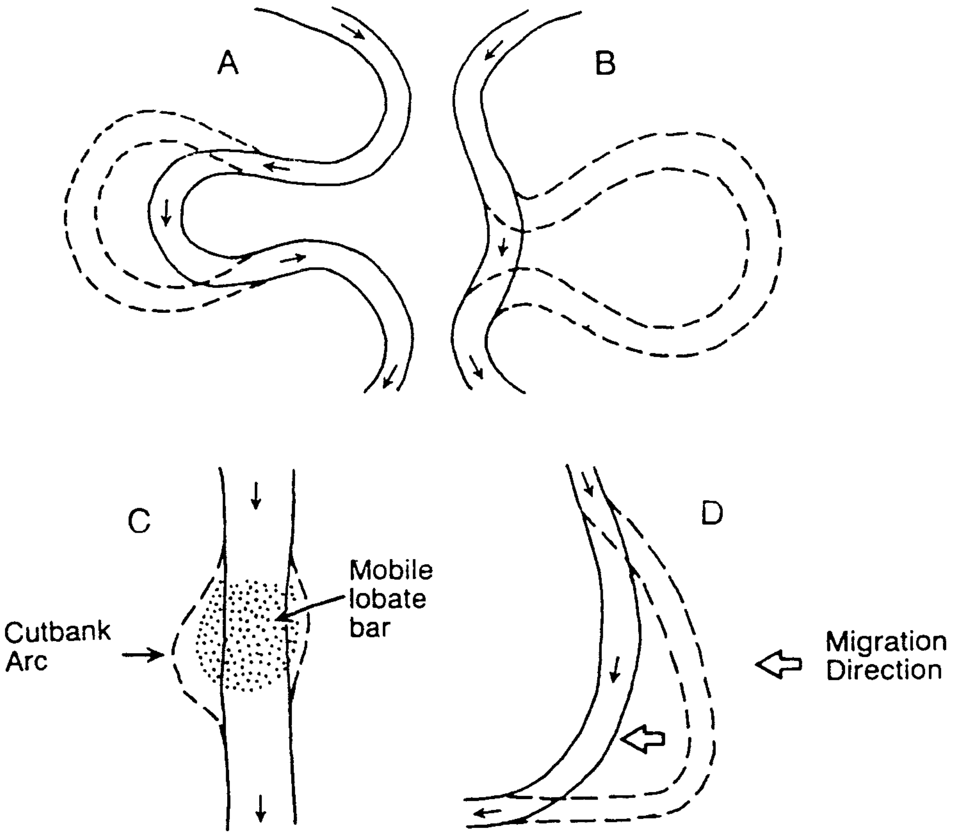


FIGURE 7: **Types of Alluvial Cut-offs: (A) Chute Cut-off, (B) Neck Cut-off, (C) Mobile Bar Cut-off, (D) Bend Flattening (Source: Erskine et al., 1992)**

Avulsions involve the abandonment of a whole reach of river (Pickup, 1986), as shown by Schumm et al. (1996) for the Ovens and King Rivers in Victoria. The abandoned channels then infill with relatively fine-grained sediment but pools or lakes can be maintained for relatively long periods of time in the abandoned channel.

5.3.4 Estuarine Valley Segments

21. Drowned Valley Estuary

Stream incision during glacial periods of low sea level cut deep bedrock palaeovalleys in resistant rocks which were subsequently drowned when sea level rose to about its present position from about 17 ka to about 6–7 ka BP in south-eastern Australia (Roy, 1984). The essential characteristics of a drowned river valley are a small tidal range (<2 m), a wide, exposed, entrance with full tidal exchange, steep bedrock valley sides, large areas of rocky shoreline, deep channels or holes and tidal flats in shallow tributary valleys colonised by mangroves. These estuaries are tide dominated and contain large flood tidal deltas of marine sand that have migrated up to 5–10 km into the estuary (Roy et al., 1994). There is only a slow attenuation of tidal range through the estuary. Mud basins develop in protected areas landward of the flood tidal delta sands and the tidal channels are floored by fluviatile muddy sand and sand (Roy, 1984). Examples include Hawkesbury River, Sydney Harbour, Georges River (Botany Bay) and Hacking River (Port Hacking) (Roy, 1984).

Roy (1984) proposed three evolutionary stages in the progressive infilling with sediment of drowned valley estuaries with increasing duration of sea level stability. Progressive floodplain and channel sedimentation progrades downstream burying the basin muds and eventually supplying fluvial sand to the coast.

22. *Barrier Estuary*

Barrier estuaries are named after the bay barriers that have formed across the mouth of palaeovalleys eroded during periods of low sea level (glacials) (Roy, 1984). They are characterised by a constricted inlet channel with broad tidal and backbarrier sand flats that reduces the tidal prism within the estuary, that attenuates tides and that remains almost permanently open to the sea (Roy et al., 1994). The flood tidal delta usually has a steep marine sand front migrating slowly landwards into the mud basin from the ocean. The mud basin also often has a fluvial sand front prograding into it at river mouths (Erskine, 1993). The mud basin forms by the deposition of fluvial mud transported into the estuary from the catchment. Barrier estuaries are very common on the lower sections of NSW and Victorian coastal rivers (Roy, 1984; Bird, 1993).

Roy (1984) proposed four evolutionary stages in the progressive infilling with sediment of barrier estuaries with increasing duration of sea level stability. Fluvial deltas progressively extend downstream over estuarine muds and floodplains eventually infill the area between the tidal channels.

23. *Saline Coastal Lake*

These lakes are also separated from the sea by a sandy barrier but have inlets that are mostly closed and only open briefly when flood waters erode through the beach (Roy et al., 1994). Therefore, they are usually non-tidal and contain brackish or saltwater (Roy, 1984). Some saline coastal lakes have been permanently separated from the ocean while others have evolved from barrier estuaries to saline coastal lakes as the size of the coastal barrier increased during the mid-Holocene (Roy, 1984). They are rarely hypersaline (saltier than sea water) in NSW but can be in South Australia and Western Australia when evaporation exceeds the input of freshwater (Morrisey, 1995).

Roy (1984) proposed three evolutionary stages in the progressive infilling with sediment of saline coastal lagoons with increasing duration of sea level stability. While the evolutionary sequence is similar to barrier estuaries, the water bodies are usually smaller and marine sand deposits are less extensive.

24. *Interbarrier Creek*

There are two sand barrier systems common along the coast of south-eastern Australia. The landward barrier system is Pleistocene in age and is called the Inner Barrier. It has a subdued dune topography and well developed podzol soils. The seaward sand barrier is Holocene in age and is characterised by greater dune relief and poorly developed soils (Outer Barrier). Tidal channels often exist at the boundary between these barrier systems and are called here, interbarrier creeks. These estuaries are remnants of larger embayments that formerly existed in the void between the two barrier systems.

25. *Fluvial Delta*

A fluvial delta is a depositional body of river-derived sediments where rivers debouche into estuaries and includes deposits that have been secondarily moulded by waves, currents and tides (Wright, 1978). The subaqueous part of the fluvial delta plain occurs below low tide level and is divided into the pro-delta, delta front and river-mouth bar (Wright, 1978). The pro-delta is the basal portion of the active delta and is a blanket of clays deposited almost entirely from suspension. These deposits merge into the basinal muds in deeper water. The delta front is the seaward sloping portion of the delta where the sediment is coarser than in the pro-delta. A river-mouth bar is a sandy shoal formed near the seaward limit of the source channel. Flack and Erskine (1996) discuss the river-mouth bar and delta front of the Middle Creek (Narrabeen Lagoon, NSW) fluvial delta. The sub-aerial portion of the fluvial delta plain lies above low tide level and is a veneer capping the subaqueous delta sediments (Wright, 1978). It consists of a wide variety of landforms including river channels, natural levees, crevasses, splays, marshes and swamps (Flack and Erskine, 1996).

Some fluvial deltas have a straight channel flanked by well developed natural levees which extend as silt jetties into the receiving water body (Bird, 1962; Flack and Erskine, 1996). Silt jetties are long finger-like silt bodies along the margins of the straight channel. Flack and Erskine (1996) found that the preservation potential of most fluvial delta sediments can be low where reworking by lateral migration, avulsions and floodplain stripping is active on medium to high energy streams.

26. *Funnel-Shaped Macro-Tidal Estuary*

Macro-tidal estuaries in northern Australia experience tidal ranges of about 5 m and exhibit four distinct zones that have been described in detail by Woodroffe et al. (1986; 1989). The estuarine funnel is characterised by a channel that tapers at a negative exponential rate with distance upstream of the mouth or the ocean (Woodroffe *et al.*, 1986; 1989). There are often locally extensive marginal mangrove forests also (Stephens, 1993). Inter-tidal sand flats often occur on either side of the mouth of these estuaries and extensive inter-tidal shoals may be present within the funnel (Stephens, 1993).

Further landward is a section with a sinuous estuarine channel pattern characterised by a series of abrupt angle bends separated by long, slightly curved sections. Sinuous estuarine segments resemble fluvial meanders (Woodroffe *et al.*, 1986; 1989). As with fluvial meanders, sedimentation occurs on the inside of bends, which often exhibit well developed point bars. The sinuous section is flanked by extensive mangrove forests (Stephens, 1993).

Cuspate meanders are located immediately landward of the sinuous section (Woodroffe *et al.*, 1986; 1989; Vertessy, 1990). The defining characteristics are a series of bends with sharply pointed, cliffed inner banks, which are the locus of erosion. Between the cusps are wide ovoid pools containing broad mid-channel islands and bars, which are exposed by low spring tides. Cuspate meanders are not present on all macrotidal estuaries and form from cut-offs and/or enlargement of regular sinuous meanders (Vertessy, 1990). They are often flanked by extensive mangrove forests restricted to supratidal mud flats (Stephens, 1993).

The fluvial-estuarine transition zone is located landward of the cuspate meandering section. River pattern is relatively straight (that is, very low sinuosity) with a very large meander wavelength, which contrasts to the channel pattern immediately downstream.

27. Delta Front Estuary

This category is proposed for estuaries that are relatively steep and debouche into the ocean in a short estuary with a relatively steep delta front. Waves, currents and/or tides are sufficiently strong to rapidly rework the supplied fluvial sediment. As a result, spits and beach ridges form down drift and the delta does not rapidly prograde seawards.

28. Prograding Delta Estuary

This category is proposed for estuaries that have an intermediate energy slope between fluvial deltas and delta front estuaries and that discharge into more protected coastal areas where waves, currents and tides are not effective in reworking fluvial sediment away from the river mouth. As a result, fluvial sediment progressively progrades seawards. Avulsions may occur episodically and switch the locus of deposition.

