Leon Bren

Forest Hydrology and Catchment Management

An Australian Perspective

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Preface

This book provides a concise account of the discipline and findings of forest hydrology in Australia, with some considerations of overseas work as well. The book is complementary to textbooks on river hydrology – although the world of engineering hydrologists and forest hydrologists do intersect, their problems are rarely the same. The book is aimed at undergraduate students, practising land managers, and interested citizens. It should be suitable for a first course in forest hydrology and is based on the teaching experience in such courses at The University of Melbourne.

The subtitle of the book suggests that Australia is somehow "different." At the hydrologic process level, there appears little difference between Australia and other countries. However, Australian hydrology does seem to go from extremes more than other countries – particularly droughts to floods. Chapter 8, which examines the role of fire, also highlights some distinctly Australian behaviour. We also have the only known forest tree in which water use is a clear function of age, so perhaps we are different.

The book is not an encyclopaedic reference on all things to do with forest hydrology; rather, it attempts to give a "snapshot" of this discipline in Australia. Thus, for instance, although there is some consideration of stream flow measurement, the student who needs to know about such structures is expected to find a more detailed account of the technology of measurement. Similarly, many other techniques worthy of a book of their own are rather superficially dealt with. There is a huge, worldwide literature on forest hydrology, and I have attempted to use only material relevant to Australia. The result has been a tendency to generalise and reduce referencing to improve readability.

Finally, I would like to thank my wife, Elizabeth, and family for their support in the production of this. Let me also thank my colleagues (particularly Professor Gerd Bossinger) at the University of Melbourne, Department of Forest and Ecosystem Science Campus at Creswick, Victoria, for their unstinting support. A large number of colleagues – too many to name – from the world of forestry and hydrology have also helped me in so many ways.

Creswick, VIC, Australia Leon Bren

List of Symbols and Units Used in the Book

Chapter	Symbol	Definition	Units
1	A	Area of catchment	Ha
	s	Catchment slope	
	V	Volume of water	m^3
	D	Depth of water	m
	q	Stream flow	Ls^{-1}
	t	Time	Seconds (s)
2	P	Depth of precipitation	mm
	Q	Depth of stream flow	mm
	ET	Depth of evapotranspiration	mm
	S	Catchment storage	mm
	ε	Error	mm
	Δ	Symbol for change in	
	p	Fraction of grassland	
	$\in$	Elasticity	
4	q	Stream flow	Ls^{-1}
	h	Depth of water	mm
5	C	Annual flow, Clem Ck	mm
	E	Annual flow, Ella Ck	mm
	p	Daily flow (Picaninny Ck)	mm day^{-1}
	s	Daily flow (Slip Ck)	mm day^{-1}
	r	Daily rainfall	mm
	a_1 to a_6	Regression constants	
	R	Estimated residual	mm day^{-1}
	d	Day number	
	ε	Error	mm day^{-1}

(continued)

Chapter	Symbol	Definition	Units
	T	Treatment effect	mm day^{-1}
	NS	Nash-Sutcliffe coefficient	
	O	Observed value (N-S eqn)	
	P	Predicted value (N-S eqn)	
6	T_f	Throughfall	mm
	S_f	Stem flow	mm
	I_n	Interception	mm
	Q	Annual stream flow	mm
	P	Annual rainfall	mm
	g	Change in annual yield	mm
	L_{max}	Kuczera parameter	
	K	Kuczera parameter	
	Aetash	Annual evapotranspiration	mm
	t	Age of forest	year
	e	Euler's number	
	p1a-p7a	Watson model parameters	
7	Q	Annual stream flow	mm
	P	Annual rainfall	mm
	t	Age of plantation	years
	Δ	Change in	
11	Q	Annual stream flow	mm
	P	Annual rainfall	mm
	A	Area	ha
	v	Daily water consumption	Litres
	y	Percentage of catchment	
	w	Buffer strip width	metres

Contents

Chapter 1
The Basics of Catchment Hydrology

Abstract The water catchment is the fundamental concept underpinning quantitative hydrology. After considering equivalent terminology, the reader is introduced to analytical methods including flow vectors and catchment flow nets. The methods of defining catchments on a map, using a digital terrain model, or in the field are explained. The reader is introduced to streams (and catchments) of higher order and geomorphic rules which apply to the geometry of these in Australia. The arithmetic of catchment computations involving volume, area, and depth is explained, with particular consideration of the issue of avoiding confusion in units. Finally the reader is introduced to the stream hydrograph and the type of short-term and long-term variation encountered in these. Considerations of the differences between forest hydrology and the more general discipline of hydrology and how Australian hydrology differs from that of other parts of the world are made.

As befits a book on forest hydrology, we have used three small forested catchments to illustrate many of the concepts described. These catchments – Clem Creek (46 ha), Ella Creek (113 ha), and Betsy Creek (44 ha) comprise the Cropper Creek Paired Catchment Project detailed in Sect. 5.2 of this book. Access to small streams and following their behavior is a great learning process; hence the use of data from these in this volume.

1.1 About Water Catchments and Stream Networks

The most basic concept of hydrologic science is the catchment – the area of land contributing water to a nominated point on the earth's surface. This is illustrated in Fig. 1.1 by a view of Clem Creek research catchment, in which the contributing area to the stream measurement weir is evident. This concept works well where there is a well-defined stream and ridge system. Equivalent terms are watersheds (US) and drainage basins (US & UK). The catchment can be further divided into spurs and ridges forming the boundaries (also occasionally called "watersheds"), the slopes which comprise the bulk of the land (often divided into upper and lower slopes), the stream, sometimes drainage lines (old stream beds which don't usually carry water), and the riparian or gully zone in direct association with the stream.

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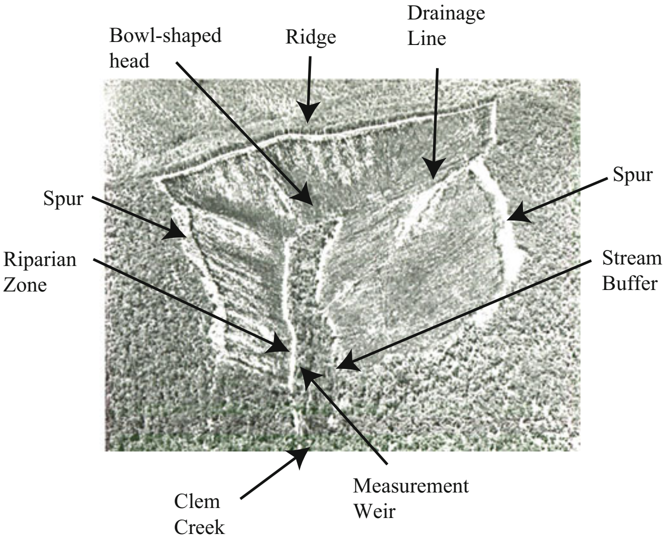


Fig. 1.1 A small catchment – the fundamental building block of hydrology. This is an oblique aerial photograph of Clem Creek research catchment, after clearing of native forest and conversion to pine to determine water yield effects

Although flow through the catchment is commonly referred to as “runoff”, the reality for Australian forested catchments is that most of the flow occurs underground.

Figure 1.2 illustrates a stream network (sometimes referred to as a “blue-line network”). It can be seen that the smaller streams pass water into larger streams, and that the water effectively always moves downhill and is lost to the catchment. Elucidating the mechanism and quantification of the processes involved is the basis of hydrology. This water participates in the global water cycle. Water is always seeking to find a point of lower energy and hence it moves downhill under the influence of gravity, either as groundwater flow (under the surface) or streamflow (on the surface). Some is evaporated into the atmosphere, either from the soil surface or by passing through plants. Water is never still for long, and hence catchments are very dynamic places.

1.2 Topographic Analysis and Catchment Boundaries

In general, accessible water in a catchment is at or close to atmospheric pressure. Thus, assuming it is not moving fast, its height above sea level (or above any other convenient datum) is a measure of its relative potential energy. Contour maps or their modern alternative, digital elevation models, are a fundamental tool of quantifying hydrologic energy.

Fig. 1.2 The "*blue-line*" network of the 67 km^2 "Tarago" catchment approximately 100 km east of Melbourne. The Strahler Ordering of a portion of the streams in the north-eastern corner is shown in Fig. 1.10

1.2.1 Catchment Flow Vectors and Streamlines

Figure 1.3 shows a vector (arrow) analysis of a contour map of a small catchment above the point marked A. The arrows ("flow vectors") mark the path of steepest ascent or descent and are at right angles to the contours. A streamline (also called a flowline) is a locus of these arrows from a point and marks the path taken by a hypothetical flow of water emanating at the upstream end of the flowline. The catchment boundary of point A on the stream is the envelope containing all the vectors that ultimately pass water to A. The concept does not work in flat country because the energy gradients are so small. When crossing a stream or ridge, the direction of the arrows usually becomes undefined, meaning the start or end of that particular flow path. A ridge means that the flow vector changes direction to flow into the next catchment. A stream means that the water passes from the slope to the stream and is lost to the catchment.

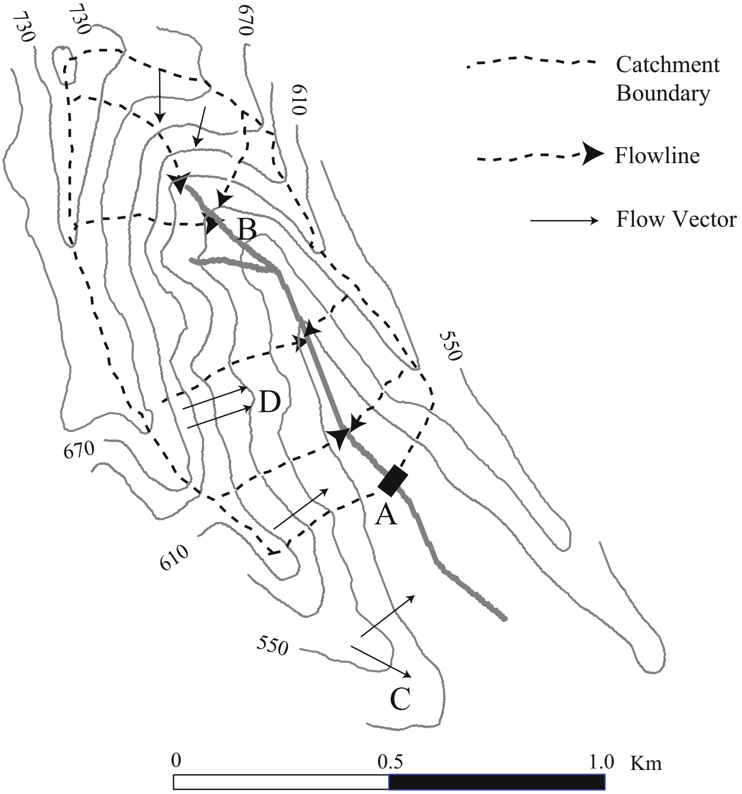


Fig. 1.3 Plan of a small catchment showing flow vectors, streamlines, and a point of convergence forming the stream head

The vector concept is a useful first step in providing an understanding of where areas contributing water to a point on a stream are, and in defining areas of flow convergence. Thus, in Fig. 1.3, Point B shows a convergence of flow vectors (streamlines). This indicates an area with a possible propensity for erosion because of this concentration of flow (and water energy). The concentration of flow is often associated with a groundwater outflow ("spring") in which a point source of water bubbles to the surface. Erosion and surface flow associated with this leads to the start of a stream. This is commonly called a "gully head." Figure 1.4 shows such an area in the field. Over long periods of time these gully heads move upstream by "headward erosion", thereby entrenching the stream in the landscape. Area C shows a divergence of flow vectors; these are often areas of low erosion because of the low concentration of water, and are usually found at the end of spurs. Area D shows parallel flow vectors; these areas are the most common and are generally stable.

The upslope geometry of catchments has a direct influence on the behaviour of the element. One quantification of this is the "specific area" (S_a) – the ratio of

Fig. 1.4 View of a gully head. It's a burnt research catchment (see Fig. 1.1) and the pine is being salvage-logged, so the gully head is easy to see. The radial geometry converges to a focus at the gully head. The level of soil disturbance associated with severe forest burning is evident

upslope contributing area to contour length. This is a measure of "hydrologic slope load". The concept is illustrated in Fig. 1.5 for an isolated portion of a catchment. Figure 1.6 illustrates a classification of the geometry of slopes (convergent, planar or parallel, and divergent) and their specific areas. The specific area of these is shown as a function of distance downslope. It can be seen that the convergent geometry gives a far higher slope loading than either the planar or divergent geometries. A consequence is that convergent areas ("hollows") should be paid particular attention in land management. It is an instructive (and useful) exercise both on maps and in the field to observe such areas.

The combination of streamlines and contours can be refined to a "flow net. Figure 1.7a, b shows such a network for a proposed forest harvesting area which includes a small catchment and land from neighbouring catchments. The purpose of this is to determine zones with a high specific area; these might be given particular scrutiny in planning and management. The contours correspond to lines of equal energy. The streamlines show the direction of water movement. The flow lines must always be at right angles ("orthogonal") to the contours (by definition). The boundaries of the catchments form an envelope for the streamlines. Area ABC on Fig. 1.7 is sometimes called a "facet" and defines the catchment contributing to the right hand side of the stream between A and B; ultimately an entire catchment can be divided into facets using a contour map. It can be seen that the facets shown have different shapes which can be classed into "convergent", "divergent" or "parallel." When viewed as a groundwater system these give different outflow responses (see Chap. 4). The catchment outflow response is the net sum of these individual

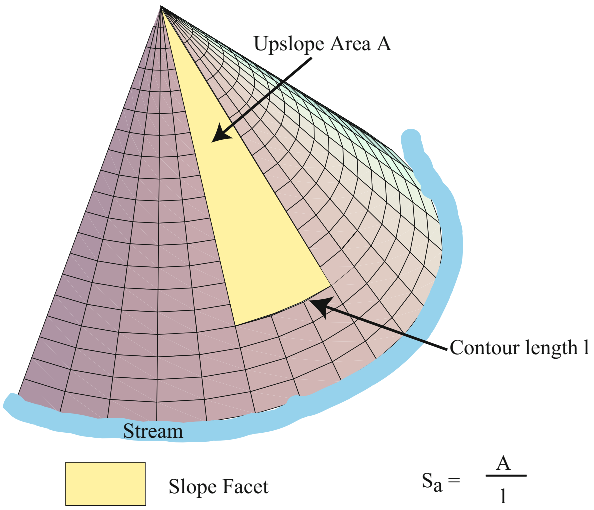


Fig. 1.5 The concept of specific area for a small portion of a catchment slope

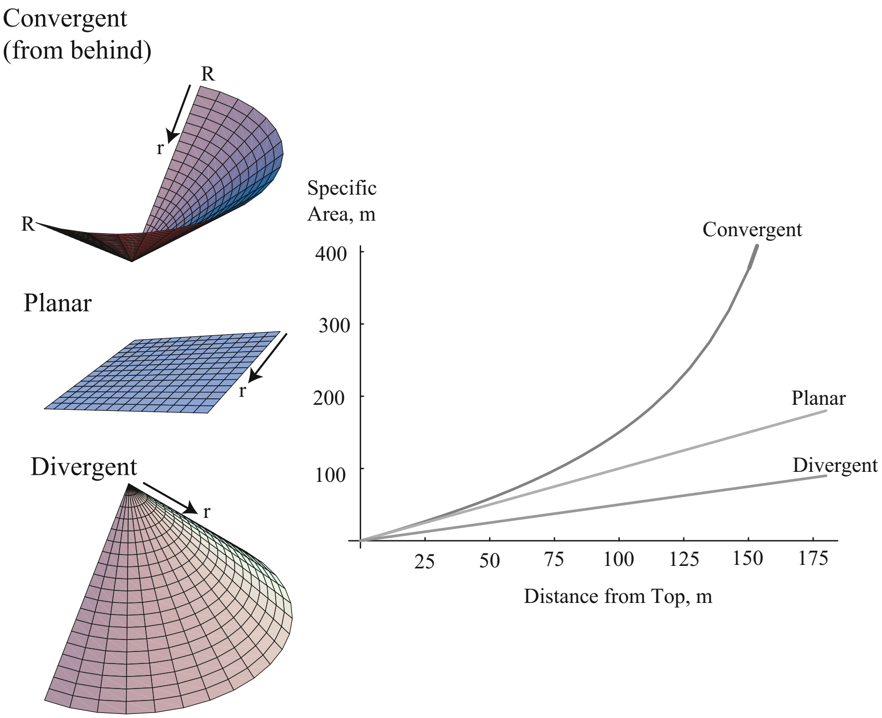


Fig. 1.6 Convergent, planar/parallel, and divergent catchment geometries and the slope hydrologic loading associated with each