5.3.5 Marine Valley Segments

To include the full length of rivers, gullies, lakes, estuaries and artificial channels from source to ocean, it is necessary to also cover fully marine bays landward of the open ocean. This nearshore zone is the most sensitive part of the marine environment to changes in discharge, sediment and nutrients from the catchment and should be included in any integrated monitoring program of environmental flows, where appropriate. Although not all estuaries transport fluvial sediment to the ocean, especially on the NSW north coast (Roy, 1977; Roy and Crawford, 1977), this is certainly not the case everywhere (for example, Stephens, 1993). The O'Connell River near Proserpine, Queensland has a well developed subaqueous delta extending into Repulse Bay, indicating that it is a significant sediment source to the nearshore zone (Stephens, 1993). Numerous other examples can also be cited. Therefore, it is essential to include marine valley segments in this classification scheme.

29. Semi-Enclosed Bay

These are relatively deep bays that are open, to varying degrees, to the ocean and into which various types of estuaries discharge. Although they are dominated by ocean swell and wind waves, wave refraction still occurs as swell approaches the shore, producing a concave up nearshore profile. Twofold Bay, into which the Nullica and Towamba Rivers flow, is an example.

30. Barrier Mouth

Barrier estuaries and saline coastal lagoons often breach the sand barrier at their mouth and discharge directly into the ocean at a site that is usually protected from the incident swell. Ocean swell and wind waves act directly on the sand barrier which is nearly aligned to the refracted swell. The Hunter River and many other estuaries on the north coast of NSW are examples of barrier mouths.

31. *Inter-Tidal Sand Bars*

Many north Queensland macro-tidal estuaries discharge into the ocean through a series of inter-tidal sand bars that can extend some distance offshore. Chenier ridges are often present along the landward side. These bars produce a gentle offshore gradient that dissipates the incident swell.

5.3.6 Lacustrine Valley Segments

For the purposes of this classification scheme, the lake types proposed by Timms (1992) are adopted, pending further research on their suitability for Australian conditions, with the addition of an extra class for artificial lakes impounded by constructed dams. Lakes are included in this classification scheme because many rivers originate in, or flow through, lakes. Therefore, it is essential that a national river classification can accommodate all situations. The discrimination of different lake types within Timms' (1992) general morphogenetic categories may be necessary when assessing the need for, or impacts of environmental flows. Therefore, Timms' (1992) subdivisions within each morphogenetic category are also outlined briefly below.

32. *Tectonic Lake*

Timms (1992) proposed four types of tectonic lakes, namely lakes resulting from epeirogenic earth movements, lakes formed on old erosion surfaces as intermontane basins, lakes resulting from local subsidence and lakes associated with fault scarps. Uneven and slight warping of the earth's crust over large areas are called epeirogenic movements. Lake Eyre is the best Australian example and was formed by upwarping across its southern boundary blocking drainage to the sea (Timms, 1992). Old erosion surfaces are sometimes uplifted to form intermontane basins that can be locally deepened by faulting. Lake Buchanan in Queensland is a large playa formed by such processes. Local subsidence during earthquakes can produce depressions in which lakes form. The most important type of tectonic lake is that produced by faulting. The uplifted block impounds the river forming a lake. Lakes George and Omeo are examples in south-eastern Australia.

33. *Volcanic Lake*

Timms (1992) proposed a hierarchical morphogenetic classification of volcanic lakes with the first level based on the general nature of the volcanic area (four categories) and with the second level based on the specific formative process. At the first level of the classification, there are no known Australian lakes in volcano-tectonic depressions and these are not discussed further. There are five lakes in volcanic vents, namely lakes in cinder cones, true crater lakes, maars, diatremes and calderas. Lakes in cinder cones are rare because of the porous scoria but there is a permanent lake in one of the scoria cones at Tower Hill, Victoria. True crater lakes lie in former vents at the summits of non-active volcanoes and examples are present in western Victoria and Queensland. Maars are formed by volcanic explosions, often caused by the conversion of water to steam when it meets hot lava. These explosions produce deep round holes with little ejecta. There are many examples in South Australia, Victoria and Queensland. Diatremes are formed by a high pressure gas explosion through basement rock and the resultant crater often holds water. Calderas are round, steepsided and flat-floored cavities in a former volcano. Tower Hill is a possible caldera lake (Timms, 1992).

There are three types of lakes on lava fields which are lakes on lava flows, lakes between lava flows and lakes dammed by lava flows. Lakes can form in hollows in lava flows that develop on the surface of the original flow or by collapse of the lava surface. Many examples are found in western Victoria and on the tablelands of NSW (Timms, 1992). Lava flows often form discrete tongues that may coalesce to form hollows in which lakes subsequently develop. Many examples exist in western Victoria (Timms, 1992). Lava often flows down existing valleys, damming tributary valleys. Lake Condah in western Victoria was formed when the Tyrendarra flow from Mt Eccles dammed a tributary valley (Timms, 1992).

The only lake formed by volcanic damming in Australia is Buckleys Swamp in western Victoria which was formed when the Mt Napier volcano blocked a tributary of Darlot Creek (Timms, 1992).

34. Landslide-Dammed Lake

Lakes may form in valleys blocked by landslides or in depressions on the surface of the landslide. Lakes impounded by landslides include Lake Tali Karng in Gippsland and Lake Elizabeth in the Otways, Victoria (Timms, 1992). Such lakes can be short-lived because the landslide barrier can be eroded rapidly. Lakes developed on the surface of landslide deposits are usually very small but are present in areas below escarpments in south-eastern Australia.

35. Glacial Lake

Pleistocene glaciation has produced many lakes in Australia, particularly in Tasmania. Timms (1992) identified four types of glacial lakes, namely, lakes in contact with ice, lakes produced by glacial erosion, lakes produced by glacial deposition and lakes of complex origin. As there are no extant glaciers in Australia the lake types in contact with ice are not considered further here. The four types of lakes produced by glacial erosion are ice-scour lakes, cirques, glacial valley lakes and piedmont lakes. Pleistocene ice sheets in the Central Plateau of Tasmania removed all loose material, leaving behind small rock basins eroded into rock fracture zones which are now ice-scour lakes. Cirque lakes occupy rock basins at the head of glacial valleys and four such lakes occur near Mt Kosciuszko (Timms, 1992). Valley glaciers can erode rock basins along the valley which fill with water on deglaciation and become glacial valley lakes. Examples are described in Tasmania by Timms (1992). Piedmont lakes are formed by large glaciers which descend a long valley to relatively low elevations, excavating an impressive rock basin. Lake St Clair in Tasmania, Australia's deepest natural lake, is an example (Timms, 1992).

The three lakes in Australia produced by glacial deposition are lakes dammed by moraines, kettles and lakes dammed by outwash. Lakes dammed by terminal and recessional moraines are very common. Hedley's Tarn below Blue Lake is impounded by a terminal moraine (Timms, 1992). Kettles are water-filled basins formed when stranded ice masses on ground moraine melt and examples exist near Mt Kosciuszko and in Tasmania (Timms, 1992). Lake Pedder was originally dammed by glacial

38. *Aeolian Lake*

Timms (1992) separated lakes formed by wind action in coastal and arid areas. Deflation or wind erosion can form hollows that can intercept the water table and/or collect surface run-off and form deflation lakes in coastal dunes and in arid areas. A special case of deflation lake is the type formed within the two arms of a parabolic dune. Large deflation basins in arid areas are often called playas and smaller ones pans, while saline lakes are called salinas. Timms (1992) lists many examples of both types in Australia. Lunette lakes are formed by deflation of at least an ephemerally dry lake floor. When such lakes are full of water, sand beaches develop. Sand lunettes form by landward wind transport of sand from such beaches. Clay lunettes form by landward wind transport of clay pellets from the lake floor. Clay pellets are produced by seasonal lake drying and salt efflorescence of the lake bed clays. Lunettes have an asymmetrical dune shape with a low-angle windward face and a steep leeward side. Vegetation is important for trapping the deflated sediment.

Migrating sand dunes can advance across the swale between successive dunes or bedrock valleys and form dune barrage lakes in both coastal and arid areas. Again there are many examples in NSW (Timms, 1992). Lakes can also form in the swale between parallel dunes in coastal and arid areas.

Perched dune lakes are formed by the development of a perched water table above impermeable coffee rock in high Pleistocene dune fields (Timms, 1992).

39. *Artificial Lake*

This category is intended to include all water bodies impounded by various types of engineering structures. Hardie and Lucas (2001) found that such a category was necessary when applying Brierley's (1999) scheme to the Hawkesbury-Nepean River catchment. Brierley's (1999) classification did not include such a category and hence was unable to classify long sections of reservoirs within that catchment.

5.3.7 Aeolian Valley Segments

40. *Floodout*

A floodout in aeolian valley segments differs from the floodout in alluvial valley segments (reach type 11) in that the channel progressively looses competence to transport sediment and ceases to flow by high transmission losses into aeolian sand dunes in arid areas (Sullivan, 1976). These transmission losses result in the deposition of all bedload and the formation of a terminal floodout where rivers spill out, loosing all definition of a channel (Tooth, 1999). All sediments and solutes are deposited in the floodout and subsequently reworked by wind.

5.3.8 Artificial Valley Segments

41. *Grassed Swales*

Grassed swales are an engineered reach type where the natural channel is replaced by a grassed trapezoidal section with a buried concrete pipe which passes low flows

(*Figure 5*). Local run-off is directed to the pipe by a series of drains constructed along the invert of the section. Flood flows are only passed down the grassed swale when the capacity of the pipe is exceeded. This urban channel type serves no ecological function and can be hazardous to humans who rarely see flood flows in the swale and hence have no perception of the dangers associated with the grassed swale during floods. Detention basins or dry reservoirs are usually built upstream of grassed swales to control downstream flood peak discharges.

42. Concrete Canals

Concrete canals (*Figure 5*) are an example of a lined channel which is intended to maximise flow velocity by maximising slope and hydraulic radius and by minimising resistance to flow for a given discharge. As a result, the minimum area possible is reserved for drainage purposes and the maximum area possible is available for urban development. Concrete canals serve no ecological functions and flood flow velocities are often so high (up to 7–8 m/s) that many people have been drowned when they have fallen into these canals because they could not escape. Examples of concrete canals are common in most Australian cities.