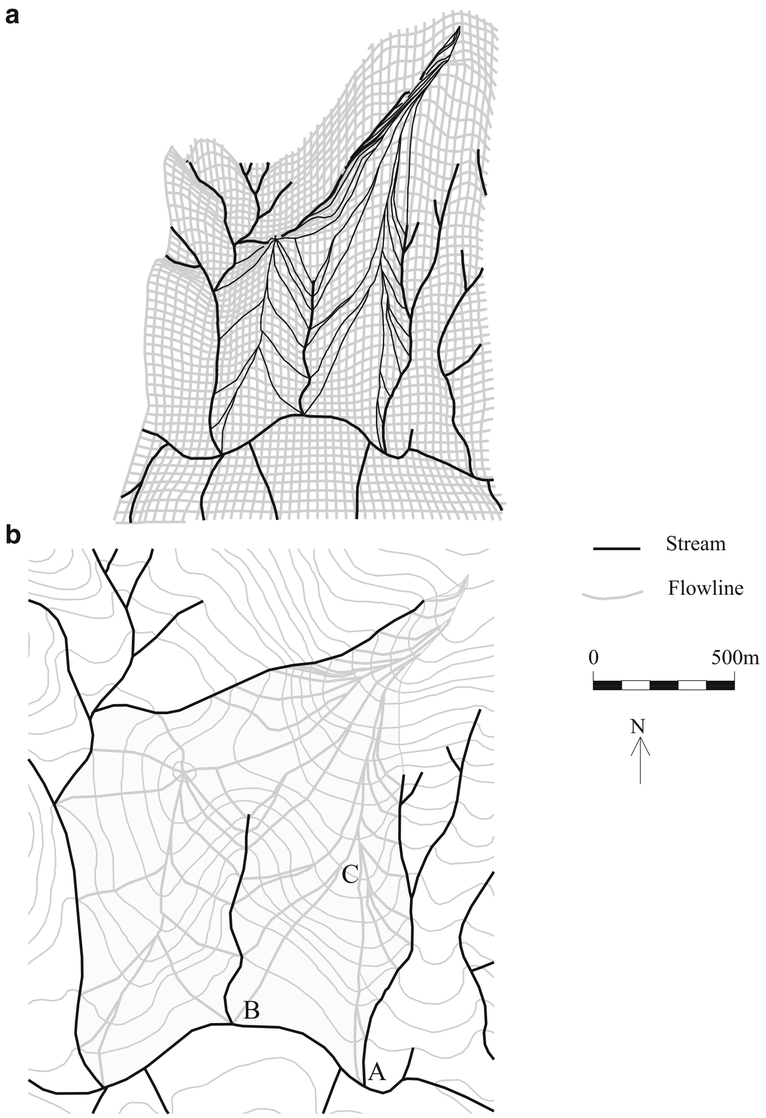


Fig. 1.7 Illustrating a facet analysis of a catchment and surrounds to determine areas with a high specific loading. (**a**) 3D perspective, (**b**) map

contributing areas, with some time weighting to allow for the outflows from different facets to travel along the stream. Preparation of a flow net for a small catchment is an excellent way to start quantification of catchment properties and gives analysts a good understanding of the role of topography.

1.2.2 *Defining Catchment Boundaries for a Specific Stream Cross-Section*

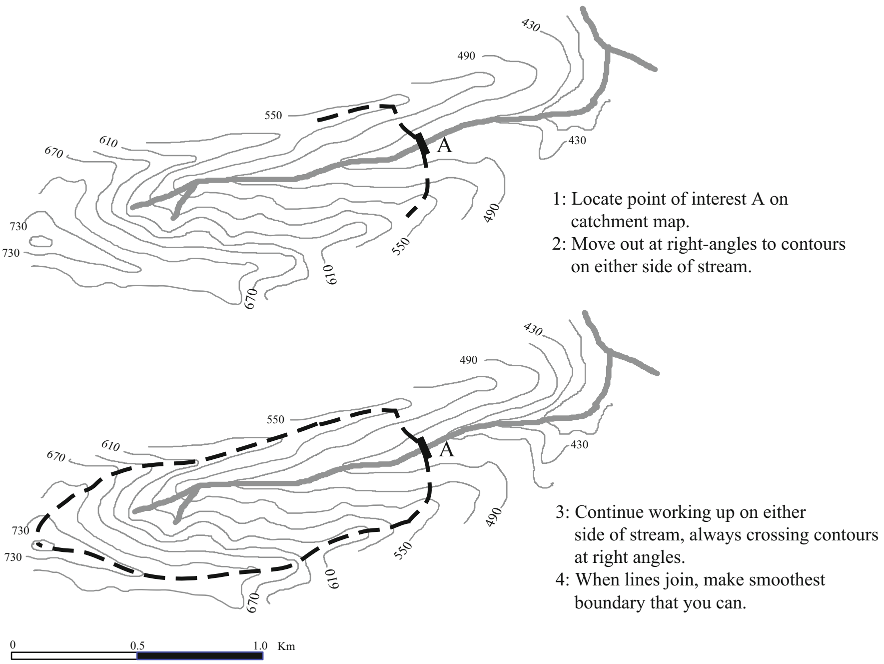
Catchment definition using any method can be difficult; the skill of the analyst greatly improves with practice. Although flow net analysis will provide catchment boundaries, it is not a satisfactory method for anything but small catchments. Large catchments may be hundreds of kilometres in length, cover many map-sheets and have large, flat areas in which the concept of catchment boundaries is not very applicable.

Catchment definition must start with nomination of a specific point (or cross-section) on a stream – typically this is the site of a dam, a road crossing, or a point of flow measurement. Methods of catchment definition are described below.

Walking the Boundaries Small catchments can be delineated (and hence the area determined) by walking around the boundaries starting from a nominated point on the stream. Usually the left side and the right side are walked around separately, with the boundaries being marked as you go. On the second leg, the walker intersects the previously marked boundary from the first leg, completing the boundary survey. This can be mapped using a GPS or surveying techniques. The technique requires some skill (and physical ability) and may need a number of attempts until a satisfactory definition is achieved, with the walker moving from the stream to the catchment ridge. Repetition of the method shows how imprecise the definition of the catchment boundaries can be, even in well-defined topography. The author views a 10 % variation in area between independent determinations of area as reasonable. For most cases the method is not practical because of time, vegetation density, and obstructions due to physical obstacles, private property, etc.

By Contour Line Analysis This works by defining the line of slope successively from the starting point on the stream to the ridge of the catchment using a contour map. Again, the left hand side of the catchment and the right hand side are defined until they intersect. For a small catchment the task is simple. However for a large catchment occupying many maps the task may take many hours and involve much reworking. The area of the enclosed figure which results is the catchment area. Figure 1.8 illustrates steps in the process. Each boundary segment must cross contours at right angles. The boundary segments should ultimately be overdrawn as a smooth curve, but with contours crossed at right angles. This is a fundamental hydrologic skill and should be a first step in resolution of hydrologic issues.

By Dotting the Approximate Catchment Boundary Topographic data are not always available. If this is the case, then the stream network in the area is mapped. Streams are defined as being “within the catchment” or “outside the catchment.” By taking the tip of a stream “inside the catchment” and finding the closest streams outside the catchment, a “dot” is placed on the map approximately halfway between the tips. Then, by joining the locus of the dots and with some interpolation, the catchment boundary can be defined. The method is illustrated in Fig. 1.9. This



1: Locate point of interest A on catchment map.
2: Move out at right-angles to contours on either side of stream.

3: Continue working up on either side of stream, always crossing contours at right angles.
4: When lines join, make smoothest boundary that you can.

Fig. 1.8 Process of defining a catchment boundary on a map. The catchment is that of Ella Creek

approach is often helpful with contour line analysis as well in giving some guidance.

By DEM Analysis There are a collection of algorithms incorporated into most GIS systems which effectively replicate the approaches above for digital elevation analysis. Although most algorithms are refined and reliable, the output of these should be checked against contour maps and field inspection. Problems may include inadequate detail in the digital elevation model (DEM), presence of flat areas in which the catchment boundary is not defined, and inadequacies in the catchment definition algorithm used. The major difficulties with this method are the overhead of obtaining and learning a suitable package, obtaining an adequate DEM, and sometimes subtleties in the algorithm. The reader is referred to the documentation of GIS systems.

Difficulties in catchment definition usually include the non-availability of topographic mapping, or the overhead of obtaining topographic data, the size of the catchments (which may occupy many map sheets), and the presence of large, flat areas which do not have a well-defined catchment boundary. It is usually assumed that the surface boundaries of the catchment correspond with the subsurface boundaries, but (particularly in karst (limestone) landscapes) this is not always the case. In practical terms, it is almost impossible to determine sub-surface catchment boundaries with any degree of accuracy.

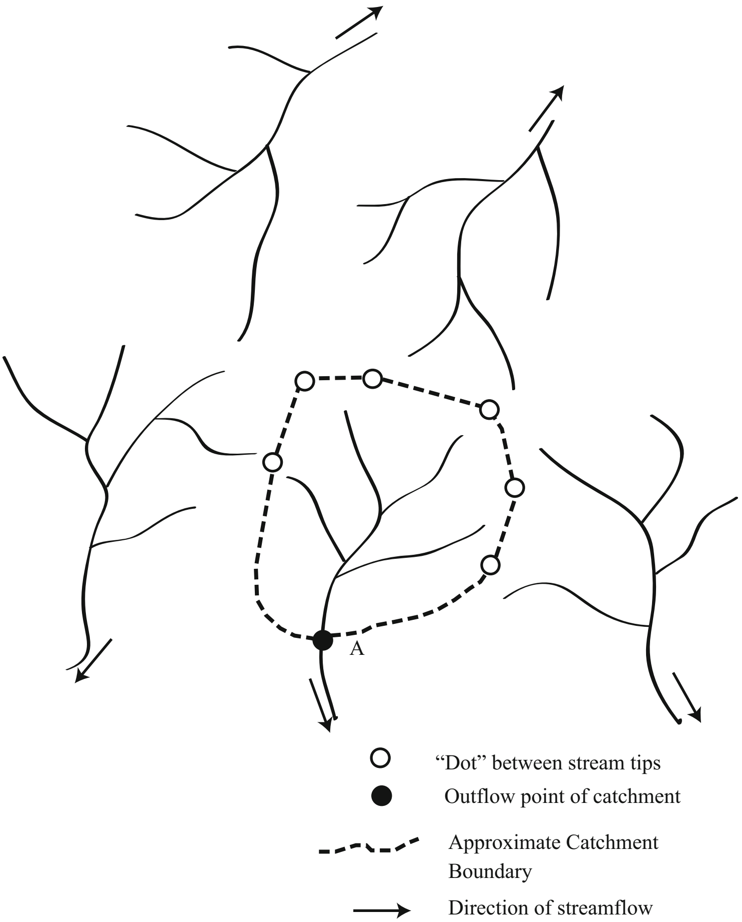


Fig. 1.9 Applying the “dot method” of determining catchment boundaries

In general all, the methods above have been approximate. More recently the advent of LIDAR mapping has sometimes allowed delineation of catchments and their micro-topography with hitherto unknown accuracy. Although this is to be applauded, we usually do not have the computational methods to take advantage of this.

1.3 Stream Networks

All rivers of the world are formed by the coalescence of large numbers of smaller streams. In humid headwater environments which support forests, this commonly results in a “space-filling network” in which no point on the catchment surface is more than a few hundred metres from a stream. The dendritic (“tree-like”) structure of stream networks has led to the concept of stream ordering. This is based on the fact that (usually) smaller streams combine to make a larger stream, and this then combines. . .*ad infinitum*. . .until they either pass into an ocean or lake or lose their water by evaporation or infiltration to groundwater. The concept of Strahler ordering (Strahler 1952) gives a useful terminology for discussion of streams. Figure 1.10 shows this applied to a stream network extracted from the stream network of Fig. 1.2. Strahler ordering is one of a number of comparable ordering systems, but appears to be the most commonly used around the world. It provides a useful terminology for dealing with small streams

In Fig. 1.10 the streams are marked with their Strahler order. In this, the smallest flowing streams are designated as first order. Moving downstream, we change to the next highest order at a confluence with a stream of equal order. If we have a confluence with a stream of different order we retain the higher order. Thus if two first order streams meet, the resultant stream is 2nd order. If two second order streams meet, the result is a third order stream. If a first order and a third order stream meet, the resultant stream is third order. If three streams meet at a point, the fiction is that one stream merges with the confluence of the other two some distance downstream and the rules are then applied (this does not change the ultimate outcome). Figure 1.11 illustrates the decisions to be made to assign such orders.

In general:

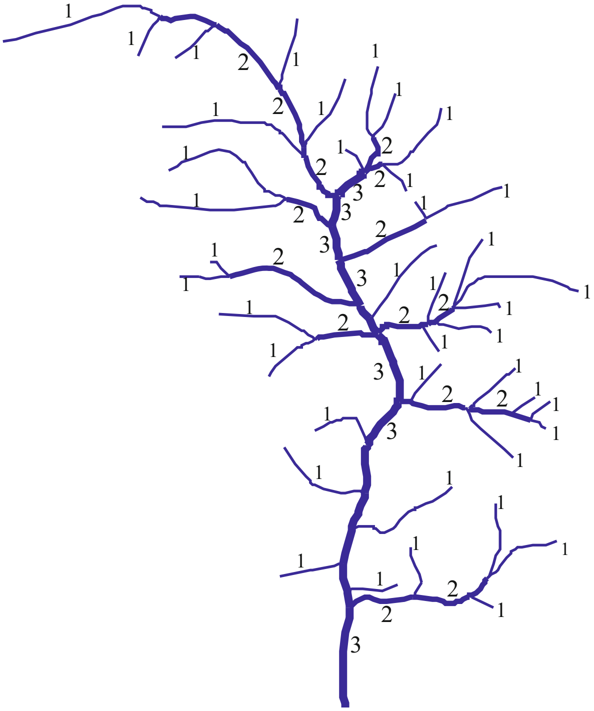
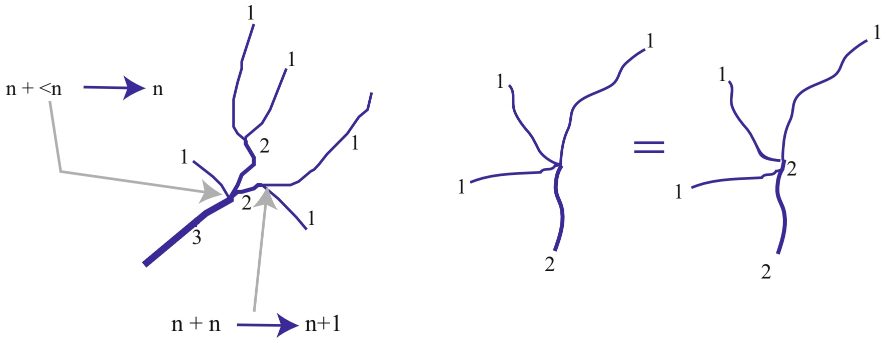


Fig. 1.10 The concept of Strahler Ordering applied to a stream network. The streams are from the north-east area of the catchment of Fig. 1.2



(1) Basic ordering rules (2) Special case of three streams joining

Fig. 1.11 Details of Strahler Ordering (equal streams, n and n + 1, 3 n streams)

1. The higher the order of the stream, the larger the stream. Exceptions are when larger streams pass over areas which allow them to infiltrate ("influent streams" – common in Australia in summer).
2. The larger the scale of stream mapping, the higher the order which is allocated to a particular stream. Many smaller scale (and sometimes large-scale) topographic maps omit first and sometimes second-order streams, and hence their "blue line" network tends to give erroneous results if used.

Most catchment management issues in forests are concerned with first to fourth order streams. Fifth and above order streams tends to cross political and administrative boundaries and show complex cumulative hydrologic effects. The largest rivers of Murray-Darling River system in Australia are about 9th or 10th order (the answer depends on the details of the map used for the small streams). With such high order streams the concepts of catchment hydrology tend to be difficult to apply because of dams, water diversion structures, and river modification.

Relative Areas of Catchments As a rule of thumb

$$\frac{A_{n+1}}{A_n} = 4 \tag{1.1}$$

where A_n is the area of catchment of an n-th order stream; this was shown to apply in Australian semi-arid catchments (Woodyer and Brookfield 1966). More generally, the ratio of areas ranges from 3 to 5 but, for a given area, tends to be constant (Eagleson 1970).

Law of Stream Slopes In general stream slope decreases with increasing catchment order (Horton 1945). This can be expressed as:

$$\frac{S_{n+1}}{S_n} = 0.55 \tag{1.2}$$

in which s_n is the slope of an n-th order stream expressed as a gradient. There is no general theory as to why this should be.

What is the Value of Empirical Relationships? Many workers have come up with empirical relationships for streams and natural catchments, with the classic work being that of Horton (1945) and Leopold (1971). Sherbon-Hills (1975) examined the fit of a number of empirical rules including Eqs. 1.1 and 1.2 to Victorian catchments and concluded that they were approximately valid. In general, such rules may be useful for the problem being tackled but usually give little theoretical insight into the evolution of the hydrologic system.

Streams and catchments tend to have a geometry best described as "fractal." This can be viewed as a subset having the same statistical properties (relative to its own dimensions) as the whole over a range of scales. A practical consequence of this is that concepts such as "stream length" are functionally dependent on the minimum length of the measurement device adopted and the methodology of measurement (e.g. see Mandelbrot (1983) and his examination of the question of measuring the length of coastlines). This is in contrast to the more familiar measurement involving the Euclidean geometry of straight lines and curves. Hence concepts such as stream length, stream perimeter, or cross-sectional area tend to become difficult or meaningless when applied to small, natural streams. This particularly limits the application of hydraulic theory based on deep, smooth, artificial channels with a very regular geometry to small streams emanating from forested catchments.

1.4 Hydrologic Units and Catchment Arithmetic

Many people struggle with the units of catchment hydrology. In Australia, these should conform to the International System of Units ("SI"). However, more commonly variants of these (related by a power of 10) are used. Table 1.1 shows the inter-conversions between common units encountered in catchment hydrology.

Example 1:

The average flow of a catchment is quoted at 12 Ls^{-1}. How many Megalitres per day is this?

Answer: From the table above, 1 Ls^{-1} corresponds to 0.0864 ML day^{-1}. Hence the answer is $12 \times 0.0864 = 1.037\,\mathrm{ML\,day}^{-1}$.

Table 1.1 Interconversion between commonly used forest hydrology units. *A* is the area of the catchment in hectares

From/to	L Second^{-1}	L Hour^{-1}	L Day^{-1}	ML Day^{-1}	Mm Day^{-1}
Litres Second^{-1}	1	3,600	86,400	0.0864	$\frac{8.64}{A}$
Litres Hour^{-1}		1	24	0.000024	$\frac{0.0024}{A}$
Litres Day^{-1}			1	10^{-6}	$\frac{0.0001}{A}$
MegaLitres Day^{-1}				1	$\frac{100}{A}$
Mm Day^{-1}					1

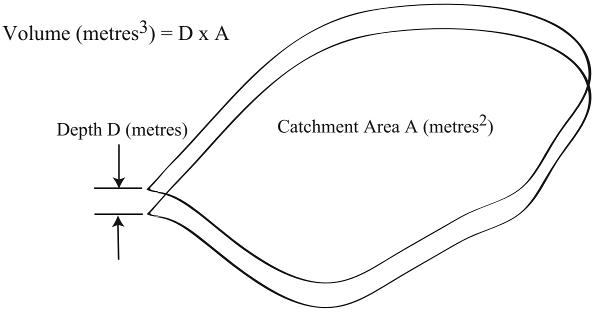


Fig. 1.12 Fundamental catchment arithmetic – computing the volume of water falling on a catchment

Example 2:

Question: If the catchment area for Q.1 is 52 ha, how many mm per day runoff is this?

Answer: From Table 1.1 above, 1 Ls^{-1} corresponds to $\frac{8.64}{52}\text{mm day}^{-1}$. Then, multiplying by 12 gives $1.99\ \text{mm day}^{-1}$.

Fundamental to all hydrology is the arithmetic of volumes, expressed as:

$$V = D.A \tag{1.3}$$

where

V = Volume of water on the catchment (m^3),
D = Depth of water on the catchment (m), and
A = Area of catchment (m^2).

The concept is illustrated in Fig. 1.12. The simplicity of the units in Eq. 1.3 (metres, square metres, and cubic metres should be noted). The use of this relation is often obscured by the variety of units imposed; the first and sometimes the most difficult task is to decompose these to a simple unit base. Complex questions should be broken down to the units of (m, m^2, m^3). Care must be taken when aggregating powers of 10 since this is the most common cause of error. Common units found in Australia are ML (megalitres – 1,000 m^3 or 1,000,000 L), hectares (10,000 m^2), and square kilometers (10^6 m^2 or 1,000,000 m^2).

Examples 3–5 below are examples of common computation which underpins most hydrology theory.

Example 3:

Question: Rainfall of 0.05 m depth falls on a catchment of 300,000 m^2. It is known the 40 % of this will run into a dam. What is the volume of runoff in m^3?

Answer: $\text{Volume} = 0.05 \times 300,000 \times 0.4 = 6,000\,\text{m}^3$

Example 4 – Example 3 in More Common Units

Question: Rainfall of 50 mm falls on a 30 ha catchment. It is know that 40 % if this will run into a dam. What is the volume of runoff in megalitres (ML)? This is, of course, Example 1 represented in different units.

Answer:

$$\text{Depth of rainfall} = 50/1,000\,\text{m} = 0.05\,\text{m}.$$

$$\text{Area of catchment} = 30 \times 10,000 = 300,000\,\text{m}^2.$$

$$\text{Volume} = 0.05 \times 300,000 \times 0.4 = 6,000\text{m}^3$$

But 1,000 m^3 = 1 ML. Hence volume is 6 ML

Example 5: Shortcutting Computations

Many computations can be shortcut by the rule:

100 mm = 1 ML ha^{-1}

Then, for Example 4, volume = (50/100) × 30 × 0.4 = 6 ML.

Hydrologic discussions often become bogged down due to lack of knowledge of units by participants. Students should endeavor to thoroughly master the intricacies of hydrologic units. Note that it is bad practice to quote instantaneous flow in long units of time; Thus although flow could be stated in the numerically equivalent units of Litres second^{-1} or ML day^{-1}, the former is conceptually correct for instantaneous flow.

1.5 Introduction to Hydrographs and Averaging of Units

The basis of hydrology is the continuous measurement of streamflow at a given location and, as necessary, measurement of other variables such as water quality and rainfall as a function of time. The flow rate is expressed in units of volume per unit time ($m^3\ s^{-1}$) or one of its variants or, less commonly, computed as "runoff depth" per unit time (e.g. mm day^{-1}). Often units used for the same quantity will vary in the context of discussion.

Streamflow is defined as the volume of water per unit time passing through a cross-section of a stream. With occasional exceptions (tidal rivers, influence of downstream activities), water will only flow downstream, so the direction of flow does not need to be considered.

Consider a small stream in which the flow rate, q, is small enough to be conveniently expressed in Litres per second (Ls^{-1}). If the streamflow was measured at 4 pm on January 12th, 2014 as 5 Ls^{-1} then $q = 5\ \mathrm{Ls}^{-1}$. More usually q is written as q(t) where t = time, and q(t) denotes that the flow varies with time. A plot of q as a function of t is referred to as a hydrograph and is often written as q(t). Consider the integration of our instantaneous streamflow, q. Then, for instance, we might define

$$q_{17} = \int_{t=5pm}^{6pm} q(t)dt \tag{1.4}$$

where q_{17} = Volume of water passing the stream cross-section between 5 and 6 pm. The subscript 17 means that the time period starts at 5 pm. Logically this should be given in Litres. Hourly flow might be expressed as a sequence of hourly discharges (Q_0, Q_1, Q_2. etc. where the subscript denotes the starting hour of the day). However, for convenience and comparisons, hydrologists tend to use flow averaging:

$$\overline{q}_{17} = \frac{1}{3,600}\int_{t=5pm}^{6pm} q(t)dt \tag{1.5}$$

Thus $\overline{q}_{17}$ has the units of Ls^{-1} (the divisor of 3,600 reflects 3,600 s per hour), and the bar indicates averaging over that period. Use of this approach allows easier visualisation of data and checking by plotting averages over the instantaneous data when looking for computational mistakes. In practice the bar would be dropped since this is understood and more usually the time would be inferred by the position of the value in a long data sequence.

The question of the minimum time interval over which flow might be averaged is of importance in collection and storage of data. Measuring equipment effectively averages data over a few minutes due to inertia and volumes of water stored in the measurement system. Most users are interested only in the volumes of water and averaging over hours, days, months, or years is often satisfactory. However the detailed stream hydrographs contain much information about the dynamics and hence some hydrologists have a penchant for studying short-time interval data of interesting events. The difficulty with this approach is that it leads to much redundant data being collected and stored.

The question of the information gained by continued measurements of catchment streamflow has been a continuing theme in science since the first streamflow measurements were made. Catchment managers require such information to manage their water, schedule diversions, and sell water. Hence there is a proliferation of different time intervals and units to suit each particular case. Aspects of hydrograph details are discussed in Chap. 2.

1.5.1 Runoff Expressed in Depth Units

Suppose we have a catchment of 40 ha passing water into a measurement weir. The volume of runoff in a given hour is measured as 8,000 L. Then we might say:

$$\text{Average runoff} = \frac{8,000}{3,600} = 2.22\,\text{L}\,\text{s}^{-1}, \quad \text{or}$$

$$\text{Average runoff} = \frac{8,000}{40 \times 10,000} = 0.02\,\text{mm}\,\text{h}^{-1}$$

Either would be commonly used, as evidenced by examples used in this book. The divisor in the second case is the number of square metres in the catchment and relies on the fact that 1 L is 1 mm depth over a square metre.

Our experience is that units and their inter-conversions are one of the largest sources of confusion to both new and practising workers in the field. Hydrologic practitioners need to be adept at using a variety of such units in day to day work.

1.5.2 The Instantaneous Hydrograph

The basis of this is that the stream is passed through a weir or flume. In such a structure, the height of water in a measurement section is a function of the flow entering the structure. For a well-constructed structure there is little error in the relationship between height and flow. Then, by measuring the height of water over time, we can compute the flow over time. This is called the instantaneous hydrograph. Sometimes this is supplemented by a measurement of rainfall intensity over time (known as the hyetograph). Although these can be used directly, more usually the hydrograph is transformed to values such as hourly flow, daily flow, monthly flow, or annual flow.

Figure 1.13 shows an instantaneous flow hydrograph and hyetograph of a storm from Clem Creek. The response at three positions on the stream – at the stream head, 211 m downstream, and 458 m downstream (at the weir) – is shown. There is a clear link between the record of rainfall and the stream response, but the response is complex and lasts far longer than the rainfall period. It can be seen that:

1. Periods of intense rainfall lead to an increased rate of rise of streamflow with time.
2. The maximum peak flow may occur hours or days after the cessation of rainfall – particularly near the stream head.
3. The “smoothness” of the recorded hydrograph suggests that the streamflow response is due to groundwater entering the stream; there is no evidence of “overland flow.”

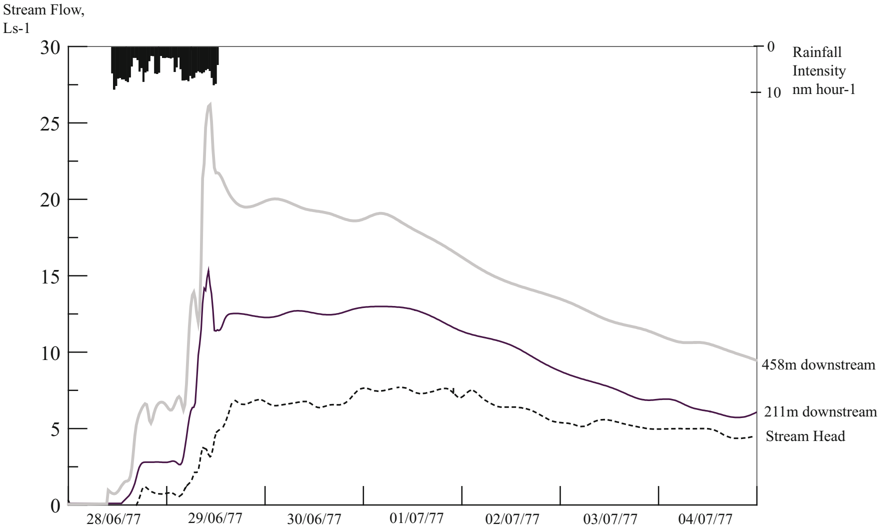


Fig. 1.13 Stormflow hydrographs measured at the stream head, 211 m, and 458 m downstream respectively. The differing characteristics reflect the ratio of "parallel" catchment to "convergent" catchment

4. The stream rainfall-response characteristics are very dependent on the position of measurement on the stream.

Figure 1.14 shows an annual hydrograph of Clem Creek (46 ha) using hourly flow data. The insets show successive enlargement of a portion for January, 2002, and give details of the diurnal variation. The hydrographs can be viewed as representative of a wider class of stream hydrographs from Australian streams with forested catchments. Features shown are:

1. A strong late-winter-spring (August to November) streamflow maximum, followed by a streamflow recession into a long period of low flow (Clem Creek) or the stream drying up completely (Ella Creek). Clem Creek is "perennial" in that it has never been known not to have flowing water. Ella Creek is "ephemeral" in that a usual summertime response is for the stream to stop flowing about December and not resume flowing until late autumn rainfall (typically about May) is received.
2. A clear diurnal variation in streamflow develops in late spring and early summer. This is usually interpreted as being due to riparian zone transpiration, but it is hard to quantify this link. Typically the streamflow reaches a minimum flow about 4 pm and a maximum flow about 2 am.

Hydrographs collected over long periods of times usually have many features which can be linked to or interpreted in terms of dynamic slope processes. This can be misleading however in the sense that if a formal simulation process is carried out, it is impossible to find a parameter set that accurately models the exact

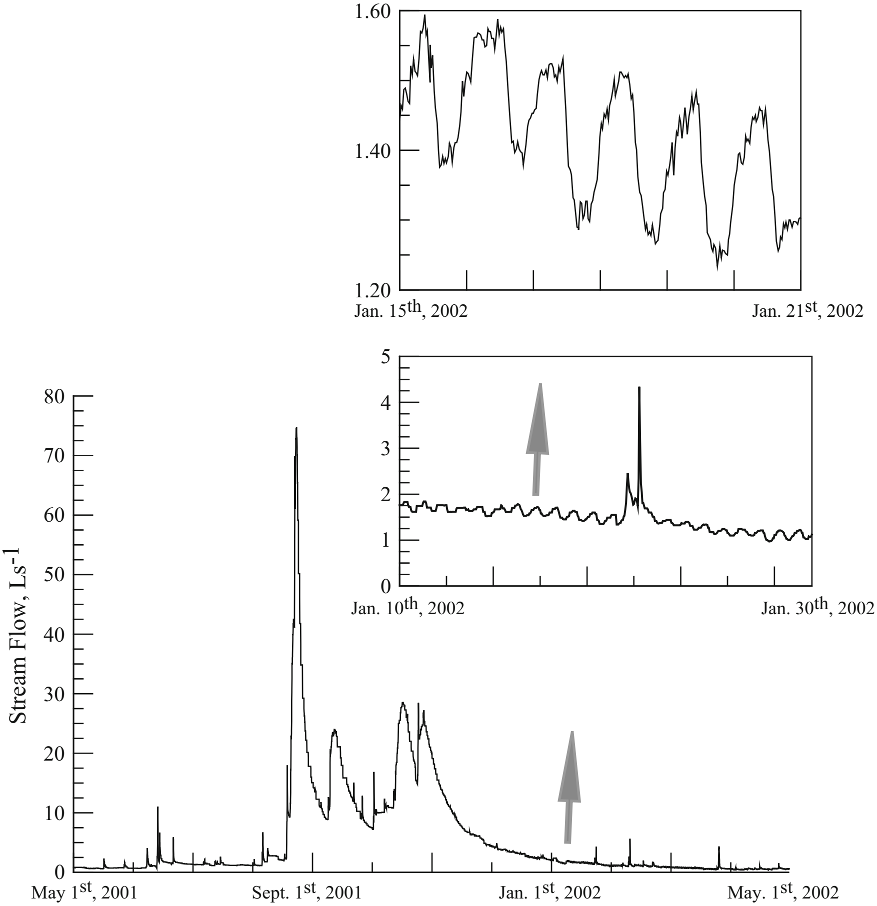


Fig. 1.14 Annual hydrograph of a catchment with successive enlargements of portions to reveal detail

processes. This suggests additional factors and much statistical variability. For these reasons most hydrologists prefer to integrate the data to obtain volumes rather than to attempt to partition the hydrograph into distinct processes.