43. Excavated Drains

Excavated drains are a common channel type throughout rural and urban Australia. However, they do *not* mimic the morphology of natural channels and are consequently very unstable. Many natural urban channels erode during and immediately after the construction phase (Wolman, 1967; Neller, 1988). They are then extensively excavated with the removed sediment often stockpiled on the top of the bank (*Figure 5*). Cumbungi and weeds invade the disturbed channel and greatly increase resistance to flow, partially negating the enlargement. Appropriate geomorphic design can be used to rectify this problem.

44. Embanked Rivers

Embanked rivers are channels of any type continuously flanked by artificial levees (*Figure 5*). The channel can be natural or engineered but the embankment must be an artificial levee. Artificial levees are used to protect some low lying areas from flooding and are common in many parts of south eastern Australia.

45. Floodway

A floodway is an excavated depression parallel to the natural channel (*Figure 5*) which is designed to preferentially convey food flows in excess of channel capacity. It should be designed so that no erosion occurs. Floodways have been constructed on rivers in urban and rural areas.

46. Piped Channels

These are artificial channels where a buried pipe replaces the surface channel (*Figure 5*). If the capacity of the pipe is exceeded, extensive local flooding can result. Piped channels provide no ecological function and should be avoided as far as is possible.

47. *Constructed Wetlands*

Artificial wetlands (*Figure 5*) are being constructed in many areas to improve the water quality of run-off from urban areas and of treated effluent from sewage treatment plants and various industries. Many are being built on rivers and involve converting a flowing water habitat to a still water habitat.

48. *Detention Basins*

Detention basins or dry reservoirs (*Figure 5*) are built to temporarily retain run-off on reserved land so as to reduce downstream flood peak discharges. They achieve this by having a limited outlet capacity that cannot convey flow at the same rate at which it enters the detention basin. Playing fields are commonly impounded for this purpose.

49. *Water Pollution Control Ponds*

These are similar to constructed wetlands and detention basins. They are deeper than wetlands but are still intended to act as nutrient and sediment storages. They also often have reserved capacity for the detention of flood run-off, but maintain a permanent pond below the outlet level (*Figure 5*).

50. *Irrigation Canals and Drains*

These are usually excavated drains that convey high flows during a part of the year when crops need water or that evacuate drainage water away from irrigated fields. For the remainder of the year, they are usually dry. Irrigation canals may not be located in the lowest topographic positions because they are usually not designed to convey local run-off.

5.4 Bedform/Habitat Classification

While classification at reach level is considered the appropriate scale for the primary purpose of this classification system, the bedform/habitat scale is appropriate to river ecology and is provided here for completeness.

Bedforms are geometric configurations of bed material on the river bed surface that are more than one grain diameter high and that are formed by the flow. For this level of the classification, large scale bedforms only are relevant. They have lengths of the same order as the channel width or greater and heights comparable to the mean depth of the generating flow (Brush et al., 1966). Small scale bedforms, such as ripples, dunes, plane beds, etc. (Simons et al., 1965) are microhabitat scale and are not discussed here. Hawkins et al. (1993) definition of channel units is also appropriate for bedforms, that is, "...quasi-discrete areas of relatively homogeneous depth and flow that are bounded by sharp physical gradients..." (Hawkins et al., 1993: 4). *Figure 8* outlines the bedform classes proposed for this classification.

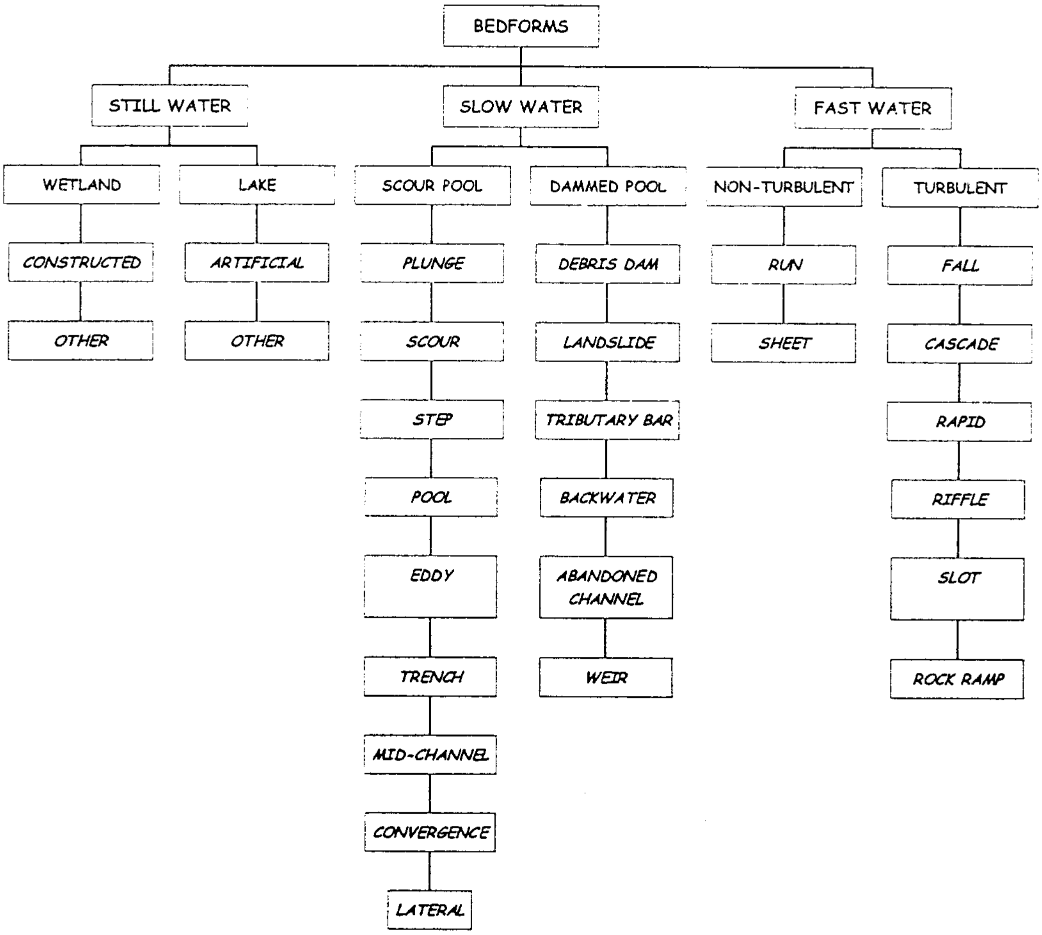


FIGURE 8: **Classification of Large Scale Bedforms**

Following Hawkins et al. (1993), a three tiered system is proposed so that the investigator can select the level of bedform/habitat resolution appropriate to the question being addressed. At the highest level, a tripartite division of bedforms has been adopted, namely *still water, slow water* and *fast water* (*Figure 8*). Each highest level bedform has then been subdivided into two types, which are then further subdivided on the basis of hydraulic characteristics and the principal kind of habitat-forming structure or process (Bisson and Montgomery, 1996).

While rivers are usually called lotic environments and lakes are called lentic environments, there is no clear and meaningful distinction between them when many rivers discharge into natural and artificial lakes and lagoons throughout Australia. For example, many estuaries are characterised by one of more estuarine channels discharging into a coastal lagoon (Cann River discharges into Tamboon Inlet in East Gippsland, Victoria (Erskine and White, 1996) and Middle, South, Deep and Mullet Creeks discharge into Narrabeen Lagoon near Sydney (Flack and Erskine, 1996)). Similarly, many rivers discharge into terminal lakes (Cooper Creek and Diamantina, Neales and Macumba Rivers discharge into Lake Eyre) or pass through wetlands and lakes. Wheeny Creek passes through Wheeny Lagoon before flowing into the Colo River and Mogo Creek passes through the lake on the St Albans Common before flowing into the Macdonald River. Therefore, any Australian river classification scheme must include lakes and wetlands or else ignore large sections of aquatic habitat.

5.4.1 Still Water Habitats

Still water habitats are divided into *wetlands* and *lakes*. For the purposes of this classification, Riley et al. (1984) definitions have been slightly modified. Lakes are defined as relatively deep standing water bodies with restricted, generally littoral emergent vegetation. Wetlands are relatively shallow standing water bodies with common emergent vegetation. Careful consideration needs to given to the antecedent hydrological conditions because many wetlands and some lakes will be dry during a drought. Furthermore, stock and the alien fish, *Cyprinus carpio,* can influence the amount of emergent macrophytes present. No attempt has been made to construct detailed classes for either still water bedform because such schemes already exist for Australia (for example, Bayley and Williams, 1973; Riley et al., 1984; Timms, 1992). Therefore, emphasis is only given to artificial still water bodies, which are ignored by most classification schemes. Timms' (1992) scheme is recommended for initial trials.

5.4.2 Slow Water Habitats

Slow water habitats are defined on the basis of low flow conditions and various types of pools, which are either formed by erosion (*scour pools*) or damming (*dammed pools*).

Scour Pools

For the scour pool category (*Figure 8*), additional classes have been added to those of Hawkins et al. (1993) and Bisson and Montgomery (1996) for "scour holes", step pools and pools. Each scour pool bedform is now briefly defined.

Plunge pool is defined narrowly here as a deep pool eroded at the base of a waterfall (cf. Bisson and Montgomery, 1996). Magela Falls, Jim Jim Falls and Twin Falls in Kakadu National Park have eroded deep plunge pools where the rivers flow over the resistant sandstone of the Arnhem Land Escarpment. Turner and Erskine (1997a) coined the term *"scour hole"* for large deep holes eroded at the boundary of a bedrock gorge with alluvium. Bents Basin on the Nepean River (Turner and Erskine, 1997a) and Edith Falls on the Edith River in Nitmiluk National Park, Northern Territory are examples. There is no waterfall at the transition from bedrock gorge to alluvium at either site and hence the holes are not plunge pools. Furthermore, scour holes are often sand-floored rather than lined by boulders or bedrock. Unlike Grant et al. (1990), Hawkins et al. (1993) and Bisson and Montgomery (1996), *step pools* are differentiated from plunge pools because of the substantial difference in the surface area and depth of the pools and in the height of the fall at the upstream end of the pool, that is, step pools are usually orders of magnitude smaller and have smaller drops into them. Step pools are small pools impounded by bedrock, boulder and log steps in steep channels. They are more closely spaced than pools associated with riffles (Grant et al., 1990). *Pools* are intended to cover standard pools eroded by high flows in many alluvial channels (Richards, 1976; Keller and Melhorn, 1978). They are rhythmically spaced at 5–7 channel widths apart and are closely associated with riffles, which are formed by the deposition of the sediment eroded from the pools by high bankfull flows. They are not associated with the specific formative mechanisms listed below for the remaining types of pools. *Eddy pools* are eroded by eddies downstream of obstructions and are proportional to the size of the obstruction. Large woody debris is a common obstruction. *Trench pools* are uniformly eroded deep pools sandwiched between resistant, usually bedrock banks. They are a feature of inner bedrock channels (Schumm et al., 1987; Wohl, 1992b; 1993). *Mid-channel pools* are formed by flow constrictions that concentrate scour in the centre of the river. They differ from trench pools in that the constriction is oriented perpendicular to the channel rather than parallel. *Convergence pools* form by the erosion of converging currents from two channels. These may be two independent channels (that is, a tributary joining the main stream) or two channels forming part of a braided or anabranching network. *Lateral scour pools* develop by erosion around an obstruction or resistant material on one side of a river. They are common on bends.