1.6 How Does Forest Hydrology Differ from Hydrology?

It is of instructive to compare the contents of texts on forest hydrology with those of texts on the discipline of hydrology as taught in, say, engineering schools. We have used the excellent text of "Hydrology: an Australian Perspective" (Ladson 2008) as a comparator here. As expected there is substantial overlap, but the two disciplines also tend to be complementary in much of their knowledge. In particular:

1. Engineering hydrology is much more concerned with large catchments and large rivers. Forest hydrology is concerned with small catchments and small streams.
2. Engineering hydrology tends to deal with a much wider range of extreme conditions (and flows) than those of the forest hydrologist. Forests (by definition) grow in humid, well-watered parts of the world. Thus the extreme events associated with deserts, alpine environments, and other "difficult" parts of the world are usually not encountered.
3. A major part of any engineering course is computation of maximum flows and flood frequency analysis. These are fundamental aspects of river management and structural design. Forest hydrologists would only occasionally concern themselves with such computations. The computation of these type of statistics (usually) hardly figures in forest hydrology.
4. Related to this is "flood routing" in which the time of travel of flood peaks along a stream network is computed. Again this is usually of little concern in forest hydrology.
5. Forest hydrology tends to be more concerned with the detailed behaviour of small streams and the impacts of land management on this. Such changes in behaviour are only small sources of variability in the behaviour of large river systems.

The above are generalities and many examples can be found where boundaries between the two knowledge-areas are blurred, crossed, or do not exist. Thus, for instance, the impact of forest fires on the necessary spillway capacity of dams is just starting to be appreciated. A distinct trend in recent years has been the tendency of engineering schools to offer courses in "Environmental Hydrology" in which there are substantial elements of forest hydrology included.

1.7 What's Different About Australian Forest Hydrology?

Good question! Everything and nothing? Probably the best answer is that there is nothing in Australian forest hydrology that is not found elsewhere, but that Australia commonly exhibits more extremes – longer droughts followed by large floods and greater inter-annual variability than many countries. The hydrology of other parts of the world – particularly settled agricultural districts in Western Europe and Eastern USA – looks ordered and predictable compared to Australian hydrology. And perhaps, because of this, Australian hydrology issues have been much more in the political spotlight (mainly due to drought, flood, and fire) than is the case in other countries. Having said that, relationships developed between rainfall and streamflows using Australian data appear to sit very well with world-wide relationships.

There are some very obvious differences. Firstly Australia has a large arid zone, but forests hardly occur in such regions. Secondly snow does occur in Australian forests but is uncommon, short-lived, and of a high moisture content. Although snow has occurred in projects with which the author has been associated, there is rarely, if ever, evidence of "snow hydrographs." Thirdly, many Australian soils are very shallow and have a limited soil-water-holding capacity, and this can account for a tendency for low summer streamflows and high flows after rainfall. Perhaps this also accounts for a noted but hardly explored tendency for many Australian forested catchments to change from showing insensitivity to rainfall to showing extreme response to rainfall with small increases in storm size?

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Chapter 2
Hydrologic Measurements and the Water Balance

Abstract Most hydrology measurement involving input and output analysis use small catchments because long-term measurement is a feasible proposition. The fundamentals of measurement of streamflow and rainfall on a small catchment are reviewed. The integration of data to go from instantaneous to hourly, daily, monthly or annual data and the gains and losses in information are examined. The issue of extracting information from complex hydrographs is reviewed, and examples are given as to how this might be done. A formal introduction to the concept of the catchment water balance is given. This is used to introduce the methodology of "Zhang Curves" and their transformations to yield approximate measures of percentage runoff and rainfall elasticity.

2.1 Introduction

For practical purposes, most Australian hydrologic measurement comes down to measurement of rainfall and streamflow. These may, occasionally, be supplemented by measures of evapotranspiration (particularly sapflow measurements), soil moisture and/or groundwater in catchment slopes, and sometimes detailed measurements of the fate of the water. The usual purpose is forming some sort of water balance of the catchments and looking at the long term variations in streamflow with changes in catchment land-use.

Active researchers have used more sophisticated and detailed measurements at various stages but the measurement of rainfall input and streamflow output is a necessary first step. More specialised techniques are usually found in research projects and tend to "come and go" with funding or organisational changes.

There are many excellent books such as Chang (2006) detailing the technology of hydrologic measurement. Projects which may last for four decades or more usually pass through several phases of recording activity and technology (e.g. from recorder charts to simple data loggers to complex data loggers). Notwithstanding implicit technological advances, each medium has its share of advantages and disadvantages for reliable long-term measurement. Maintenance and updating of data handling and storage is a continuing chore for project managers.

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2.2 Basics of Measurement on a Catchment

Most “catchment measurement” uses small (<200 ha) catchments because the logistics of projects involving larger streams becomes overwhelming. The very real question of “scaling up” is considered in Chap. 3. Accurate input/output analysis of a catchment requires good measurement of rainfall and other meteorological inputs and good streamflow measurement. Larger streams may have measurements stations from a routine hydrometric network, but the accuracy of the data (particularly usually the “rating” – the relation showing volumetric flow as a function of stream water level) are commonly inadequate for anything but gross hydrologic inference.

Box: Systematic Errors Do Occur!
Occasionally, evaporation is measured by large “Class A” pans. The idea is that water level is measured, and by comparison with the last measurement, the net evaporation is calculated. My colleague visited a paired catchment project with such a pan at the time of the weekly service. It was a hot day and the service-man had a dog. This raced up to the Class A pan, jumped in, and splashed around. The dog then leapt out and shook himself dry. “Does he often do that?” asked my colleague. “Only when it’s hot” said the service-man who then carefully took a reading of the level and noted it in the results.

2.2.1 Rainfall and Hyetograph Measurement

The most fundamental (and often neglected) hydrologic measurement is rainfall. In general, this is measured by collection in a number of containers of known cross-sectional area at the mouth – usually a 203 mm diameter standard rain gauge. By measurement of the volume of water collected over time, the total depth of rainfall since the last measurement can be calculated. In some cases there may be a device to measure the rate of accumulation of rainfall. The most-common “rate-of-rainfall” device passes rainfall into a “tipping bucket” which, as it fills, “tips” to bring an unfilled portion under the inflow. The time sequence of tips is a measure of rainfall intensity. This is known as a “hyetograph.” Figure 2.1 shows such a tipping bucket gauge being serviced in a field study of rainfall variation on a catchment. Figure 2.2 shows a matched hydrograph and “hyetograph” (the record of rainfall intensity over time) obtained from neighbouring streams at Croppers Creek.

Occasionally other measures have been identified as of importance. These include snow-related variables in the Snowy Mountains (e.g. Costin et al. 1961), fog and mist in mountain forests (e.g. O’Connell and O’Shaughnessy 1975), rainfall interception (e.g. Langford and O’Shaughnessy 1977) and deep-seepage outputs from catchments (e.g. Daniels and Kulik 1987). Such measurements are, however, exceptional and, in terms of volumes tend to be small in Australia.

Fig. 2.1 Technical officer John Costenaro downloading a recording rain-gauge in a study of rainfall distribution on the burnt Clem Creek catchment

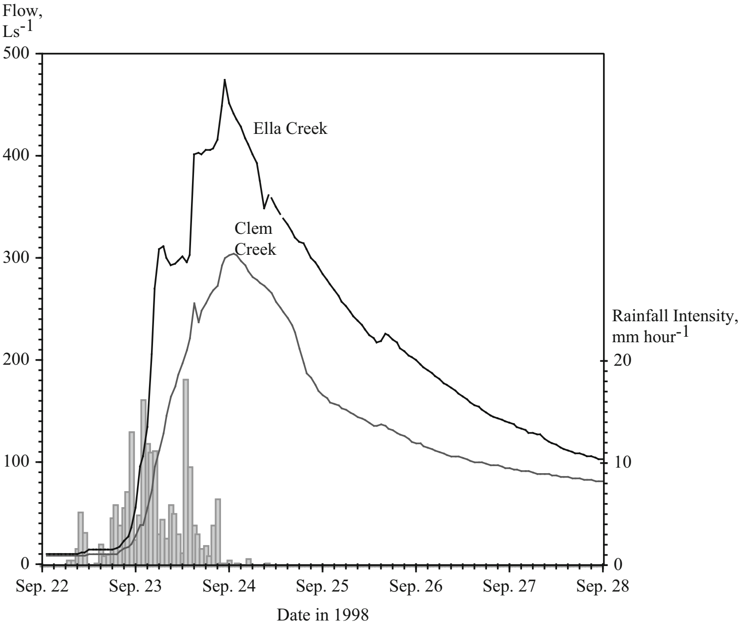

Fig. 2.2 Matched hydrograph and hyetograph record for Clem Creek (46 ha) and Ella Creek (113 ha)

In measuring rainfall in forested environments, it is of particular importance to reduce the "shading" influence of trees. Usually this involves cutting a "cone of clearance" such that there are no trees within a 45° (or better, 30°) from the horizontal (Figs. 2.3 and 2.4). This can be an onerous condition to fulfil in steeper areas. Corbett (1967) provides a discussion of accurate and reproducible measurement of rainfall in forests; issues include the variation between two identical gauges located side by side and systematic variations associated with factors such as proximity to ridges or the aspect of location. Figure 2.5 gives a cumulative plot of total rainfall achieved in three rain gauges at Croppers Creek in north-eastern Victoria over a 15 year period of weekly readings, The gauges are consistent in their relative differences, which mainly reflect relative topography. A previous study showed that rainfall in this area decreased slightly with elevation (Bren et al. 1979). Such studies are difficult in heavily-forested and mountainous terrain because of the tree-falling necessary to get adequate gauge exposure. Options such as mounting gauges on towers above the canopy place the gauge in a very different environment from the forest floor and give unreliable results because of this. They are also difficult to routinely service.

In all long-term hydrologic experimentation, the siting of gauges such that overhead clearance can be maintained is critical. A common experience is the location of a gauge in a regenerating forest, only to find a few years later that the gauge is being overtopped by massive regeneration. The forest owner is usually not impressed by proposals to clear this to give the gauge adequate exposure.

Hydrology projects should attempt to assess the rainfall variation across their catchments and the errors associated with the measurement base. However the Australian experience was that it was difficult to maintain a comprehensive measurement network for more than a few years. Hence usually a "weighting factor" was computed with this data such that rainfall on one gauge would be used to estimate total catchment rainfall. Thus, in the example of Fig. 2.5, the gauge at Ella

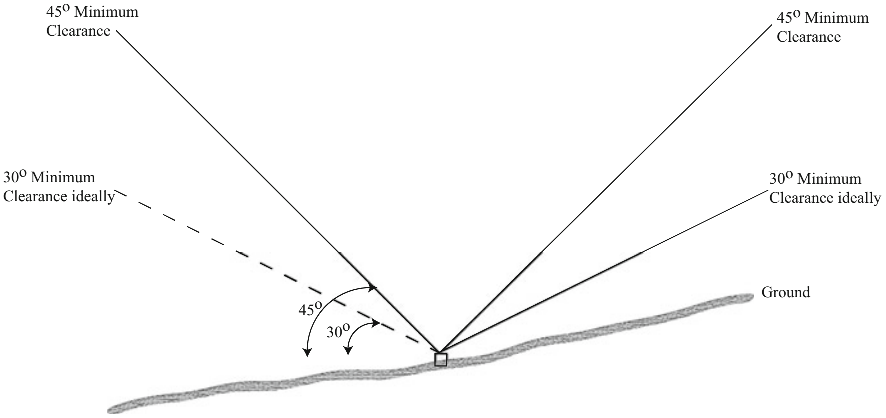

Fig. 2.3 Schematic showing the minimum and preferred "cone of clearance" for a rain-gauge in a forest (Based on the work of Corbett 1967)

Fig. 2.4 Locating a rain gauge in a clearing in a forest usually involves a lot of cutting. This (just) gave a 30° cone of clearance. To the far right is a standard 203 mm storage gauge. A tipping bucket gauge sits on a convenient stump. The cable carries the data to a nearby data logger. Technician Leon Stephens is decanting a rainfall sample collected in the storage bottle on the ground for chemical analysis (see Hopmans et al. 1987)

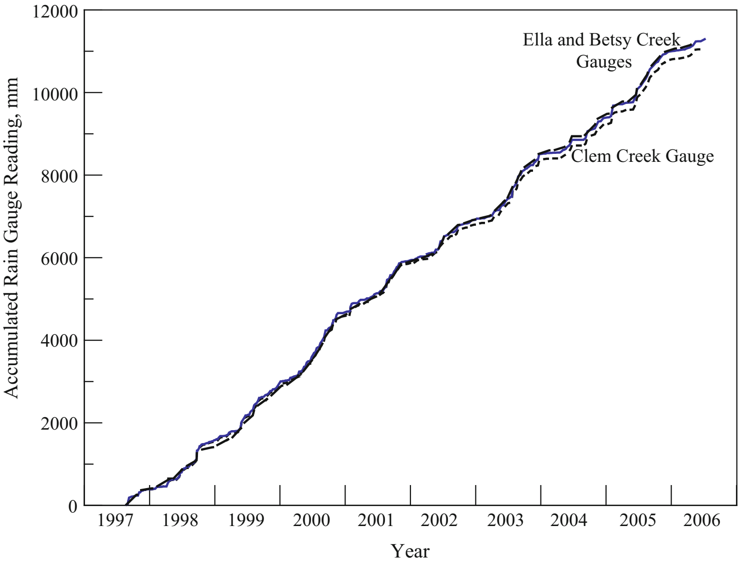

Fig. 2.5 Single-mass plots of accumulated rainfall at three separate rain-gauges at Croppers Creek. The gauges were read weekly as a part of routine servicing. The similarity of the record is apparent

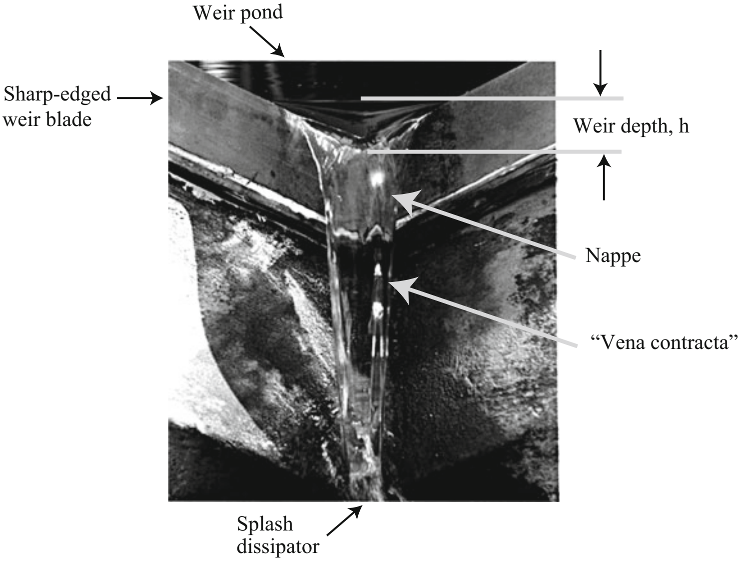

Fig. 2.6 Annotated photograph of a 120° streamflow measuring weir, showing terminology

Creek was viewed as giving close to the catchment mean rainfall. In general, other than integrated measures of rainfall (e.g. total rainfall) over various periods, it has proven difficult to link direct measures of rainfall over time with measures of hydrologic outflow in forested catchments, and hence the value of detailed hyetographs is arguable. This is because forested catchments are so "damped" by the massive vegetation and deep porous zones that it is hard to show much streamflow response to short-term rainfall variation.

2.2.2 Hydrograph Measurement

The basis of measurement is a streamflow structure in which height of water passing through the structure can be used as an independent variable to estimate flow). The usual structures used for measurement are weirs (Fig. 2.6) or flumes (Fig. 2.7). A weir consists of a small "smoothing pond" and a downstream calibrated section – usually a V-notch with a machined, standardised metal opening. Water falls through this such that downstream water levels cannot impact on pond levels. Because the water accelerates as it falls, the cross-sectional area decreases – this is called the "vena contracta". The smoothing pond allows the dissipation of turbulence. A flume is best approximated as a short section of stabilised channel with an accurate flow-measurement section. In each case the calibrated section gives a reproducible relation between height and flow.