Dammed Pools

For the dammed pool category, beaver dams have been deleted from Hawkins et al. (1993) and Bisson and Montgomery's (1996) list for obvious reasons and tributary bar, disconnected and weir pools have been added. Each dammed pool category is now briefly defined. *Debris dam pools* are impounded by one or more pieces of large woody debris that is anchored in the channel. These pools are very common on east coast rivers dominated by *Tristaniopsis laurina*. *Landslide dam pools* are impounded by the debris deposited by a mass movement in the channel. These are relatively rare in Australia but are found in bedrock-confined rivers. Tributary bars are downstream elongated sediment bodies originating at the confluence of one, usually smaller channel with another (Petts, 1984). Such bars can accumulate in the channel, impounding a pool upstream. Erskine et al. (1999a) reported *tributary bar pools* on the Snowy River downstream of Jindabyne Dam which had formed by the deposition of sediment in the regulated main stream and its subsequent persistence due to a lack of reworking by main stream flows because of flood suppression. Benn and Erskine (1994) also reported tributary bar pool formation on the Cudgegong River below Windamere Dam. *Backwater pools* occur along the edge of channels at local expansions or at the junction with secondary channels. Flow separation envelopes with reverse currents are often present in the expansions. *Disconnected pools* are completely separated from the main channel at low flows by a bar or mound but are deep enough to be a window in the water table. They may be associated with secondary channels. *Abandoned channel pools* are ponded sections of a cut-off or avulsion that have no surface water connection to the main stream. *Weir pools* are common on many Australian rivers (Erskine, 1998; 1999; Turner and Erskine, 1997b) and represent an artificial pool impounded by the concrete, sheet pile or similar structure.

5.4.3 Fast Water Habitats

Fast water habitats are divided into *non-turbulent* and *turbulent* bedforms. Only the two types of non-turbulent fast water defined by Hawkins et al. (1993) and Bisson and Montgomery (1996) are included here. A *run* is a deeper, slower, less steep fast water bedform than a riffle (see below) that exhibits no supercritical flow. A *sheet* is a section of uniform water flow over smooth bedrock of variable gradient.

The turbulent fast water bedforms are similar to Hawkins et al. (1993) and Bisson and Montgomery's (1996) classes and are characterised by the presence of supercritical flow, that is, hydraulic jumps sufficient to entrain air and create localised patches of white water. However, different definitions are proposed below for some of their bedforms. *Falls* are high, essentially vertical drops, spanning the whole channel. The distinction between a fall and a bedrock, boulder or log step (see below) is height. Falls are higher than the bankfull channel depth and vice versa. Falls excavate plunge pools at their base. *Cascades* are steep sections composed of a series of bedrock, boulder and/or log steps that span the channel in a staircase fashion separated by closely spaced step pools (Grant et al., 1990). More than 50 percent of the stream area exhibits supercritical flow (Grant et al., 1990). *Rapids* are less steep than cascades and consequently exhibit irregular bedrock, boulder and/or log steps that partially or fully span the channel (Grant et al., 1990). Between 15 and 50 percent of the stream area displays supercritical flow (Grant et al., 1990). *Riffles* are less steep than rapids and do not display bedrock, boulder of log steps (Grant et al., 1990). They are characterised by shallow subcritical flow with only 5–10 percent of the water surface area exhibiting supercritical flow (Grant et al., 1990). The chutes of Hawkins et al. (1993) and Bisson and Montgomery (1996) have been renamed *"slots"* because chute already has an established, alternative meaning in geomorphology, namely a secondary flood channel across the inside of a bend or parallel to the main channel (Warner, 1988; 1997). *Rock ramp* has been added to the list to accommodate fishways constructed at many weirs on Australian rivers.

5.5 Microhabitat

Microhabitats are patches within a particular bedform that have relatively homogeneous substrate, water depth, flow velocity and cover. No attempt has been made to define relevant microhabitat classes at this stage, as this was considered to be outside the role and application of the proposed national management-based river classification system.

Valley Segment	Description	Channel Reach Name	Description	Reach Type
Bedrock Valley	Relatively narrow, deep valley cut into a range of Paleozoic rocks	Lucas Point Reach	42 km long, less steep (1.2 m/km), laterally and vertically bedrock confined channel with bedrock and gravel rapids and riffles and long pools. A narrow inner bedrock channel is often present but there is also sand storage in pools, bars and benches.	Bedrock-Confined Channel (Mixed Bed Material)
Bedrock/ Alluvial Valley	Deep, irregular sinuous valley cut into a range of Ordovician sedimentary and metasedimentary rocks	Long Point Reach	18 km long, relatively flat (0.7 m/km), laterally bedrock confined, sand bed channel with prominent sandy point bars, side bars, transverse bars and longitudinal bars. Little persistent pool development.	Bedrock-Confined Channel (Sand Bed)
Alluvial Valley	Extensive Holocene floodplain with backswamps, flood channels, natural levees and crevasses set in an embayment flanked by Miocene marine terraces.	Orbost Alluvial Reach	11 km long, compound sand bed channel exhibiting common transverse, longitudinal and side bars, and in-channel benches. Channel capacity is highly variable depending on the number of flood channels on the floodplain.	Slightly Sinuous Unconfined Channel (Sand Bed)
Estuarine Valley	Barrier estuary at an advanced stage of infilling with Holocene estuarine and fluviatile sediments and flanked by Miocene marine terraces	Orbost Estuarine Reach	20.5 km long estuarine channel, with a distinct sand slug in the upper reaches. Flanked by a broad floodplain with a series of remnant estuarine lagoons. Persistent salt stratification develops to the tidal limit during periods of extended low flow and anoxic, reducing conditions occur below the halocline/oxycline.	Barrier Estuary at an advanced stage of infilling with sand

For further information, see Erskine (1996c), Erskine et al. (1999a; 1999b; 2001) and Webb and Erskine (2000).

6.1 Catchment Classification

6.1.1 Climatic Regions

The Snowy River catchment experiences a Cfc climate over the upper catchment but a Cfb climate over the remainder (Linacre and Hobbs, 1977; Gentilli, 1986). The first letter (C) means that the mean temperature of the coldest month ranges between -3 and 18°C. The second letter (f) means that rain is experienced in all months. The third letters (c and b) mean that either there are less than four months when the temperature is over 10°C (c) or that the mean temperature of the of the warmest month is less than 22°C and that there are not less than 4 months with temperatures over 10°C (b). There are annual snowfalls in the highest part of the catchment which produce high spring streamflows when they melt (Erskine et al., 1999a).

6. Example Application: The Snowy River

The National River Classification System proposed in *Chapter 5* has been applied to the Snowy River below Jindabyne Dam (*Table 3*) to demonstrate its use.

Table 3: Application of the proposed river classification scheme to the Snowy River below Jindabyne Dam

Valley Segment	Description	Channel Reach Name	Description	Reach Type
Bedrock Valley	Narrow, deep valley cut into Late Silurian Bullenbalong Granodiorite of the Kosciuszko Batholith	Jindabyne Gorge	11.5 km long, steep (7.1 m/km), laterally and vertically bedrock confined channel, exhibiting gravel riffles, rapids and cascades with boulder steps separating long remnant pools. Post-dam vegetation invasion to the limits of the inner bedrock channel	Gorge (Granodiorite)
Alluvial/Bedrock Valley	Broad shallow upland valley where the Snowy River flows across the Monaro Tablelands	Dalgety Uplands Reach	57.5 km long, flatter (2.1 m/km) section of laterally and vertically bedrock confined (not as pronounced as in the above reach), slightly sinuous channel with well developed and vegetated side bars and tributary mouth bars. Mud, sand and gravel storage in the flatter parts of the reach	Bedrock-Confined Channel with short Gorge sections
Bedrock Valley	Narrow, very deep valley cut largely into Late Silurian Buckleys Lake Adamellite and siltstones of the Silurian Yalmy Group	Burnt Hut Gorge	57 km long, steep (5.9 m/km), laterally and vertically bedrock confined channel with steep bedrock rapids, falls and long deep pools	Gorge (Adamellite and siltstone)
Bedrock/Alluvial Valley	Slightly broader, very deep valley cut into granodiorites and adamellites of the Silurian Kosciuszko Batholith	Willis Sand Zone	93.5 km long, alternating relatively flat sand bed sections flanked by extensive sandy side bars and steeper bedrock sections with rapids, falls and a bedrock inner channel. Flatter than adjoining reaches (1.6 m/km) and the valley floor trough is sufficiently wide to allow limited floodplain development	Bedrock-Confined Channel with Short Gorge sections
Bedrock Valley	Narrow, very deep valley cut largely into Amboyne Granodiorite, Campbells Knob Granodiorite and multiple formations of the Snowy River Volcanics Group	Tulloch Ard Gorge	41.5 km long, relatively steep (2.4 m/km), laterally and vertically bedrock confined channel with steep gravel and bedrock rapids and falls separating long deep pools. Little sand storage and a narrow inner bedrock channel.	Gorge (Granodiorite and Volcanics)

6.1.2 Geomorphological Characteristics

The Snowy River catchment includes four geomorphic regions of Jennings and Mabbutt (1986), including the highest elevations in Australia. Upstream of Jindabyne, the headwaters of Snowy River flow through the *Australian Alps* which are a dissected high upland that has been locally glaciated but which experienced more widespread periglaciation during the last glacial maximum (Jennings and Mabbutt, 1986). The Alps are composed largely of granitoid rocks of the Kosciuszko batholith with minor areas of metasediments. Mean annual rainfall is very high, exceeding 2,000 mm on the high range. In this part of the catchment, there are two large dams, two small dams, one pumping station, one power station, five tunnels and nine aqueducts that form part of the Snowy Mountains Hydroelectric Scheme and that have significantly altered natural flow and sediment transport patterns (Erskine et al., 1999a).

Downstream of Jindabyne, the Snowy River initially flows across the *Monaro Tableland* before rapidly incising into the Tableland, producing a very deep valley. The Monaro Tableland is an undulating upland plain with tabular basalt relief and granite tors (Jennings and Mabbutt, 1986). The basalts of the Monaro Volcanic Province were extruded during the Palaeocene, Eocene and early Oligocene and overlie Palaeozoic granitoid plutons and their metamorphic aureoles (Taylor et al., 1990). There is a distinct rainshadow over the Monaro Tableland because they are in the lee of the Alps.

The *East Victorian Uplands* are extensive dissected plateaux on resistant rocks with large topographic depressions on outcrops of granodiorite (Jennings and Mabbutt, 1986). The Snowy River has deeply dissected the Uplands. Mean annual rainfall varies from about 580 mm in the lee of the Alps to about 1,200 mm near the coast. The Monaro Tableland and East Victorian Uplands are separated from the coastal slopes by a high escarpment which is generally continuous from far north Queensland to western Victoria. Ollier (1982) called this line of separation, the Great Escarpment, which characterises the seaward edge of the Monaro Tableland but then cuts across the southern part of the East Victorian Uplands along the Yalmy River and across the Snowy River.

The *Gippsland Plain* is a narrow coastal plain of sand and gravel terraces (Jennings and Mabbutt, 1986). The present floodplain of the lower Snowy River consists of fluviatile sediments overlying estuarine muds. The Snowy River estuary is of the barrier type of Roy (1984). Mean annual rainfall is about 1,200 mm.

The Snowy River is closely bedrock confined for most of its length until it debouches from the East Victorian Uplands onto the coastal Gippsland Plain near Jarrahmond. Flow should be strongly seasonal and controlled by the wet climate in the headwaters because there is a large rainshadow area in the lee of the Alps along the middle section of the Snowy River. Inter-basin water transfers have severed the high yielding headwaters from the rest of the river (Erskine et al., 1999a; 1999b).

6.1.3 Flow Regimes

Table 4 compares the percentage change in mean annual flow and mean monthly flow before and after flow regulation of the Snowy River with the standardised percentage change at all long term gauging stations. Data were taken from Erskine et al. (1999a) and the location of the gauging stations on the Snowy River are shown in *Figure 9*. This table demonstrates four main points. Firstly, inter-basin water transfers for hydroelectric power generation as part of the Snowy Mountains Hydroelectric Scheme caused a reduction in both mean annual and monthly flows at all stations (Erskine et al., 1999a). Secondly, the magnitude of this reduction decreases with increasing distance below Jindabyne because of flow recovery due to the inputs from unregulated tributaries (Erskine et al., 1999a). Thirdly, the spring snow melt produced sustained high flows right along the river (Erskine et al., 1999a). Fourthly, there has been a natural reduction in flow since the commencement of the Snowy Mountains Scheme and so a simple pre- and post-Scheme comparison of annual and monthly flows overestimates the impact of flow regulation (Erskine et al., 1999a). This highlights the importance of standardising change in hydrologic parameters against an unregulated control station. Therefore, unregulated rivers should be conserved to ensure that appropriate controls are available in all areas.

Table 4: Percentage change and standardised percentage change in mean annual flow and mean monthly flow after flow regulation on the Snowy River

Gauging Station	Percentage Change	Standardised Percentage Change
Regulated	**Mean Annual Flow**	**Mean Annual Flow**
Snowy River at Jindabyne Catchment area: 1850 km^2	–98.7	–98.1
Snowy River at Dalgety Catchment area: 3160 km^2	–96.1	93.8
Snowy River at Basin Creek Catchment area: 11836 km^2	–54.4	–28.6
Snowy River at Jarrahmond Catchment area: 13421 km^2	–43.7	–11.7
Unregulated		
Murray River at Biggara Catchment area: 1165 km^2	–36.2	N/A
Regulated	**Mean Monthly Flow**	**Mean Monthly Flow**
Snowy River at Jindabyne	Jan –98.3	Jan –98.1
	Feb –97.7	Feb –97.1
	Mar –98.1	Mar –97.5
	Apr –98.9	Apr –98.4
	May –99.4	May –99.2
	Jun –99.7	Jun –99.5
	Jul –99.7	Jul –99.6
	Aug –99.7	Aug –99.7
	Sep –99.9	Sep –99.9
	Oct –97.7	Oct –97.1
	Nov –97.6	Nov –96.5
	Dec –99.3	Dec –99.1

Gauging Station	Percentage Change	Standardised Percentage Change
Snowy River at Dalgety	Jan –94.2	Jan –93.6
	Feb –90.0	Feb –87.5
	Mar –94.4	Mar –92.9
	Apr –96.7	Apr –95.1
	May –94.8	May –93.0
	Jun –95.2	Jun –92.7
	Jul –96.6	Jul –96.1
	Aug –96.9	Aug –96.3
	Sep –97.7	Sep –97.5
	Oct -96.7	Oct –95.9
	Nov –95.0	Nov –92.9
	Dec –97.5	Dec –96.9
Snowy River at Basin Creek	Jan –64.4	Jan –60.1
	Feb 12.6	Feb 40.5
	Mar –55.5	Mar –42.8
	Apr -73.5	Apr –60.0
	May –54.7	May –39.0
	Jun –32.5	Jun 3.0
	Jul –45.4	Jul –36.6
	Aug –62.7	Aug –55.5
	Sep –59.4	Sep –55.6
	Oct –68.9	Oct –60.9
	Nov –60.5	Nov –43.7
	Dec –55.2	Dec –44.3
Snowy River at Jarrahmond	Jan –70.6	Jan –67.1
	Feb 0.1	Feb 25.0
	Mar –49.4	Mar –34.9
	Apr –68.5	Apr –52.6
	May –45.1	May –25.9
	Jun 10.9	Jun 69.1
	Jul –45.3	Jul –36.4
	Aug –51.2	Aug –41.9
	Sep –46.2	Sep –41.1
	Oct –58.7	Oct –48.1
	Nov –48.4	Nov –26.4
	Dec –36.8	Dec –21.5

N/A – Not Applicable.

Data taken from Erskine et al. (1999a).

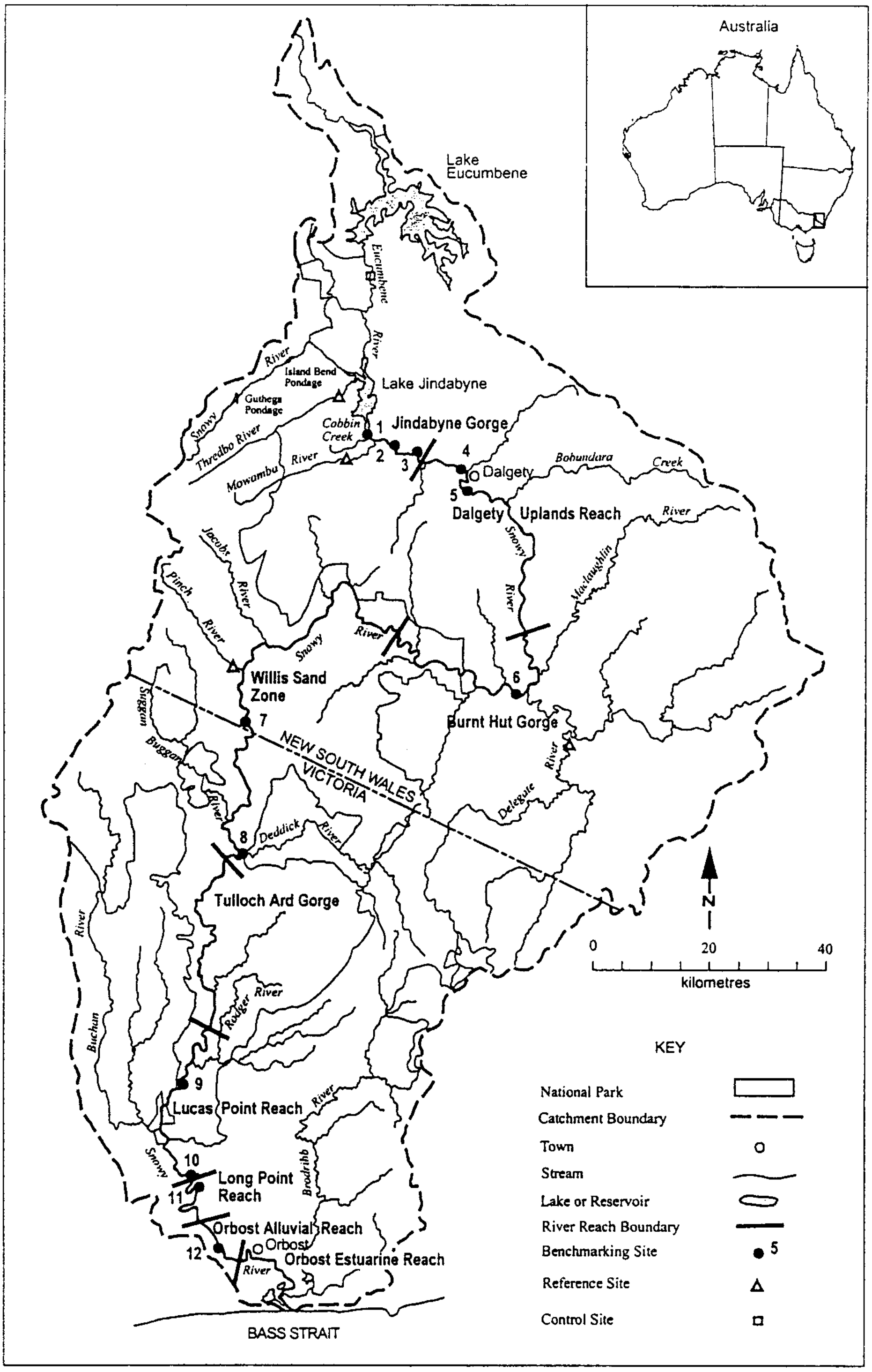


FIGURE 9: **Snowy River Catchment Showing the Nine River Reaches**

Table 5 shows the standardised percentage change in mean daily (or monthly) discharge for various durations since the commencement of flow regulation on the Snowy River downstream of Jindabyne Dam. Small duration flows are equalled or exceeded infrequently whereas large duration flows are equalled or exceeded frequently. Median and low flows (that is, high flow duration) have been reduced dramatically, even as far downstream as Basin Creek (Erskine et al., 1999a). The highest flows (1 percent duration) have experienced the least reduction and, in one case (Basin Creek), an increase since the commencement of flow regulation (Erskine et al., 1999a).