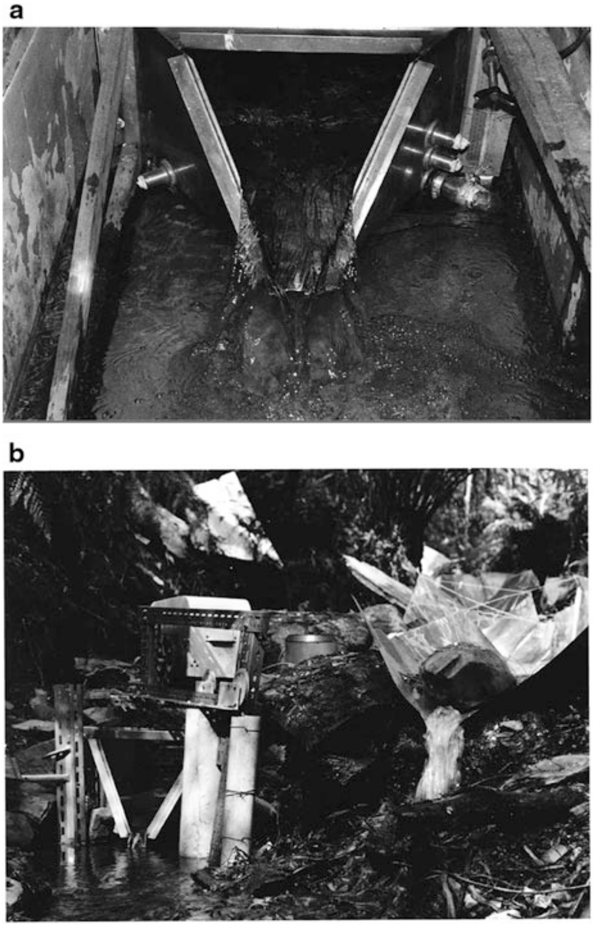

Fig. 2.7 A Type H Streamflow measurement flume being calibrated in (**a**) an hydraulic laboratory and (**b**) in a temporary installation in the field. To the right is a diversion race allowing isolation of a reach of channel from upstream effects. The large white box is an electromechanical data logger

Some form of water level transducer (commonly a pulley and float device) and a data logger recording this height gives a measure of the water level over time. This record is then processed to give flow over time, and then interpolated and integrated to give measures such as hourly, daily, or monthly flow.

The relation giving volumetric flow rate through the structure as a function of water height is called a "rating." Figure 2.8 shows a measured and a theoretical rating for the weir of Fig. 2.6. Streamflow is usually obtained as a continuous measure of height of water passing through the structure. By applying this rating to the sequence of water level measurements, the volumetric flow rate as a function of time is obtained. Integration of this then gives the volumes of flow per hour, day, month, or year. Implicit in the process is the sampling interval – the minimum time interval at which streamflow can be estimated. In electronic recording it is set by the controlling program, and may vary from minutes to hours. Thus, during long

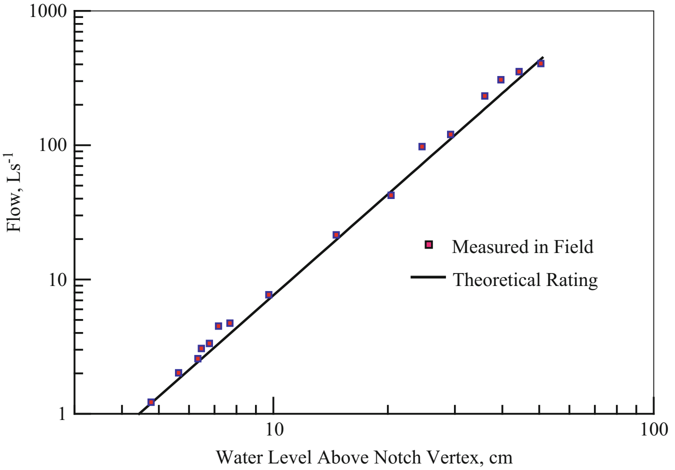

Fig. 2.8 Comparison of field rating and theoretical rating of Clem Creek weir (From Bren 1979)

periods of low flow the recording interval may be some hours. In periods of intensely varied flow a short sampling interval (commonly 5 min) is needed if hydrograph detail is to be "picked up."

Readers are referred to measurement manuals such as Stevens (1998) for a full account of the issues associated with each type of structure and the technology of data-logging. Smaller structures may be accurately rated in a hydraulic laboratory. Larger structures should be rated in the field but this is a difficult and expensive task. An alternative is to use a theoretical rating or a rating obtained for a structure of the same shape in a hydraulic laboratory.

For prolonged measurement of flows in a field location, the structures represent a substantial investment. Often their installation is a major disturbance because of necessary structural works. Ideally the structures should last for a half-century or more, and this is an onerous requirement. The recording equipment is often located in a corrosive, moist environment which quickly shows any quality deficiencies in equipment and housing. Bren and McGuire (2011) looked at Australian hydrology research projects and found that the projects had a high initial cost reflecting this; however once this was overcome the maintenance costs were relatively low. Their long-term survival was often due to the reliable functioning of measurement weirs.

2.2.3 Measurements of Slope Water Storage

Occasionally rainfall and streamflow measurements may be supplemented by measurements of slope water storage. Figure 2.9 shows an example taken from Langford and O'Shaughnessy (1978) and shows the cyclic soil moisture variation in the top 5.2 m of soil in Melbourne's water catchments obtained by use of a neutron

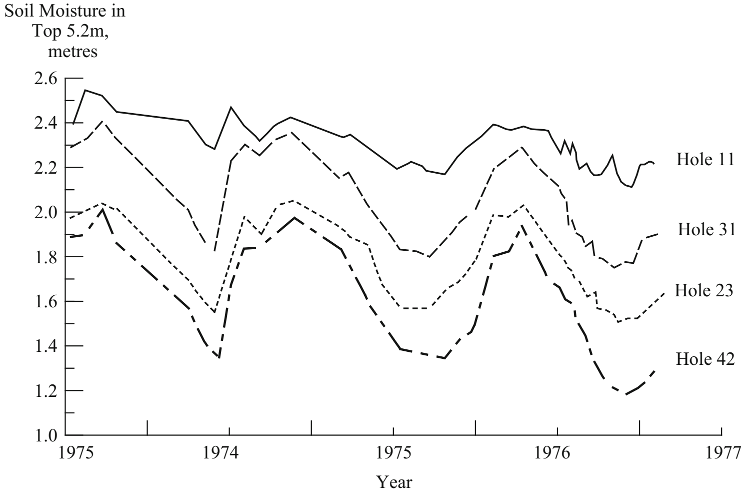

Fig. 2.9 An example of slope water storage – soil moisture variations to 5.2 m depth at four locations in a regrowth mountain ash forest at Coranderrk, Victoria (From Langford and O'Shaughnessy 1978)

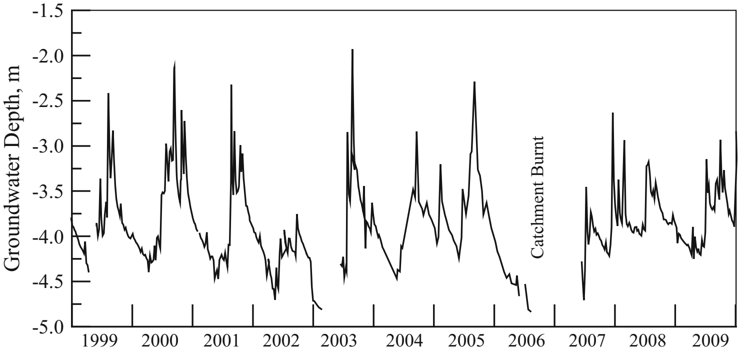

Fig. 2.10 Slope water storage variation: groundwater depth on the slopes of Clem Creek catchment in north-eastern Victoria (From Bren 2011)

probe (a soil moisture measuring device). Figure 2.10 shows cyclic groundwater variations in the lower slope position of a steeply forested catchment in north-eastern Victoria. Both these are imperfect measures of slope water storage. In the case of the neutron probe, calibration issues include the role of roots and macropores in the calibration, and that the top 5.2 m of soil accessible to a neutron-probe is only a small part of the moisture-bearing slope zone. In the case of groundwater, the permeability and conductivity of the catchment material must be considered, and this is almost impossible to determine accurately because of depth and inaccessibility.

Although such measurements supplement rainfall and streamflow records, the experience is that it is hard to link these to wider hydrologic behaviour. This reflects issues of adequacy of spatial sampling, that measurement (particularly with soil moisture probes) may be slow and laborious, and that there are substantial theoretical issues concerning spatial variability and the nature of the processes involved in their use. A major problem is always getting an independent and valid measure of transpiration. The measurements can, however, give considerable insight into the nature of hydrologic processes on the catchment slopes.

2.2.4 Measurement of Plant Water Use

Over the years many methods have been tried, including ventilated chambers (e.g. Denmead et al. 1993), weighing lysimeters (e.g. Pook 1986), complex micrometeorological methods, satellite imagery, air-borne radiometers, and specialised devices for measuring water content and water content gradients in air Although all these methods have useful features, they involve resources beyond those available to most organisations, and usually involve complex questions of just what is being measured.

One method that has found favour in recent decades has been the use of sap-flow monitoring (e.g. Green et al. 2003). In this special probes are inserted into the xylem of woody vegetation. These produce a periodic heat pulse. The velocity of upward travel of this is measured, thereby allowing the rate of transmission of water up stems to be computed. If the area of water-transmitting media (“sapwood”) is known then that volumetric rate of water transmission through a tree can be computed. By careful measurement across a selected and representative tree population, good estimates of tree transpiration from catchment slopes can be made. The technique is feasible to use, although laborious because of the overhead of installation and maintenance. Figure 2.11 gives an early example of instantaneous sap movement measured at the base of two 50-year old mountain ash trees using the sap flow method (from Dunn and Connor 1991). Of note is the diurnal nature of the variation and that transpiration does not cease at night.

2.3 Analysis of Streamflow Hydrographs

To this author, it is study of hydrographs that makes hydrology. An alternative view is that “hydrograph analysis is the last resort of the desperate hydrologist.” Both views reflect that hydrographs contain much information, but that only some of this can be extracted by systematic analysis, and that extraction is slow, tedious, and frustrating.

An “instantaneous” hydrograph shows the exact flow at a given time. Usually the measurement system will effectively average flow over about 2–5 min – this reflects

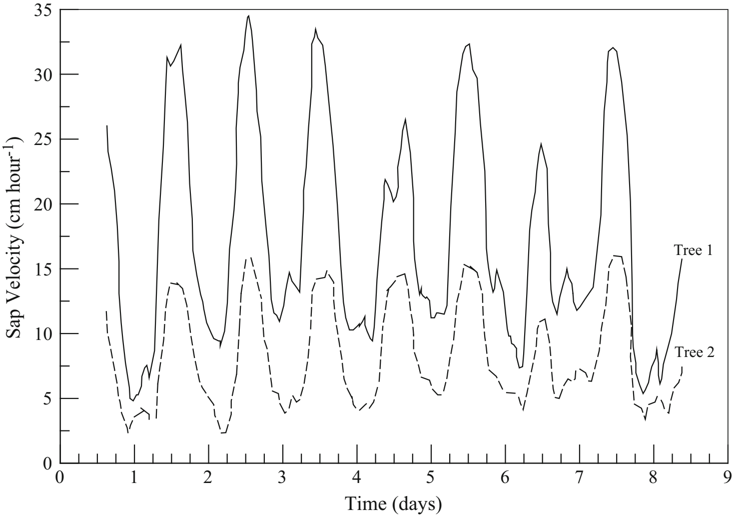

Fig. 2.11 Variations in sap velocity as a function of time in two mountain ash (*Eucalyptus regnans*) trees of age 50 years (Dunn and Connor 1991)

water storage in the pond of measurement weirs and lags in instrument response. For most practical purposes this is negligible. Occasionally hourly hydrographs will be processed from a record; more usually daily, weekly, monthly, seasonal, or annual hydrographs are used.

Figure 2.12 shows a hydrograph (and hyetograph) and illustrates terminology for streamflow generated by an intense period of rainfall at Croppers Creek as a result of an autumn thunderstorm. This storm consisted of a moderately intense period of rainfall (about 16 mm in 40 min), well separated from other periods of rainfall. The streamflow responded by increasing, reaching a maximum, and then receding with a smooth, "classic" hydrograph. Defined parameters include:

1. Antecedent flow – the flow in the stream at the start of a period of storm rainfall.
2. Peak flow – the maximum flow reached during or immediately after a period of rainfall.
3. Stormflow rise = Peak flow – Antecedent flow
4. Recession – the period of declining streamflow after a peak flow is reached.
5. Stormflow volume – the volume of streamflow attributable to a given period of rainfall. This is represented by the plot area (or equivalent volume) above the "separation line."

The "stormflow separation line" is sometimes used to define the response attributable to a particular rainfall. The line has to have an upward slope or it may not intercept the receding hydrograph for many hours (or days, or weeks). The procedure is discussed below.

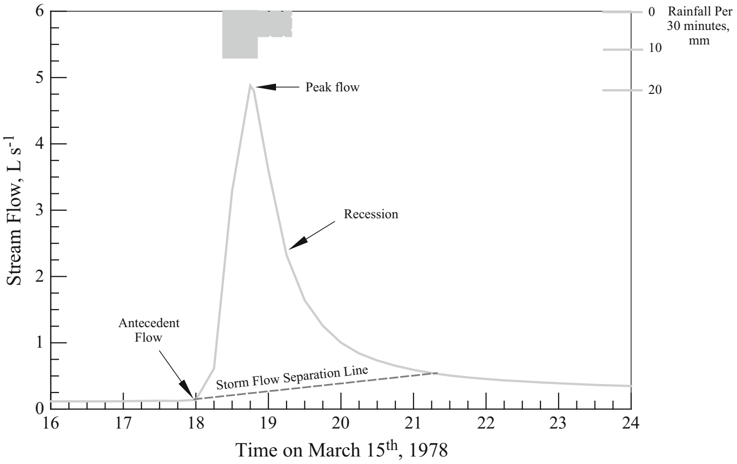

Fig. 2.12 Example of a hydrograph associated with an intense summer thunder-storm on Clem Creek

2.3.1 Flow Separation Analysis

The stormflow of Fig. 2.12 has been partitioned by an upward-sloping line using the method of Hibbert and Cunningham (1966). Based on this, one would assume that it would be a simple matter to sample, say, 30 hydrographs and derive a regression of stormflow volume as a function of storm rainfall or stormflow rise as a function of maximum hourly intensity. This was a popular quest in the 1970s (e.g. Hibbert and Cunningham (1966); Hewlett et al. 1977) and has been a recurrent quest since. Unfortunately, unless some unusual assumptions or methods are used, it cannot be done. Figure 2.13 shows a more complex period of storm rainfall and streamflow; the hydrograph is fictitious (real hydrographs show many more small periods of rainfall) but does show reproduce major features of Clem Creek storm hydrographs. In particular:

1. "Storm 1" leads to a peak flow ("Peak 1") followed by a higher peak flow some days after the cessation of rainfall ("Peak 1A"). This represents the increasing groundwater outflow from the stream head. This is followed by a second set of peaks (Peaks 2 and 2A, and Peaks 3 and 3A).
2. Lines AB, CD, and EF represent "stormflow separation lines". It can be seen that the stormflow associated with Storm 1 will include that of Storm 2 and Storm 3. Similarly stormflow associated with Storm 2 will include that of Storm 3, and so on. In particular, if line AB was extended until it met the receding hydrograph, the period could be weeks or months after Storm 1; this is unsatisfactory as a definition of "storm flow".

If each storm is viewed as an independent event (with storm rainfall as an independent variable), then the response to that storm is confounded by the

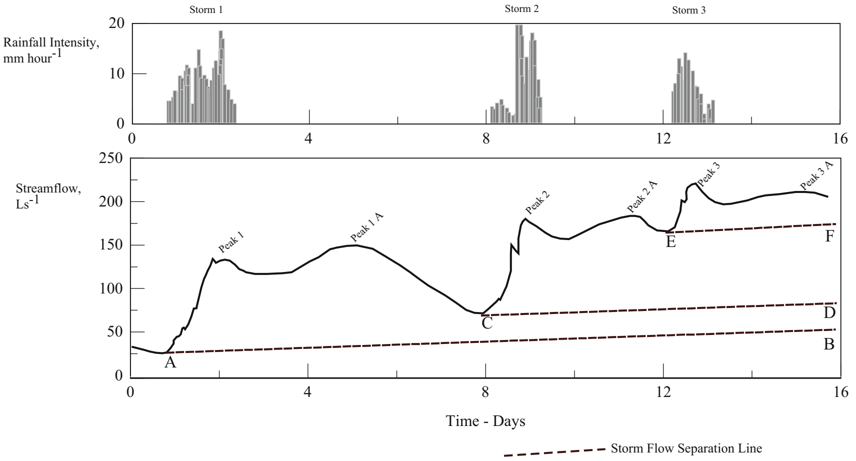

Fig. 2.13 A complex storm hydrograph generated by three substantial periods of rainfall over a fortnight. Lines *AB*, *CD*, and *EF* are portions of "stormflow separation lines."

presence of the storm before it and the storm after it. Unlike the previous example, it is impossible to separate the response of the stream to a single periods of rainfall with any certainty. The "double-peaked response" associated with the convergent geometry of the stream head differs from the classic "recession" of textbook hydrology (as shown by Fig. 2.12). This was (and is) commonly evident after larger storms in this environment. This double peak is often the highest flow but does not meet the usual expectations of a storm flow peak in the sense of being achieved during the storm rainfall period. Such examples are typical of the conundrums in hydrograph examination. Stormflow separation techniques also often involves defining the independent variable (storm rainfall) in terms of the dependent variable (stormflow), which is statistically dubious.