Table 5: Standardised percentage change in mean daily discharge for a range of flow durations before and after flow regulation of the Snowy River by Jindabyne Dam

Flow Duration (%)	Standardised Percentage Change in Mean Daily Discharge after the Snowy Mountains Scheme (%)			
	Jindabyne	Dalgety	Basin Creek	Jarrahmond
1	-92.0	-55.0	78.9	-7.5
5	-99.5	-93.6	-30.8	-47.7
10	-99.4	-96.7	-44.7	-52.9
20	-99.3	-98.1	-58.4	-58.9
50	-99.1	-97.5	-67.6	-66.7
80	-99.9	-94.5	-68.2	-70.0
90	-99.9	-92.3	-63.8	-66.6
95	-99.6	-90.5	-58.2	-66.1

* Monthly flow data only available.

Data taken from Erskine et al. (1999a)

Table 6 shows the standardised percentage change in post-Scheme peak instantaneous discharge for a range of recurrence intervals at the Dalgety, Basin Creek and Jarrahmond gauging stations. There has been a substantial reduction in flood peak discharge for recurrence intervals less than 1.25 years. The slope of the post-Scheme annual series flood frequency curves is always steeper than the pre-Scheme curve and they approach each other or intersect at recurrence intervals greater than 20 years (Erskine et al., 1999a). The increase in flood peak discharge for recurrence intervals equal to or greater than 5 years at Basin Creek and Jarrahmond has been caused by a combination of increased post-Scheme peak discharges on the lower Snowy River and decreased post-Scheme peak discharges at the control station on the upper Murray River (Erskine et al., 1999a).

Table 6: Standardised percentage change in peak instantaneous discharge for a range of recurrence intervals post-Scheme on the Snowy River downstream of Jindabyne Dam

Recurrence Interval (years) on the Annual Maximum Series	Standardised Percentage Change in Peak Instantaneous Discharge Post-Scheme (%)		
	Dalgety	Basin Creek	Jarrahmond
1.0101	-98	-93	-98
1.0526	-95	-82	-93
1.1111	-93	-72	-84
1.25	-89	-54	-70
2	-80	-1	-25
5	-65	63	21
10	-55	89	34
20	-46	102	38

Data taken from Erskine et al. (1999a).

Data on water extractions downstream of Jindabyne Dam have not been obtained but are known to be very small in relation to the volumes diverted for hydroelectric power generation.

6.2 Valley Segment and Reach Type Classification

The application of the new scheme to the Snowy River below Jindabyne Dam using the valley segment and reach type classification levels is outlined in *Table 3*. *Figure 9* shows the spatial distribution of the reaches.

7. Comparison of Proposed System with Existing River Classification Systems

There is no existing river classification scheme that is capable of being applied to, or that would accommodate, all Australian rivers. Rivers change greatly in character from their source to the ocean, or to a terminal lake or floodout. The diversity of Australian rivers is so great that any regionally-based scheme will always experience shortcomings when applied to an area outside that for which it was developed. This is well recognised in the river classification literature (Kondolf and Downs, 1996).

Many schemes have been developed which either only focus on rivers (Brierley, 1999) or lakes (Timms, 1992) or estuaries (Roy, 1984) or some aspect of the condition of a river, lake and/or estuary (Department of Land and Water Conservation's stressed rivers assessment reports; Brierley, 1999). There is no existing scheme that meaningfully attempts to cover all water bodies. This deficiency was one of the reasons that this project was commissioned.

Riley et al. (1984) proposed a hierarchical classification scheme of all water bodies in NSW and applied it to selected areas in NSW, as part of the first State Water Plan. It covered rivers, floodplains, wetlands and lakes. No subsequent scheme, except for the one proposed in this report, has attempted to be so comprehensive. The Riley et al. (1984) scheme has not been subsequently developed and applied to Australian water bodies.

Timms (1992), as outlined in *Section 5*, developed and selectively applied a morphogenetic classification scheme for lakes. This scheme, with only slight modifications, has been adopted as the basis of lake classification in the system proposed in this report.

Brierley (1999) developed and field tested a scheme for classifying rivers and, to some degree, floodplains, but it is only based on rivers in NSW. As it currently stands, the scheme cannot accommodate the full range of rivers, let alone estuaries and lakes, in Australia. Further developments of the scheme as it is applied to new rivers by more geomorphologists (for example, Hardie and Lucas, 2001) will undoubtedly lead to further improvements.

Bisson and Montgomery (1996) proposed that channel reaches consist of relatively homogeneous associations of landforms and habitat types, which distinguish them from adjoining reaches. The river styles of Brierley et al. (1996) and Brierley (1999) correspond to reaches but introduce a new, specialised terminology based on limited criteria. More criteria are required for a national classification scheme. Furthermore, river styles are a bottom up approach based on the expensive and time consuming collection of lower level information, work that has to be done before the river can be classified.

Webb and Erskine (2000) used ten geomorphic criteria to formally define nine channel reaches on the Snowy River below Jindabyne Dam. Erskine (1996b) used four geomorphic criteria to informally define three channel reaches on Congewai Creek and Wollombi Brook in the Hunter River. Erskine et al. (1995) used five geomorphic criteria to informally define nine channel reaches on the Wingecarribee River downstream of Wingecarribee Dam.

No attempt has been made to construct detailed classes for still water bedforms because such schemes already exist for Australia (for example, Bayley and Williams, 1973; Riley et al., 1984; Timms, 1992). Therefore, emphasis is only given to artificial still water bodies, which are ignored by most classification schemes. Timms' (1992) scheme is recommended for initial trials.

8. Conclusions and Recommendations

PPK Environment & Infrastructure, in association with Dr Wayne Erskine and Mr Bob Junor, were commissioned by the Murray-Darling Basin Commission and Environment Australia to develop a National River Classification System.

The specific objectives of the project were:

1. to review and evaluate river classification methodologies and approaches relevant to flow, natural resource planning and management of riverine environments;
2. to develop a practical, management-orientated, hierarchical framework for the classification of Australian rivers and their associated riverine environments to:
    - assist environmental flow allocation and management; and
    - facilitate the development and application of the Environmental Flows Decision Support System and Ecology-Flows Handbook; and
3. to indicate how the framework relates to, and is *comparable* with, existing river classification systems in use within Australia.

The approach taken to meet the project objectives involved the review of proposed and existing river classification methodologies in use in Australia and overseas, the convening of a workshop to discuss the outcomes of the review and identify the key characteristics and most appropriate methodologies for the classification system, and finally the development of a practical, management-orientated, hierarchical framework for the classification of Australian rivers.

A literature review of proposed and existing classification systems identified a wide range of methodologies and approaches relevant to river flows, natural resource planning and river management. These methodologies differ in their purpose and management application, framework, and classification criteria. These features of the key classification systems were identified and their potential for application to environmental flow allocation assessed as part of the project.

There is no existing river classification scheme that is capable of being applied to, or that would accommodate, all Australian rivers. Rivers change greatly in character from their source to the ocean, or to a terminal lake or floodout. The diversity of Australian rivers is so great that any regionally-based scheme will always experience shortcomings when applied to an area outside that for which it was developed. This is well recognised in the river classification literature (Kondolf and Downs, 1996). Many schemes have been developed which either only focus on rivers (Brierley, 1999) or lakes (Timms, 1992) or estuaries (Roy, 1984) or some aspect of the condition of a river, lake and/or estuary (Department of Land and Water Conservation's stressed rivers assessment reports; Brierley, 1999). There is no existing scheme that meaningfully attempts to cover all water bodies. This deficiency was one of the reasons that this project was commissioned.

The key elements of a management-based National River Classification System were discussed at the project workshop convened on 20 July 1998. Based on the outcomes of the workshop, the role, framework and classification criteria were further developed by the project team.

There was general agreement at the workshop that the framework for river classification needs to be hierarchical. A hierarchical structure allows for consideration of rivers at national, regional, local and site specific scales. It was also agreed that the National River Classification System should be based on physical characteristics, specifically climate and geomorphology, and that the open-ended structure should be capable of being expanded to include biological characteristics at various levels in the hierarchy.

During the project workshop it was agreed that the scale most relevant to water allocation and management of environmental flows is the reach.

While classification at reach level is considered the appropriate scale for the primary purpose of the proposed classification system, the bedform/habitat scale is appropriate to river ecology and is also included in the proposed system for completeness.

The adopted approach is an original nested hierarchical scheme based on the channel network, which, to varying degrees, draws on the earlier work of Kellerhals et al. (1976), Mosley (1982), Riley et al. (1984), Roy (1984), Frissell et al. (1986), Hawkins et al. (1993), Rosgen (1985; 1994; 1996a), Bisson and Montgomery (1996), Brierley et al. (1996), Thorne (1998), Erskine et al. (1999a), Webb and Erskine (2000) and Brierley (1999). At the highest level of the classification, broad characteristics of catchments and sub-catchments are defined based on existing inventories of climate and landform at a scale of 1:1,000,000, and on the degree of flow regulation and water extraction. The channel reach (usually 10–100 km long) is the basic unit of classification and 50 reach types are proposed and described. In addition, a range of still water, slow water and fast water habitats has also been proposed and described for use with the scheme.

The proposed classification system is intended for application to rivers from their headwaters to the ocean or to a terminal lake or floodout. As a result, it covers rivers, gullies, lakes, estuaries and artificial water bodies. No other scheme currently in use in Australia has attempted to cover whole river systems.

The proposed National River Classification System has been applied to the Snowy River below Jindabyne Dam (in Chapter 6) to demonstrate its use. The Snowy River example clearly demonstrates the suitability of the proposed classification system to regulated as well as national rivers.

Trialing of the system on some rivers in other regions of Australia is recommended.

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Appendix A

Reviews of Other Proposed and Existing River Classification Systems

Appendix A1: References

The following reference documents were briefly reviewed and determined those that warranted more thorough evaluation. The papers that were subsequently considered in detail are indicated in bold typeface and summarised in *Appendix A2*.

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Appendix A2: Summary of Reviewed Classification Systems

The following tables summarise the key characteristics of each of the classification systems reviewed in detail.