Hewlett et al. (1977, 1984) used the Hibbert and Cunningham (1966) technique to analyse world-wide data sets including one from Clem Creek (Victoria). This examined the relationship between dependent variables such as stormflow volume and peak flow and independent variables such as the depth of storm rainfall, antecedent flow, and various measures of rainfall. The results showed that the only rainfall variable that had much predictive power was the total depth of storm rainfall, and that stormflow rise was significantly correlated to both total rainfall depth and antecedent flow. Further analysis of this data by Richard Hawkins (University of Arizona) showed that many forested catchments (but particularly ones from South Africa and Croppers Creek) had an interesting transition from "complacent" in which the streamflow was insensitive to rainfall to "violent" in which the streamflow was very sensitive to rainfall. This occurred after about 100 mm in a single storm. Thus, essentially, the stream response is not always a continuous and smooth function of rainfall. The sudden transition from little response to flooding appears to be a common feature of the response of forested

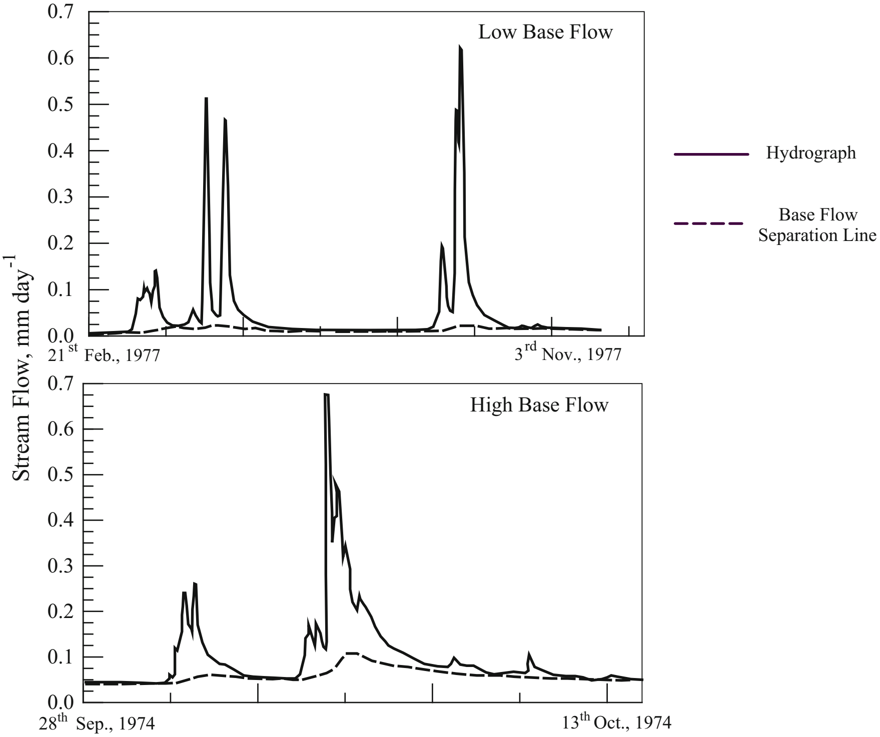

Fig. 2.14 An example of a "band-pass method" (O'Loughlin et al. 1982) which used the method of Lyne and Hollick (1979) to partition streamflow into "base-flow" and "quick-flow"

catchments in Australia to heavy rainfalls. It is thought that it reflects the relatively low storage capacity of Australian forest soils compared to those in the United States.

A further analysis of storm data (Bren et al. 1987) used complex "integral" measures of rainfall intensity to further examine the role of rainfall intensity. The results suggested that simple measures of maximum rainfall intensity were a poor measure of storm intensity. All other things being equal, a period of high intensity rainfall had greater influence in shaping a hydrograph than the same depth of rainfall delivered at a lower intensity, but that no one period of rainfall in a storm was dominant.

"Band-Pass Filter Methods" Over the years, many attempts have been made to make useful "baseflow" separation methodology; one such method is illustrated in Fig. 2.14. Lyne and Hollick (1979) drew on "filtering" methodology and the concepts of low and high band-pass filters. This was used to define a "base flow" and "quickflow." The term "base flow" has persisted, generally meaning sustained streamflow in the absence of the last large storm (or storms). However in any physical sense it is meaningless in that there is no evidence of "baseflow" involving

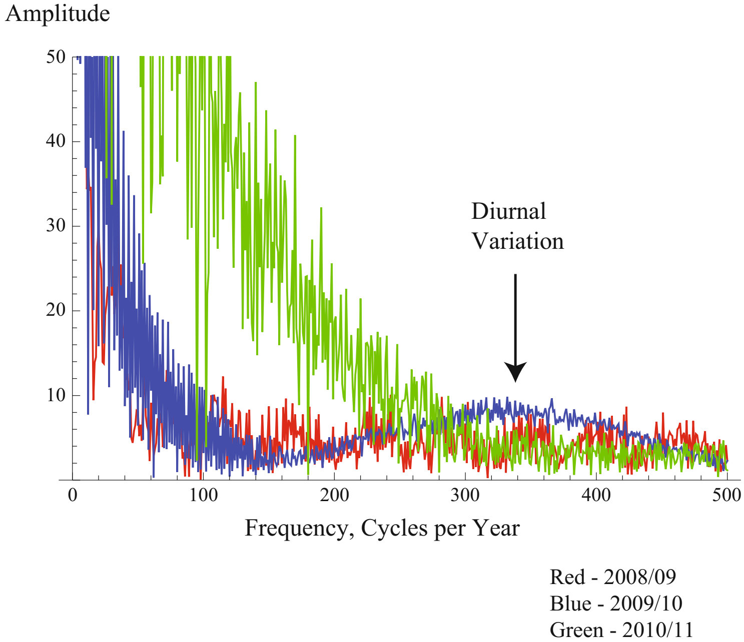

Fig. 2.15 Example of spectral analysis of hourly data from successive years. Note that only the diurnal cycle in the 2010/2011 data is distinctive enough to be detected by this

a different set of hydrologic processes. A good account of such filtering methods for Australian streams is given in Nathan and McMahon (1990); they note that there is no "correct method."

Spectral Analysis Other methods applied to hydrographs include variants of spectral analysis or its more modern cousin, wavelet analysis. Figure 2.15 shows an example of this applied to a 3-year flow sequence of hourly data from Clem Creek post-burning. A weak spectral peak can be associated with diurnal variations and a diffuse peak with annual variations but, in general, there are no other pronounced spectral peaks. Figure 2.16 shows the diurnal variation found on most forested catchments during summer; this probably reflects transpiration by the riparian strip. The lower part of the illustration shows the measured variation with other trends removed. However the variation is surprisingly difficult to link to measureable physical processes by trees in this area. Figure 2.17 shows the averaged diurnal variation compared to a sinusoid; there is a consistent and distinct variation from this mathematical curve that is substantially unexplained.

Although spectral analysis techniques are useful, the usual finding (e.g. Bren 2011) was that if the variation was not already apparent to a skilled hydrologist on the recorded outputs it would not show up by any other form of analysis. This reflects that the human eye is excellent at perceiving patterns. Many attempts have

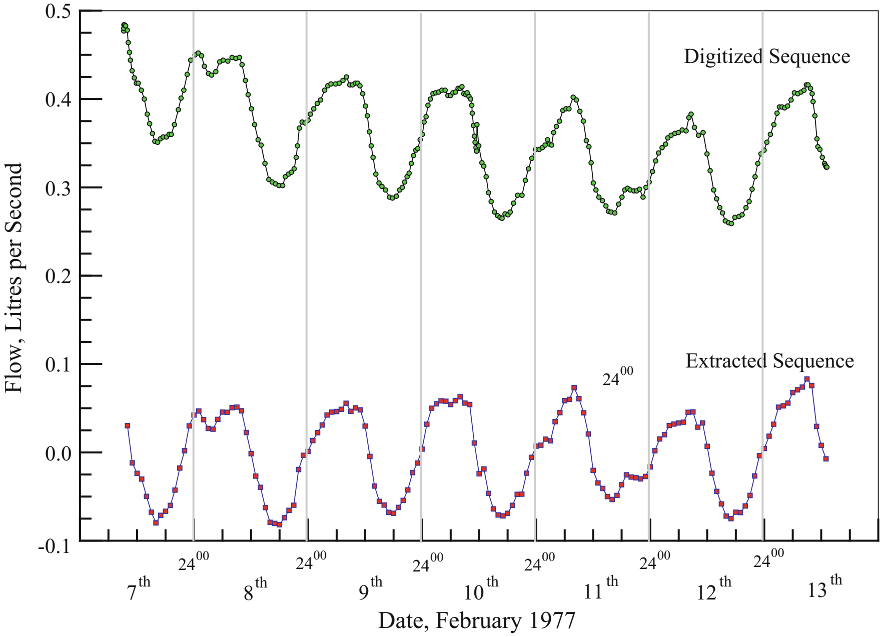

Fig. 2.16 Example of the diurnal variation in flow from Clem Creek. The *top plot* is the flow record as recorded. The *bottom plot* is of a "pure extracted sequence" in which the running mean of daily flow has been subtracted

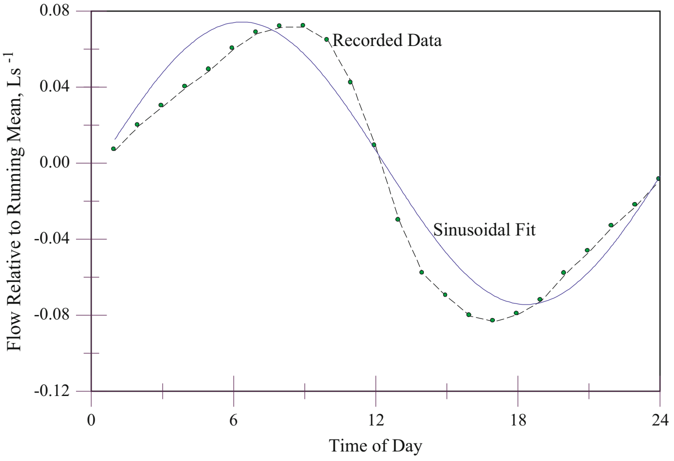

Fig. 2.17 Comparison of the Clem Creek diurnal variation averaged over all summer records and a fitted sinusoid

been made to find evidence of bidiurnal (“tidal”) streamflow variations and 21 year (“sun spot”) cycles in Australian streamflow data but we are unaware of any being found.

Taming of Hydrographs and Hyetographs by Integration To date, the most successful analytical methods for hydrographs have involved “taming” the variation by integration over a day, month, or year, and by comparison of hydrologic change with a stable “reference catchment” or a similarly integrated record of rainfall. This is the basis of paired catchment experimentation discussed in Chap. 5.

2.4 Using Field Data to Form a Water Balance

Conservation of mass for water in a catchment over a given time period, Δt, is:

$$P = Q + ET + \Delta S + \varepsilon \tag{2.1}$$

where

P = Precipitation input (usually rain in Australia), mm,
Q = Streamflow, mm,
ET = Water loss by evapotranspiration mm,
ΔS = Change in catchment storage, mm,
ε = Error estimate, mm.

Most commonly, the time period, Δt, is a full year. The errors reflect the difficulties of quantifying the inputs and outputs. There is also no easy way of measuring catchment storage directly. Usually the assumption is made that if a “water year” begins and ends in a period of relatively constant and stable flows (e.g. at the end of summer or early autumn) then ΔS is close to zero. However, since we have no way measuring this, we cannot know if this is true. When long sequences of data are involved, the question of errors (and their accumulation) from the instruments, the recorders, and the arithmetic processing is very real, but usually unknown.

Although there are many sources of error in such computations, a number have been shown to particularly influence results. These include:

1. Spatial variation in rainfall. Particularly on a large catchment or one with variations in topography, there may be very large variations in the total rainfall from point to point.
2. Deep seepage. Much water that falls on a catchment leaves as “deep seepage.” This may be recharge to distant aquifers or may be through a porous, weathered rock zone in the slopes allowing water flow under measurement structures. Daniels and Kulik (1987) argued that the results of various paired catchment projects in Australia were better explained by deep seepage than by changes in transpiration associated with forest regeneration. Certainly many Australian

> streams and rivers will dry up in summer, although one can show that there is some water entering from the slopes into the river channel. Presumably ephemerality of streams reflects deep seepage.

If the first three terms in Eq. 2.1 are measured, and ΔS can be reasonably assumed to be low, then an estimate of error can be made. This is said to be “closing the balance.” More usually, there is no independent estimate of evapotranspiration, ET. If the last two terms, ΔS and ε, are ignored then, with rearrangement of the equation,

$$\mathrm{ET} = \mathrm{P} - \mathrm{Q} \tag{2.2}$$

This is commonly used to estimate vegetation water use, particularly in “single catchment” experiments. However the error is large in such an unclosed estimate. The technique has little to recommend it but, in the absence of alternatives, is useful.

On the positive side, although hydrologic measurements have many sources of error, and much of the variation is not easily explained, the data are often consistent from year to year. Analysis of long term data sequences has shown many trends, and yielded much information about the Australian environment.

2.5 Using “Zhang Curves” to Estimate Water Balance

Zhang, Dawes and Walker (2001) presented evapotranspiration (ET) of forest and grassland as a function of annual rainfall (P). The “Zhang” curves evolved out of a research to estimate the impacts of afforestation or deforestation on runoff and recharge of alluvial catchments in the Murray Darling Basin. These curves have become particularly common in Australian forest hydrology and will be further used in Chap. 6, 7, and 11.

Zhang et al. (2001) derived curves using a world-wide data set of forest and grassland runoff using data from 250 catchments. The curves are shown in Fig. 2.18 for the range of rainfalls used for radiata pine plantations. They state that “the model is a practical tool that can be readily used to predict the long-term consequences of reforestation, and has potential uses in catchment-scale studies of land use change.” Their discussion includes a comprehensive consideration of the errors induced, and notes that the variation can be substantial, with root-mean-squares of error in the 70–90 mm range. The curves can be expressed as:

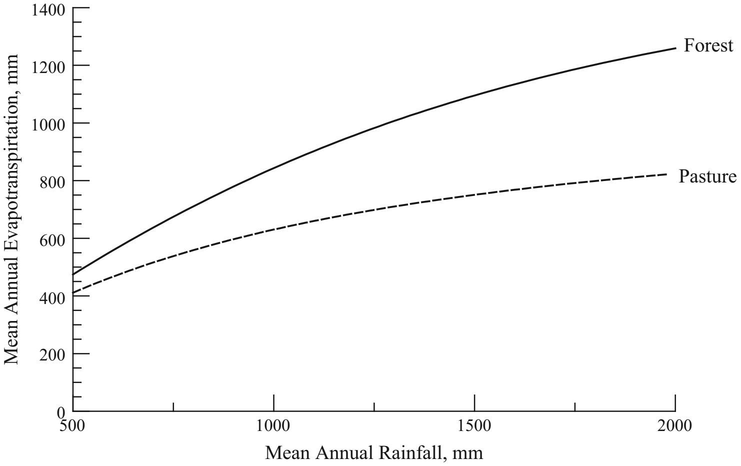

Fig. 2.18 The curves of Zhang et al.(2001) used to estimate evapotranspiration from grassland and forest. These are Eqs. 2.3 and 2.4 in the text

Forest

$$ET_{forest} = \left(\frac{1 + \frac{2,820}{P}}{1 + \frac{2,820}{P} + \frac{P}{1,410}} \right) P \tag{2.3}$$

Grassland

$$ET_{grass} = \left(\frac{1 + \frac{550}{P}}{1 + \frac{550}{P} + \frac{P}{1,100}} \right) P \tag{2.4}$$

ET refers to annual evaporation (mm) and the subscript "grass" or "forest" defines the type of community. More generally, for catchments with mixtures of forest and grassland, a weighted average would be used:

$$ET = \left(1 - p_{frac}\right) ET_{forest} + p_{frac} ET_{grass} \tag{2.5}$$

where p_{frac} is the fraction of grassland in the catchment, and the catchment is assumed to comprise only forest and grassland. Commonly the curves are expressed by using the formula:

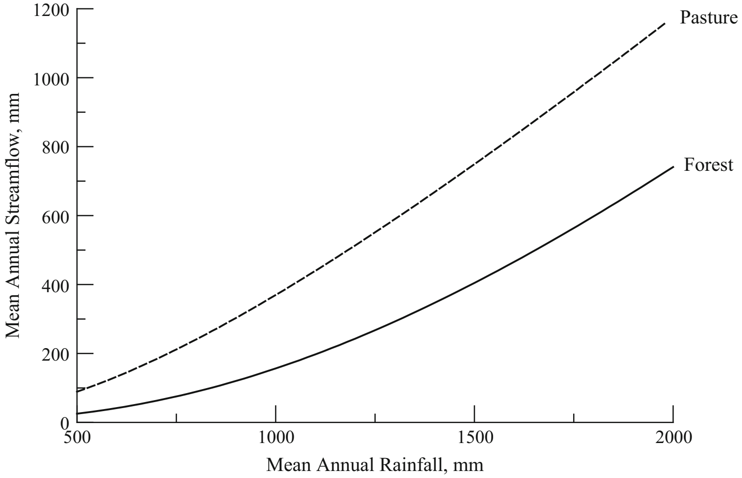

Fig. 2.19 The curves of Zhang et al. (2001) used to estimate mean annual streamflow. These are described by Eqs. 2.6 and 2.7 in the text

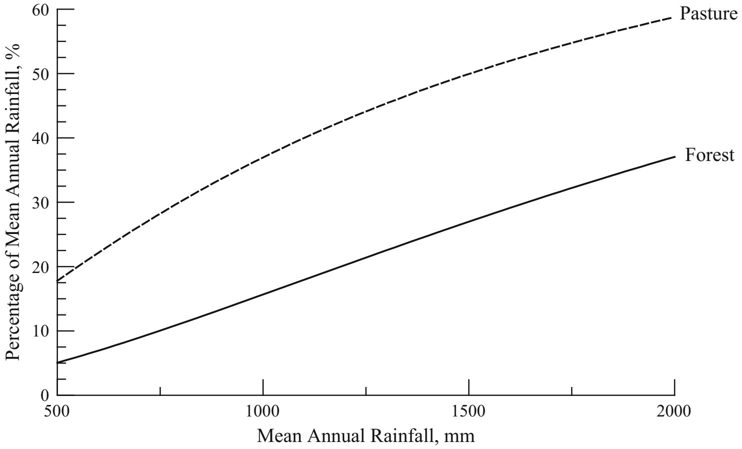

Fig. 2.20 Percentage annual runoff as a function of mean annual rainfall for forest and pasture, as derived from the curves of Zhang et al. (2001)

$$Q_{forest} = P - ET_{forest} \tag{2.6}$$

and

$$Q_{pasture} = P - ET_{pasture} \tag{2.7}$$

in which Q_{forest} and $Q_{pasture}$ are the annual yield in mm from forested and pasture catchments. Both forms of these curves are shown in Figs. 2.18 and 2.19 respectively.

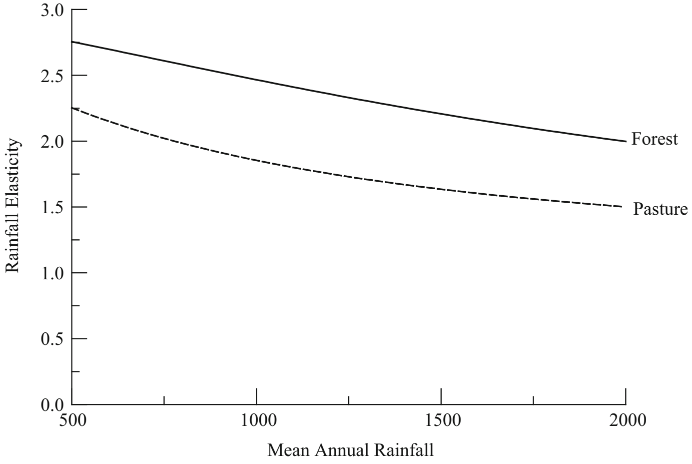

Fig. 2.21 Elasticity of runoff from forest and pasture, derived using the curves of Zhang et al. (2001)

2.5.1 Percentage Runoff and Rainfall Elasticity Using Zhang Curves

Equations 2.6 and 2.7 help us to generalise some aspects of catchment behaviour. Thus $\frac{Q_{forest}100}{P}$ and $\frac{Q_{pasture}100}{P}$ are the runoff efficiencies percentages (sometimes called the coefficient of runoff, but expressed as a ratio). Figure 2.20 show these plotted as function of rainfall for pasture and forested catchments. It can be seen that a pasture catchment gives a much more efficient return of rainfall compared to the forested catchment. Typically the forested catchment returns water of higher purity but the yield is less for a given rainfall.

More latterly there has been concern about the "rainfall elasticity of streamflow" associated with a change in annual rainfall (e.g. climate change). This is defined as the proportional change in mean annual streamflow divided by the proportional change in mean annual rainfall. Consider a change in streamflow, ΔQ caused by a change in rainfall, ΔP. Then elasticity, $\in$, is defined by:

$$\in = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta P}{P}} = \frac{\Delta Q}{\Delta P} \times \frac{P}{Q} \tag{2.8}$$

The term $\frac{\Delta Q}{\Delta P}$ is an approximation of the first derivative of Q w/r to P. Figure 2.21 shows the elasticity of the forested and the pasture catchment plotted out as a function of P. The plot shows that the elasticity of the forested catchment tends to be higher (mainly because of lower flow). Thus the same change in rainfall applied to both a forested and a grassland catchment will cause a greater proportional change in outflow of the forested catchment. Chiew (2006) looked at rainfall elasticity of streamflow in Australian catchments, and found that it fell in the range of 2–3.5 for 70 % of Australian catchments. The relatively high elasticity of streamflow as a function of rainfall for forested catchments is occasionally cited as a negative consequence of forested catchments because, it is argued, downstream communities are subjected to greater change for a given change in rainfall.

Conclusions

Stream hydrographs are the fundamental output "signatures" of streams and contain much information. They are a mixture of explainable and unexplainable cyclic and non-cyclic variations and can be decomposed to component waveforms in some cases. The most recognisable cyclic "time signatures" are the annual variations and a diurnal variation associated with transpiration by riparian vegetation; however the latter is only a small component. Matched hydrographs and hyetographs give the hydrologist more information; however statistical matching of the two signals is an arcane art.

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Chapter 3
The Fundamental Building Blocks –First Order Catchments

Abstract The role of first order streams in forming larger catchments is examined. In higher rainfall areas these form a "space-filling" network such that no area is far from a first order stream. The existence of these is presented as a battle between the ability of a groundwater outflow to carry away sediment material and the downward movement of sediment material into the channel which tends to bury the stream. The properties of channels and streams and the forest soils upslope of the streams are presented. A comparison is made between small stream and large stream hydraulic properties. The important concept of "minimum continuum levels" or "minimum representative volume" is presented; it is concluded that this is a useful concept but that the minimum level is inconveniently large for most field work applications. The outflow of differing shaped catchment elements – concave, convex, and planar is introduced. Concave catchment elements give sustained spring outflow and are also responsible for the continued headward erosion of streams pushing back into the land. Parallel and convex catchment elements contribute stream variability.

3.1 Introduction

Classical hydrology tends to have a focus on big rivers and big catchments – to build a dam, or to overcome flooding. In contrast forest hydrology deals with small streams and small catchments – they are the building blocks of forest land. Very few forested areas cover big catchments so this is appropriate. Small catchments and big catchments have many similarities but, equally many differences. Perusal of scientific literature suggests a surprising lack of recognition for these small work-horses of hydrology. This Chapter examines these smaller building blocks and how we might characterise them. Usually the small streams act independently of one another, so that there is no clear "net" signal. However, occasionally, (large storms and bushfires) they will act in concert, with disconcerting hydrologic results.

Chapter 1 introduced the concept of stream ordering using the approach of Strahler (1952). In this, the smallest flowing streams were referred to as "first order streams." First-order streams are the "front line" troops of the stream

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system – numerous, often transient, sometimes struggling for their existence against colluvium, much more ephemeral than the larger streams, surprisingly dynamic but with long periods of dormancy, their features masked by their heavy vegetation cover, and often demonstrating hydrologic principles that cannot be seen on larger streams, but refusing to show the textbook demonstrations of hydraulic principles found in larger streams.

Although much of the information in this Chapter is drawn from the discipline of geomorphology, heavily forested streams have not figured heavily in their studies until recently. This reflects that the deep forest cover and dense riparian vegetation makes study of these difficult compared to erosional landforms in more arid climates. Differences also relate to the buffering given by the presence of vegetation, the mechanical strength and extremely high "macropore" permeability imparted to the soil mass by the presence of roots, and the occasional instabilities caused by removal of the biomass in fires.

3.2 The Dominance of "Headwater Streams"

Strahler (1957) referred to first and second order channels as "headwater streams" and this terminology has become common. Less common is quantification. Table 3.1 shows the length per unit area (units km^{-1}) for the mountainous Tarago catchment in Eastern Victoria (Bren 1995). First order streams are the dominant source receivers of water from the land. Overall, the work showed that first order streams (with a length of 1.94 $km\ km^{-2}$) were by far the most common streams.

The streams form a space-filling network in the sense that no area in the catchment is ever far from the stream. The "fractal dimension" of this is a measure of the pervasiveness of this – a value of 1 means effectively a straight stream passing through the area, and a value of 2 means that the area would be completely "coloured" by streams. Table 3.2 compares the fractal dimension of the Tarago catchment with some international catchments. It can be seen that in all cases there is a high stream density in these well-watered catchments.

Table 3.1 Length of stream orders per km^2 in a mountain catchment in Victoria

Stream order	Total length
1	1.94
2	0.59
3	0.29
4	0.24
Total	3.06

Source: Bren (1995)

Table 3.2 Comparison of fractal dimensions and drainage density of the Tarago catchment compared with catchments cited by Helmlinger et al. (1993)

Catchment	Location and area, Km^2	Fractal dimension	Drainage density, Km^{-1}
Tarago River	Australia 65.4	1.75	3.06
Sth Fork Smith River	California 600.4	1.79	0.68–2.63
Schoharie Creek	New York 113.6	1.75	0.74–4.83
Big Creek	Idaho 146.9	1.76	0.68–3.45

Drainage density is the length of streams per unit area

3.3 The Prototypical First Order Catchment, and Streams

A mathematical approximation to a first-order catchment is shown in Fig. 3.1; the reader might care to compare this to the oblique aerial photo of a catchment in Fig. 1.1 in which the same features can be observed. The stream starts as a spring outflow at the focus of a convergent area of catchment. At this point the converging groundwater system has enough pressure to appear on the ground surface as a spring discharge. The catchment will contain areas of convergent, parallel/planar slopes, and divergent slope. If the groundwater outflow has enough energy it can entrain sediment and form or maintain a streambed. The water then travels downhill under the influence of gravity and is, ultimately, lost to the catchment by passing downstream. In due course the water flow will join with another first order stream to form a second order stream. And so, the stream network starts to form.

The concept of a first appearance of water in the stream channel can be used to define a minimum catchment area necessary to support a permanent stream. Thus, in high rainfall areas carrying forest only a few hectares may be needed to support a permanent stream. In lower rainfall areas, many square kilometres may be required; indeed there may be a network of first and second order streams defined on the map, but “permanent” flow may only be found in third order or larger streams. There is little published information on this.

3.4 Groundwater Outflow vs. Downslope Soil Movement

Life is not easy for a headwater stream to survive. Firstly it must have enough catchment area and the correct convergent geometry to provide a groundwater outflow for the springhead. Secondly it must have enough continuing rainfall to sustain the water flow. Thus, in the major 1997–2009 drought in southern Australia, “permanent” streams were anything but that because of inadequate rainfall. Thirdly the stream flow must be great enough to remove the accumulation of colluvium moving downslope into the stream. If this does not happen then the stream becomes “buried” or “underground”, with no surface manifestation of running water. Such an “ex-stream” is illustrated in Fig. 3.2. Many such drainage lines are relics of wetter eras associated with “climate change” and may not have carried running water for many centuries.

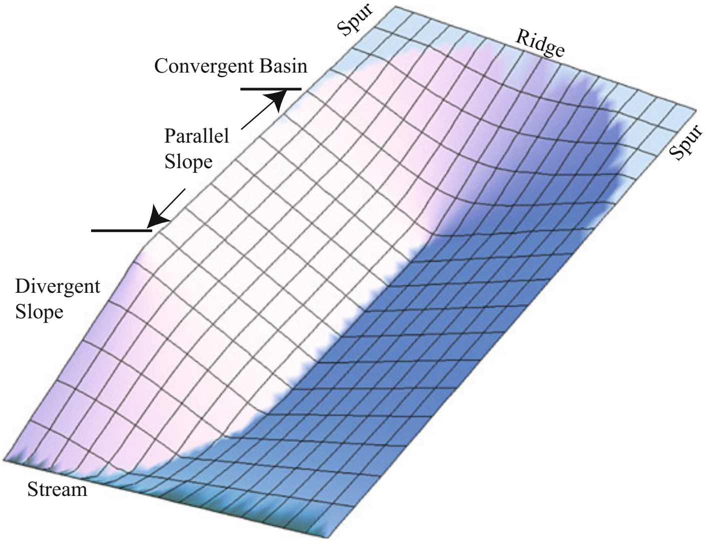

Fig. 3.1 An oblique 3-D representation of a typical first-order catchment

Fig. 3.2 A “buried stream” (*drainage line*) at Clem Creek catchment becomes highly visible after the 2006 fire killed the pines. Such drainage lines were streams during wetter periods in the past. With diminishing rainfalls, the streams do not have enough energy to remove incoming soil and hence become buried “*drainage lines*”

Fig. 3.3 A mountain stream sitting on bed-rock. The pool-riffle nature of flow and the high water quality are evident

When the rainfall is high enough, the stream bed may essentially sit on "bed-rock" – the weathered layer of the native rock (Fig. 3.3). However, sometimes the new stream will sit on colluvium deposits. In such cases an "armoured" bed of stones forms, and this helps protect the soft material below from erosion. In these situations, the vertical level of the stream bed may reflect periods of low rainfall and high downslope soil movements. Thus the stream will form a stream bed during periods of active rainfall (which may last for centuries or more). Then, because of vagaries of climate, reduced rainfall may lead to the stream becoming "buried" by downslope soil movement for long periods. Another period of rainfall may then lead to the process occurring again. In gold-bearing areas the buried streambeds were often sources of alluvial gold. Thus, in Victorian gold-mining, much effort was put into excavating below existing stream beds or depressions to find buried stream beds and associated alluvial gold. These are sometimes referred to as "leads" in this environment.

3.5 Colluvium and Bedrock Erosion

Figure 3.4 illustrates a transect across a forested, first-order catchment from the ridge to the stream. This shows:

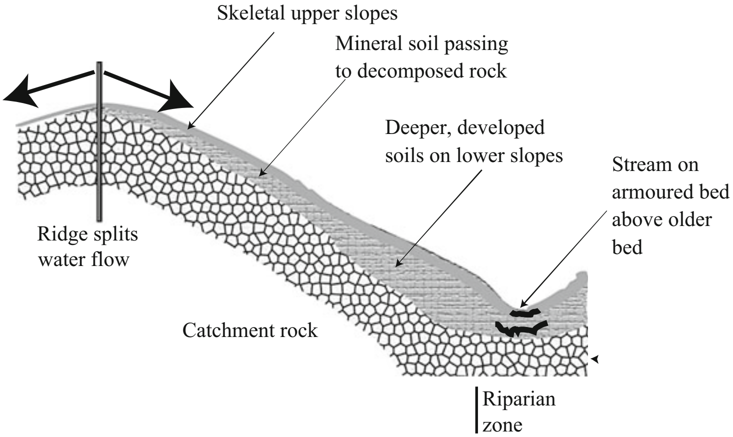

Fig. 3.4 Idealised cross-section of a slope across a catchment. Cross-sections for illustrative purposes always have massive vertical enlargements which precludes showing vegetation. See Figs. 3.5 and 3.6 to gain an appreciation of this

1. The catchment ridge or divide. The principle is that there is a highest point on the ridge that forms a "point of singularity." Water falling on the left-hand side of this passes to the left-hand catchment and water falling on the right-hand side to the right hand catchment. Commonly this is stony, although excavation reveals the rock is usually soft and porous to water.
2. The upper slope. In hilly forest country the soils on this tend to be skeletal, with outcrops of weathered rock. In many cases the vegetation carried is more xerophytic than lower slopes. In some cases it is classed as "regolith" – a loose layer of weathered rocks intermingled with soil that rest on the bedrock. Excavation of the soil material often reveals that the rock or soil can be classed as saprolite – weathered rock material containing much of the structure of rock.
3. The lower slopes. This consists of soil formed by weathering of the catchment material and "colluvium." Colluvium is soil material that has moved downslope under gravity. In practical terms it is almost impossible to distinguish one from the other since biological processes (earthworms, bird scratching, etc.) intermingle the two materials intimately. Examination of the soil often shows it as an intimate mixture of weathered rock, clay, and biological material. The concepts of uniform, homogeneous soils appear to be rarely found in such slope soils. These soils can be many metres deep in a well-developed catchment.
4. The riparian zone, adjacent to the stream. This often exhibits a surface steepening towards the stream due to the stream removing catchment material. Typically the area is very moist and hence supports the best quality forest and densest understory of ferns and shrubs in the area. Groundwater discharges ("seeps" and "weeps") to the surface are common, reflecting groundwater pressures in the

catchment slopes. The density of the vegetation provides deep shade, which in turn means that shade-tolerant plants such as mosses and ferns are particularly common. In most catchments the riparian zone provides perhaps 50 % of the plant and animal species found locally.