Paper	Brierley, G., 1999. River styles: an integrative biophysical template for river management. In: I. Rutherfurd and R. Bartley (eds.), *Proceedings of the Second Australian Stream Management Conference, Vol. 1, Adelaide*, pp. 93-99. Brierley, G.J., Fryirs, K. and Cohen, T., 1996. Geomorphology and River Ecology in south-eastern Australia: an approach to catchment characterisation. Parts One, Two and Three. *Macquarie University, Graduate School of the Environment Working Paper 9603.*
Framework (hierarchical, similarity)	Multiple assessments of river styles™, river condition and recovery potential.
Use	Characterisation of river reaches for inventory purposes, assessment of river condition and the percieved potential of a stream to be restored to an in tact condition.
Classification Basis	River styles™ based on channel confinement, nature of floodplain, channel planform, geomorphic processes, etc.
Management Application of the Classification System	Inventory purposes, condition assessments, river rehabilitation, benchmarking.
Potential for Application to Environmental Flow Allocation and Management	Useful for determining similarity of rivers and selecting benchmarking sites.
Success as a Management Tool	Useful for understanding the types of rivers present in a catchment and for broad priority setting. Too restricted a focus to cover the full length of rivers from source to the ocean.

Paper	Frissell, C.A., Liss, W.J., Warren, C.E. & Hurley, M.D. 1986. A Hierarchical Framework for Stream Habitat Classification: Viewing Streams in a Watershed Context. *Environmental Management*, **10** (2), 199-214.
Framework (hierarchical, similarity)	Hierarchical.
Use	Scales used by many investigators.
Classification Basis	Stream classification is based on a conceptual view of how stream systems are organised in space and ;how they change through time. These have been achieved via consideration of: ▪ Watershed geomorphic features and events. ▪ Biogeoclimatic landscape.
Management Application of the Classification System	For identifying locations of monitoring stations, determining local impacts of land-use practices, assessment of basin-wide cumulative impacts of human activities on streams and their biota.
Potential for Application to Environmental Flow Allocation and Management	Only relevant to specification of correct scales of investigation.
Success as a Management Tool	Unknown.

Paper	Hawkes, H.A. (1975). "River zonation and classification", in *River Ecology* (Ed. B. A. Whitton). pp. 312-374, Blackwell, London.
Framework (hierarchical, similarity)	General review of classification systems
Use	Classifying rivers based on fish species.
Classification Basis	Classifying rivers based on existing fish species
Management Application of the Classification System	Management of fish.
Potential for Application to Environmental Flow Allocation and Management	Excellent for management of fish in relation to river flow.
Success as a Management Tool	Unknown?

Paper	Hughes, J.M.R. (1987b). Hydrological characteristics and classification of Tasmanian Rivers. *Australian Geographical Studies*, **25**, 61-82.
Framework (hierarchical, similarity)	Similarity matrix.
Use	Rapid classification of large regions and identification of dynamic processes. Assists in determining channel stability.
Classification Basis	Annual flow records, monthly flow records, peak and low flow records were used in this classification.
Management Application of the Classification System	Simple system based on mean annual run-off, coefficient of variation of annual flows and catchment area. Restricted to rivers with gauged streamflow records.
Potential for Application to Environmental Flow Allocation and Management	High, as this study was carried out in the Australian environment and found statistically significant interrelationships between the small number of variables studied which provide considerable amount of knowledge on the river hydrology.
Success as a Management Tool	Unknown

Paper	Hudson, R.H. (1992). River reach characterisation: a survey strategy for river regime and environmental monitoring and analysis. *Erosion and Sediment Transport Monitoring Programmes in River Basins (Proceedings of the Oslo Symposium)*, **210**, 363-372.
Framework (hierarchical, similarity)	Hierarchical
Use	Undertaking river surveys that systematically describes river regime for "traditional" water resource engineering purposes and for biological and chemical description and analysis.
Classification Basis	Physical → Chemical → Biological ▪ *Level 1 hydraulic and morphologic surveys* Based on existing hydrometric data obtained from gauging stations including water level records, velocity distributions and stream widths and depths across gauging sections at or near hydrometric stations. Hydraulical and morphological surveys can be used for preliminary engineering analysis and provides an indication of hydraulic conditions for applications such as stream flow conditions for dispersion of toxic spills and flow dynamics for aquatic habitat conditions. It can also be used to derive the estimates of flow conditions over time. ▪ *Level 2 hydraulic and morphologic surveys* This enhances the information derived from *Level 1* and provides additional information and analysis capabilities with a minor increase in field survey and interpretation. *Level 2* provides a qualitative description of channel form and stability and describes the range of morphologic conditions in a reach. In addition, the hydraulic control of the hydrometric station is described with a cross valley bottom form survey and with longitudinal water surface profiles. ▪ *Level 3 hydraulic and morphologic survey* Provides detailed descriptions of the hydrologic regime, reach hydraulics and the composition and processes of a river reach over two or more morphological cycles (eg. pool, riffle, pool riffle) or 10 to 15 channel widths. Drainage basin conditions are also described. It describes the spatial variability of bed material in the context of they hydraulics at individual cross sections at key points across and along the surveyed. ▪ *Level 4 integrated river survey* Information on physical conditions regarding the form and processes of river reaches; the relationships of the biological and chemical regimes to the abiotic attributes of the river system such as the flow regime; the sediment regime and channel bed stability; and the behaviour of the river and historic evolution of the river reach and how these attributes may effect the biological and chemical regimes. *Level 4* survey provides the type of information required for environmental impact assessment on the physical, biological and chemical properties of a river system. ▪ *Level 5 integrated river survey* Essentially Level 4 surveys but undertaken over several reaches through river systems with repeat surveys over time. These surveys recognise that impacts are cumulative and that the range of conditions experienced at a point are determined by local conditions and by the state of the system. *Level 5* will develop an understanding of the links between the physical, biological and chemical regimes throughout river systems; predict the consequences of changes to river systems such as river diversions, damming, landuse change and climatic change; and will verify models with repeat surveys over time and space.

Paper	Hughes, J.M.R. & James, B. (1989). A Hydrological Regionalisation of Streams in Victoria, Australia, with Implications on Stream Ecology. *Australian Journal of Marine and Freshwater Research*. **40**, 303-26.
Framework (hierarchical, similarity)	Similarity Matrix
Use	Identifies hydrologic regions for Victoria based on quantitative hydrologic data.
Classification Basis	Based on quantitative hydrologic data. Annual flow series, monthly flow series, peak discharge series and low-flow discharge series were used to classify and ordinate stream gauges in Victoria.
Management Application of the Classification System	Generating hypotheses, detecting representative rivers and producing baseline stream surveys.
Potential for Application to Environmental Flow Allocation and Management	Could be used to make before-and-after comparisons of stream organisms in relation to the previous and current hydrological regimes for predictive purposes. Also enables the detection of representative rivers (or parts of rivers) for catchment conservation.
Success as a Management Tool	Has not been used.

Management Application of the Classification System	The integrated river surveys will become a key element in aquatic ecosystem description, analysis and management.
Potential for Application to Environmental Flow Allocation and Management	High
Success as a Management Tool	Unknown

Paper	Kellerhals, R., and Church, M. (1989). "The morphology of large rivers: characterisation and management", in Proceedings of the International Large River Symposium (D. P. Dodge, Ed). *Canadian Special Publication of Fisheries and Aquatic Sciences*, **106**, 31-48.
Framework (hierarchical, similarity)	Not a specific classification but a review of existing schemes with personal views.
Use	Identifies different classification variables and discusses their practicability.
Classification Basis	Looks at a wide range of variables including morphological and biological.
Management Application of the Classification System	Not applicable.
Potential for Application to Environmental Flow Allocation and Management	Discusses the impacts of flow regulation.
Success as a Management Tool	Not applicable.

Paper	Laut, P., Austin, M.P., Body, D.N., Faith, D.P., Goodspeed, M.J. & Paine, T. 1985. Hydrologic Classification of Sub-basins in the Macleay Valley, New South Wales. *CSIRO Australian Division of Water and Land Resources Technical Report Paper*, **45**, 1-64.
Framework (hierarchical, similarity)	Hierarchical
Use	To assess hydrological significance of landscapes in the Macleay Basin.
Classification Basis	Covers three aspects of the interaction between hydrology and landscape: ▪ Hydrological significance using 2 km × 2 km grid cells. Attributes used include vegetative cover, slope, relief, lithology and aspect (all obtained from topographic and geological maps. Hydrologic similarity is a function of rainfall similarity and landscape similarity. ▪ Sub-basins of the Macleay catchment within the size range of 25-50 km^2. These basins were characterised by the grid cell groups occurring within the boundaries and classified. ▪ Use of sub-basin classification to predict hydrologic and precipitation indices by numerical taxonomic methods. These equations were developed for general hydrological similarities, flood peaks or particular probability and a soil moisture storage parameter for use in a water balance model for nine gauged catchments.
Management Application of the Classification System	▪ To improve assessment of national water resources by providing a basis for interpolation between gauged catchments. ▪ To improve the basis for design of engineering structures in ungauged catchments. ▪ To provide a basis for the prediction of the hydrologic effects of changes in land use and management. ▪ To form a bank of hydrologic data for use in research.
Potential for Application to Environmental Flow Allocation and Management	While possible, it has not been used to date.
Success as a Management Tool	Applied successfully for nine gauged catchments. Overcomes difficulties associated when using a more deterministic approach to landscape characterisation.

Paper	Kondolf, G.M., (1995). Geomorphological stream channel classification in aquatic habitat restoration: Uses and limitations. *Aquatic conservation: Marine and Freshwater Ecosystems*, 5, 127-141.
Framework (hierarchical, similarity)	Both hierarichal and similarity matrix.
Use	Rapid classification of large regions and identification of dynamic processes. Assists in determines channel stability
Classification Basis	Classification based on geomorphological characteristics.
Management Application of the Classification System	Surveying existing conditions and setting priorities for restoration; defining an end state towards which restoration should proceed; and providing initial indications about restoration measures likely to succeed in a given channel.
Potential for Application to Environmental Flow Allocation and Management	Not applicable. Reviews existing schemes.
Success as a Management Tool	Not applicable.

Paper	Mosley, M.P. 19. The Classification and Characterisation of Rivers. From: *River Channels - Environment and Process*, **12**, 297-320. Edited by Richards, K.
Framework (hierarchical, similarity)	Reviews previous examples of classification: ▪ genesis, history and structural geologic relationships of rivers; ▪ morphological classification; ▪ bed characteristics and channel stability; ▪ nature of source (eg. from hills or mountains, springs and land drains, marsh or fernland); ▪ physiography (eg. in South Africa, coastal-belt rivers with mountain sources; coastal-belt rivers with non-mountain sources; rivers of the elevated central plateau); ▪ chemical characteristics
Use	Review rather than a new scheme.
Classification Basis	▪ Review.
Management Application of the Classification System	▪ Limited.
Potential for Application to Environmental Flow Allocation and Management	Could be applied with further development.
Success as a Management Tool	Unknown.

Paper	Montgomery, D.R. & Buffington, J.M. (1997). Channel Reach Morphology in Mountain Drainage Basins. *Geological Society of America Bulletin*, **109(5)**, 596-511.
Framework (hierarchical, similarity)	Similarity Matrix
Use	Identifies channel condition and interprets channel response potential
Classification Basis	Based on aspects of reach-level channel morphology such as: ▪ bed material; ▪ bedform pattern; ▪ dominant roughness elements; ▪ sediment storage elements; ▪ typical confinement; and ▪ pool spacing.
Management Application of the Classification System	Assessment of channel condition, prediction of channel response to disturbance and interpretation of the causes of historical channel changes.
Potential for Application to Environmental Flow Allocation and Management	Could be used to determine environmental flow discharge required to maintain or re-establish pre-existing channel types.
Success as a Management Tool	Not ideal for characterisation of river platforms and does not identify streams contained within lower reaches of the river system.

Paper	Orlowski, L.A., Schumm, S.A., & Mielke Jr., P.W. (1995). Reach classifications of the lower Mississippi River. *Geomorphology*, **14**, 221-234.
Framework (hierarchical, similarity)	Multivariate
Use	Multi-Response Permutation Procedures (MRPP) provides an effective tool for analysing the temporal and spatial evolution of the channel. Classifications based upon Multivariate or individual channel variables and may thus contribute to a greater understanding of local short term conditions and the manner and form of change.
Classification Basis	MRPP defines homogeneous subpopulations of the river as reaches for the collective response of the channel morphology variables (such as width, depth, cross-sectional area and width-depth ratio). The numeric analyses generate a refinement, by further subdivision, of the original proposed reach structure.
Management Application of the Classification System	Provides an unbiased classification system.
Potential for Application to Environmental Flow Allocation and Management	High provided a high quality data base is available or could be generated.
Success as a Management Tool	The results are not biased by operator input and it is possible to investigate additional causal factors.

Paper	NSW Department of Land and Water Conservation, 1999. Stressed Rivers Assessment Report. Series for all major rivers in NSW.
Framework (hierarchical, similarity)	Matrix of hydrologic stress versus environmental stress.
Use	Rapid assessment of proirity subcatchments for water resources planning.
Classification Basis	Multiple assessments of hydrologic and environmental stress, conservation values and risks for each subcatchment in a river system.
Management Application of the Classification System	Prioritisation of subcatchments for management of water extraction.
Potential for Application to Environmental Flow Allocation and Management	Possible but needs further work to establish reliability of input information and assessments.
Success as a Management Tool	Useful for broad priority setting but does not currently accommodate lakes, estuaries and artificial channels.

Paper	Rosgen, D. L. (1985). A stream classification system, *in Riparian Ecosystems and Their Management: Reconciling Conflicting Uses* (Eds Johnson, R.R., Zeibell, C.D., Patton D.R., Pfoliott, P.F. and Hamre, R.H.), 91-95, United States Forest Service, General Technical Report M-120, Rocky Mountain Forest and Range Experimental Station, Fort Collins, Colorado.
Framework (hierarchical, similarity)	Hierarchical
Use	Can be used for engineering, fish habitat enhancement, restoration and water resource management applications. More specifically, hydraulic geometry relations, sediment supply/availability, fish habitat structure evaluation, flow resistance, critical shear stress estimates, shear stress/velocity relations, streambank erodibility potential, management interpretations, sequences of morphological evolution and river restoration principles.
Classification Basis	Morphological arrangement of stream characteristics into relatively homogeneous stream types. Seven major types were identified that differed in entrenchment, gradient, width/depth ratio and sinuosity. Within each of the seven categories are six additional types delineated by dominant channel materials from bedrock to silt/clay along a continuum of gradient ranges.
Management Application of the Classification System	Provides an insight into sensitivity and consequence of change. Offers a selection and evaluation criteria of fish habitat.
Potential for Application to Environmental Flow Allocation and Management	High
Success as a Management Tool	Has been developed further by Rosgen (1996) and is currently used in the United States.

Paper	Riley, S.J., Warner, R.F. and Erskine, W.D., 1984. *Classification of Waterbodies in New South Wales.* Water Resources Commission of New South Wales, North Sydney.
Framework (hierarchical, similarity)	Hierarchical.
Use	Classification of all waterbodies in NSW.
Classification Basis	Morphogenetic and morphometric classification.
Management Application of the Classification System	Not attempted to date despite field testing in a number of areas.
Potential for Application to Environmental Flow Allocation and Management	Not attempted to date.
Success as a Management Tool	Unknown.

Paper	Schumm, S.A., Mosley, M.P. & Weaver, W.E. (1987). *Experimental Fluvial Geomorphology*, Wiley, New York.
Framework (hierarchical, similarity)	Not a specific classification
Use	Identifies different classification variables and discusses their practicability.
Classification Basis	Looks at a wide range of variables including morphological and biological.
Management Application of the Classification System	Not applicable.
Potential for Application to Environmental Flow Allocation and Management	Discusses the impacts of flow regulation.
Success as a Management Tool	Not applicable.

Paper	Rosgen, D.L. 1996. *Applied River Morphology, Wildland Hydrology, Pagosa Springs.*
Framework (hierarchal, similarity)	Similarity matrix.
Use	Adopted by the United States Department of Agriculture, Forest Service for stream assessment, classification and rehabilitation.
Classification Basis	Channel morphology based on the following features: ▪ channel gradient; ▪ sinuosity; ▪ width/depth ratio; ▪ dominant particle size of bed and bank materials; entrenchment of channel and confinement of channel in valley; and ▪ landform features such as soil erodibility and stability. After the stream type is identified, the streams were sub divided into stream sub-type criteria (identified by topos and aerials) including: ▪ riparian vegetation; ▪ organic debris and/or channel blockages; ▪ stream size (width); ▪ flow regime (perennial, ephemeral, subterranean, intermittent channels, streamflow variations and sources; stormflow, snowmelt, glacial fed etc.); ▪ depositional features; and ▪ meander patterns.
Management Application of the Classification System	▪ Management standards and guidelines for riparian areas. ▪ Developing threshold limits. ▪ Channel stability management. ▪ Aquatic ecology management. ▪ Stream restoration guidelines.
Potential for Application to Environmental Flow Allocation and Management	Would need revision for appliction to Australian rivers but offers potential.
Success as a Management Tool	Has worked successfully in the United States.

Paper	Timms, B.V., 1992. *Lake Geomorphology.* Gleneagles Publishing, Adelaide.
Framework (hierarchical, similarity)	Usually combination of hierarchical and similarity. Applied to each formative process separately.
Use	Classification of all natural lake types by processes of formation.
Classification Basis	Morphogenetic classification based on processes of lake formation.
Management Application of the Classification System	Not attempted to date.
Potential for Application to Environmental Flow Allocation and Management	Not attempted to date.
Success as a Management Tool	Unknown.

Paper	Sinha, R. & Friend, P.F. (1994). River Systems and Their Sediment Flux, Indo-Gangetic Paris, Northern Bihard, India. *Sedimentology* **41**, 825-845.
Framework (hierarchical, similarity)	Similarity matrix
Use	None known.
Classification Basis	Described in terms of their channel morphology, such as channel depth, channel width, width to depth ratio, sinuosity and braiding, and suspended sediment characteristics. The systems levels are as follows: ▪ mountain-fed; ▪ foothills; ▪ plains-fed; and ▪ mixed-fed rivers.
Management Application of the Classification System	None known.
Potential for Application to Environmental Flow Allocation and Management	Too specific for general application.
Success as a Management Tool	Not used.

Appendix B

Workshop Agenda and List of Participants

20 July 1998

MANAGEMENT-BASED RIVER CLASSIFICATION SYSTEM WORKSHOP AGENDA

10:15 am	Welcome
10:30 am	Introduction
10:35 am	**Role of a National River Classification System**

- Ecology-Flows Decision Support System (Bill Young)
- Existing River Classification Systems in use within Australia (Gary Brierly)
- The New Zealand Experience (Eric Pyle)
- The role and application of the of Classification System to be developed by this Project

11:30am	**Defining a Framework for River Classification**

- Homogeneous reaches and subcatchments
- As natural systems or in present state of degradation
- The hierarchical approach – providing a selection of scales for all users
- Agree most appropriate framework.

12:30	Lunch
1:30pm	**Key Parameters for Classification of Rivers**

- **Determine basis for selection of parameters**
  - Parameters need to reflect River in natural state at highest level
  - Information needs to be readily obtainalbe
  - Most important parameters highest up the framework

- **Discussion of potential criteria (Wayne Erskine)**
- **Identification of key criteria (workshop)**
  - Geomorphological
  - Climatic
  - Hydrological
  - Ecological

3:30pm	Workshop Outcomes & The Next Step
3:45pm	Workshop Close

Management-based River Classification System Workshop Participants

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Management Committee	**Organisation**
Louise Rose	Environment Australia
Nick Schofield	Land & Water Resources R&DC
David Leece	Environment Protection Authority
Scott Keyworth	Murray-Darling Basin Commission

Invitees

Eric Pyle	New Zealand Ministry of Environment
Bill Young	CSIRO
Gary Brierley	Macquarie University
Martin Thoms	CRC, Freshwater Ecology
Henry Nix	Australian National University
John Anderson	Southern Cross University
Paul Wettin	Department of Land and Water Conservation
Stuart Bunn	Griffith University
Ian Prosser	CSIRO
Tony Church	NSW Environment Protection Authority
Martin Shafton	Murray-Darling Basin Commission
Brian Lawrence	Murray-Darling Basin Commission
Clive Thomas	Community Advisory Committee Chairman
Sam Lake	Monash University
Helen Watts	AACM

Project Team

Wayne Erskine	University of NSW
Bob Junor	Chello Hill
Derek Low	PPK Environment & Infrastructure
Susan Calvert	PPK Environment & Infrastructure

Facilitator

Ann Shaw-Rungie	QED

Authors: S Calvert, W Erskine, B Junor

Reviewer: D Low

Approved by: D Low

Signed: ....

Date: 11 October 2001

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