6. The stream bed. This is overlain by actively flowing water passing downstream. A typical fall would be 1–2 % (falling 1–2 m per 100 m length). Stream beds of low order streams are usually rough, obstructed, and unspectacular. The streams usually provide a low-level, atonal noise; this is both highly recognisable and difficult to characterise because of the absence of any dominant "note" or pitch (e.g. Hawkins 1975). In some cases the bed may be "mature" in which case it will display "armouring" of stones or cobbles which protects the bed from further erosion. In many cases the bed is stabilised by "nick points" – often lateral tree roots or small ridges of bed rock (Figs. 3.5 and 3.6). These provide "permanent" high points in the stream bed. Upstream of these, sediment is deposited. Should these be removed or decay, the sediment moves downstream until another nick point has been formed.

Usually low-order streams do not have the water flow or energy to create hydraulic features such as waterfalls, pools, or riffles. Occasionally, if the stream is passing over colluvium or alluvial material it may erode down through this but

Fig. 3.5 A small, fallen log gives a point of stability in a stream (a "nick-point"), allowing sediment to accumulate

Fig. 3.6 An outcrop of rock forms a nick-point for a small stream. Clearly this is more stable than the log of Fig. 3.5

usually such layers are heavily stabilized by tree roots, rock debris, etc. After fires, flows may be large enough to make spectacular changes to these environments.

As one moves upstream in a first order stream, the flow may suddenly diminish or cease over a short length of channel; this is the stream head. Commonly there is a steep drop from the catchment slope to the stream, and often the stream is heavily entrenched by erosion. The groundwater outflow emanates from the convergent catchment and groundwater system above it. The outflow from such a convergent system is highly stabilised by the shape (see Sect. 3.10 below). This gives these outflows a great public image as “permanent springs”. Over centuries or millennia these stream heads erode upstream and downwards, entrenching the streams in the landscape. To a casual observer the erosion is not noticeable, but if there are fixed structures adjacent to the stream it may become apparent over a few years. Thus at Croppers Creek, the deepening of the stream has been noted as about 2 mm per year.

3.6 Moving Upstream – Can We Define Zero Order Streams?

A corollary of this is that the point of first appearance of water in a first order catchment effectively marks where the discharge of groundwater has enough energy to mobilise sediments and carry them downstream. This point will vary with recent rainfalls. Upstream of this point is a reach of dry-stream channel, often called a "drainage line" or dry gully. Much of catchment management is concerned with protecting streams. A constant source of argument is the protection status that should be given to such dry channels, which may not have carried flow for many years. Groups in favour of protection argue that the channel may become active at the next heavy rain. Others argue that there is no evidence of flow in such channels for many, many years (or centuries) and hence there is little likelihood of this happening. The usual solution is some sort of compromise.

It is sometimes argued that if a first-order stream exists then the area above the stream can be reasonably referred to as a "zero-order catchment." This concept is used in the literature but lacks definition or universal acceptance. Further, the concept of two zero order streams joining is meaningless.

3.6.1 *Ephemerality of Low Order Streams*

As stream order increases, the permanence of streams increases in humid climates. Thus lower-order streams are usually less permanent (or, better, more ephemeral) than higher-order streams.

In the Croppers Creek project in north-eastern Victoria. Clem Creek (46 ha catchment) has never been known to cease flowing. Ella Creek (113 ha catchment) usually ceases flow in early summer and resumes flow in mind-autumn. Betsy Creek (44 ha catchment) ceases flow in late spring and resumes flow in early to mid-winter. Figure 3.7 illustrates the ephemerality of Ella Creek over the period of

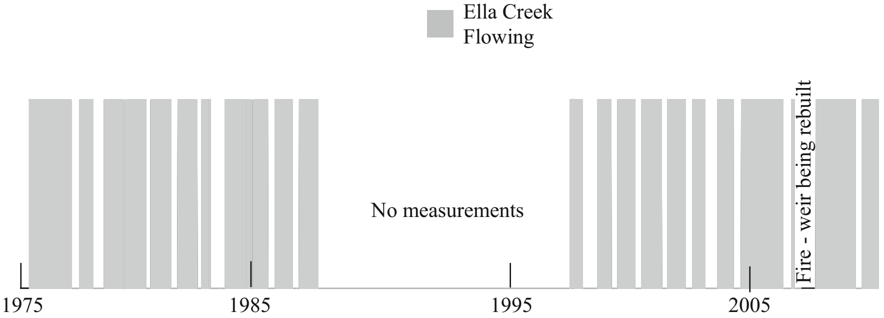

Fig. 3.7 Ephemerality of flow from Ella Creek catchment. Its neighbouring stream, with a catchment of half the size, never ceased flowing during the period of measurement

record. Although this behaviour is highly consistent from year to year, there is no observable cause in the sense that quantifiable factors such as catchment size, geology, or soil type do not explain this behaviour. Thus, at the current level of knowledge, we could not look at a map showing first-order streams and predict which might be permanent and which might be ephemeral. It is presumed that it represents a deep-seepage loss to regional aquifers.

The ephemerality of these three streams reflects the environment in which they occur. It is known that the neighbouring streams of the three gauged streams exhibit marked variability of ephemerality. In one case, at least, it is known that the stream usually discharges through a “buried stream bed” which intersects the ground surface at a point of headward erosion, presumably reflecting some sort of burying of an active stream bed by colluviums porous enough to allow infiltration to this bed. The ephemerality of streams is one more example of where expectations and actual behaviour of small streams do not agree.

3.7 Beds and Streams

Figures 3.5 and 3.6 shows a view of a reach of first order stream with vegetation (temporarily) removed by fire. The channel cross-sections are characterised by the low depth to width ratio, the complex nature of the stream bed, and the “fractal” structure. Thus, for instance, concepts used in hydraulic studies of larger channels such as “stream depth” or “hydraulic radius” (ratio of stream cross-sectional area to stream perimeter) becomes almost meaningless in application.

The streams do have an interesting microstructure, best measured in millimetres. Thus, much of the stream will consist of a myriad of small impoundments with a small “rapid” passing water out of each. The large, active exchange area means that the water is usually highly oxygenated. The shallowness of the water and the difficulties of traversing preclude larger stream fauna (platypus, etc.) from using these streams much but they do occasionally “explore” them. Gooderham et al. (2007) noted that these streams “have a suite of physical eccentricities that distinguish them from the rest of the river system.” These included a “lack of competence” in transporting sediment and a high ratio of structural component size to stream width. Structural components included large rocks from the regolith or downslope movement, tree roots, and woody debris. They concluded that these aspects gave the streams greater physical heterogeneity than downstream reaches. Benda et al. (2005) gives a good account of such streams, noting that there is no “universal definition” of headwater streams.

The presence of this microstructure means that that hydraulic geometry theory of more regular (larger) channels is not applicable over most of the flow regime. This area has not been much explored, but some aspects are touched on in the next Chapter.

3.8 Hydrologic Characteristics of Forested Catchment Soils

A cursory excavation into these will show that they are not at all like the well-ordered layers illustrated in text-books on agricultural soils. Better agricultural soils are often derived from well-ordered sequences of alluvial deposition and weathering. In contrast, soils on forest slopes are formed by a mixture of in-situ weathering, colluvium deposition, and strong "biopedoturbation" – disturbance by living creatures. In particular:

1. There is a massive vegetation layer of trees, shrubs, and herbs that provides a large and constant flow of organic matter to the surface. Correspondingly the organic layer can be thick, heterogeneous and penetrate many metres below the soil surface. Such a zone presents many opportunities for water to infiltrate and pass into the soil. In some cases there is no clear boundary between the organic layer and the "mineral soil."
2. The upper soil layer is highly penetrated by roots and holes made by burrowing organisms. The organisms themselves range from large (wombats, snakes, etc.) to microscopic. The "soil" often is a mixture of mineral matter (clay, quartz grains, etc.), decomposing organic matter, and oxidising or decomposing rock.
3. The lower soil consists of actively decomposing rock ("saprolites"). This forms a complex layer so that even simple concepts like "soil depth" become difficult to measure (e.g. auger holes side by side give widely differing answers).

Thus the catchment soils are better viewed as an "animal-vegetable-mineral soup" which is constantly turning itself over rather than as an ordered, layered structure. Depth of forest soils can be hard to judge because of this. However they may be many metres in depth in lower-slope positions.

For the neophyte forest hydrologist, this has a number of disconcerting consequences. Firstly it is hard to match up the forest soils encountered with those described in text books derived from agricultural soils. Secondly the definition of the "soil surface" can become arguable because of the dense layers of vegetation. Thirdly, hydraulic parameters beloved of hydrology journals become extremely difficult to apply. Hydrologic "constants" such as "infiltration capacity", "hydraulic conductivity" or "diffusivity" become anything but constant unless there is a careful application of "continuum concepts." The concepts are useful in forming a mental picture but are difficult (or impossible) to apply without sophisticated modification.

3.9 Continuum Levels

The most basic of sub-surface parameters is the hydraulic conductivity (“K_{sat}”) of the material. This is a measure of how much water flows between two points when there is an energy gradient. Consider the experience of Davis et al. (1996):

> Three techniques were used to measure saturated hydraulic conductivity (K_{sat}) in an upland forest soil; each employed a different scale of measurement in an attempt to investigate the consequences of the heterogeneities present. All measurements were conducted within a 50 m × 50 m field plot on a ridge top site in 1939 regrowth Mountain Ash forest. In situ measurements were made with the constant head well permeameter. Fifty five small cores (73 mm × 63 mm) and 18 large cores (223 mm × 300 mm) were removed to allow K_{sat} determination in the laboratory using constant head techniques. Results indicate significant variation (1 to 3 orders of magnitude) between the techniques in the surface soils; however, variation decreased with increasing depth. Generally, K_{sat} values increased with increasing sample size. The results of this work illustrate the difficulties associated with the measurement of K_{sat} in heterogenous forest soils and highlight the necessity to choose the most appropriate scale of measurement for a particular soil when undertaking conductivity measurements.

Thus, over 70 measurements with widely varying results! Of particular significance was that the larger the size of the measuring element, the greater the value. This reflects that larger samples are more prone to incorporate macropores. A common biasing factor in laboratory measurement of forest soils is that many samples fall apart when being taken because of root holes, voids, etc. These are then excluded from the sample, thereby biasing the result.

Such difficulties can, conceptually, be overcome by defining a “minimum continuum distance” (sometimes known as “minimum representative volume” in three dimensions) which, for forest soils, appears to be of some metres length. The concept is common to most scientific disciplines. Thus, imagine measuring the density of wood by cutting a cube of measured dimensions and weighing it. Then by dividing the mass by the volume, the density is computed. Over a wide range of measurements the value would be stable. However as the cube approached the size of 1 mm per side the density would depend on whether it was early wood or late wood being sampled. If our hypothetical sample continued to be smaller, then depending on where we were in the cell, the density would be very high (cell wall material) or very low (voids in the cell). As our measurement size decreases, our assumption of a continuum has broken down because we are at the level of the structure of the material. By skilled sampling and measurement at a sub-millimetre dimensional level we could actually compute the density accurately with the micro-measurements, but it would be a tedious exercise in measurement. A simpler method is to take a bigger sample.

The same applies to our forest soil. The continuum level appears, to the author, to be in the order of 1 or more metres. Small samples are measuring the properties of elements of the continuum rather than the properties of the continuum. The difficulty with the concept is that there are no practical laboratory methods to measure values of such dimensions. Field experimentation can be and has been established at such a level (e.g. Hewlett 1961) but the overheads of such work are beyond all but the most dedicated workers. Even this “classic” work used a repacked soil (without roots) to give known “boundary conditions” and to avoid the issues of macropores.

Although a minimum continuum distance of some metres appears large in human terms, even the smallest catchment will be of many hundreds of metres in length. Hence there is no problem in applying this to field cases (Box 3.1).

Box 3.1: Macropores

The discipline of soil science generally was based on soil water moving through a homogenous distribution of pore sizes similar to that which might occur in a column of sand. Early forest hydrologists noted that water in soils appeared to pass down a much larger series of voids or discontinuities in the forest. To the early soil physicists, they were viewed as “flaws” in the mineral soil, but forest hydrologists quickly realised that the idealised soil of agriculture really did not exist. This led to the concept of “macropores.” Auberton (1971) led a project to quantify these on a forest slope. He found that root-channels formed by the decomposition of roots were a major cause of these. As the roots decomposed water would pass through the holes and deposit clay “skins”, helping to stabilise these. New roots would occupy these voids, compressing the debris of the old route and then go through the same cycle. Stabilisation was also helped by the physical entrance and expansion of a root in the soil compressing the soil adjacent to it. Macropores are now, belatedly, being given recognition in soil physics.

3.10 Characteristic Outflow Behaviour of Catchment Elements

It is more easily said than done, but if the hydrologist measures outflow response of a first order catchment at different locations, they will find very different responses over short distances (see Fig. 1.13 for an example of this). This reflects that small catchments can be viewed as being composed of “blocks” fitted together and that the blocks will have a differing outflow to a period of rainfall that are functionally dependent on their shape. This property has been not much explored by the theoreticians of the world.

Figure 3.8 illustrates a basic classification used in Chap. 1, showing the shape and approximate outflow hydrograph from a large period of storm rainfall. This is based on the work of Bren (1979) at Croppers Creek. Hibbert and Troendle (1988) present a similar US example. In each case the rainfall recharged the stream groundwater system and then some of the rainfall passed into the stream over the ensuing days. A more modern exploration of the influence of catchment geometry on outflow is given by Troch et al. (2003).

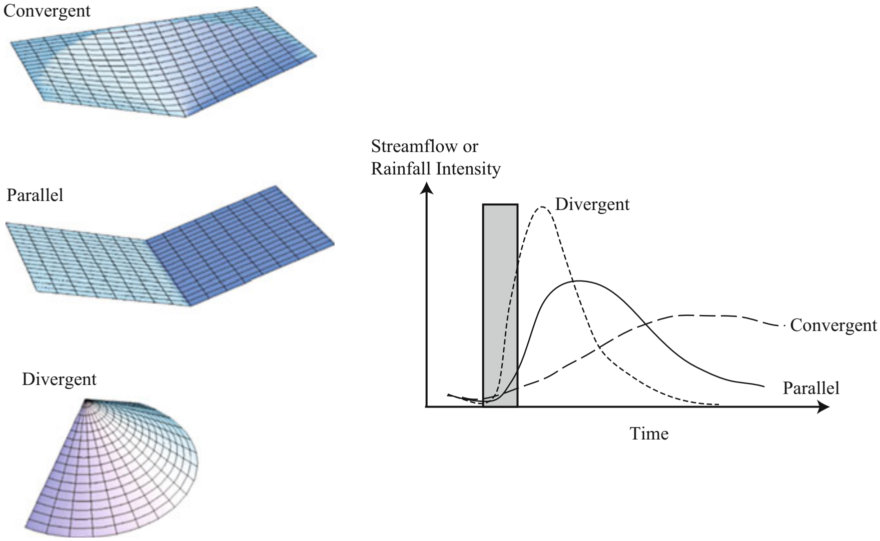

Fig. 3.8 Basic catchment plan-forms and their outflow hydrographs which tend to be associated with a short storm

The convergent, bowl-shaped head is at the start of the stream. The outflow of this is unresponsive to rain. However typically the outflow reached a maximum value 3 days or so after the rainfall and began a slow recession. This reflects the convergent geometry. Thus water which infiltrates near the ridge may take days to pass to the stream. However there is infiltration over a much larger area eventually passing down to and then through the outlet, and hence the delayed peak. The slow, delayed response is characteristic of mountain springs and reflects a convergent catchment.

The other extreme response (and the opposite geometry) is the outflow from the divergent geometry associated with the toe of spurs. Thus the great bulk of infiltration occurs close to the point of stream outflow, giving a rapid response hydrograph with dies away rapidly. The “parallel” geometry associated with the most common catchment slopes is intermediate between the two extremes, typically giving something close to the “unit hydrograph” response of text-books. A real catchment reflects combinations of the three. Thus in the double-peaked hydrograph shown in Fig. 3.9, “Peak 1” denotes the outflow from parallel and divergent components. “Peak 2” reflects the increasing outflow from the spring head, with the time rate of increase being greater than the time rate of decrease of the outflow from the parallel component downstream. The outflow hydrograph is the sum of the two. This is a common hydrograph shape from small forested catchments. The relative magnitude of Peaks 1 and 2 is a complex function of the storm size and the relative size of each component in a given catchment.

Further consideration of this is given in the discussion of groundwater processes in Sect. 4.5. An interesting visualisation is to break down a larger catchment into a

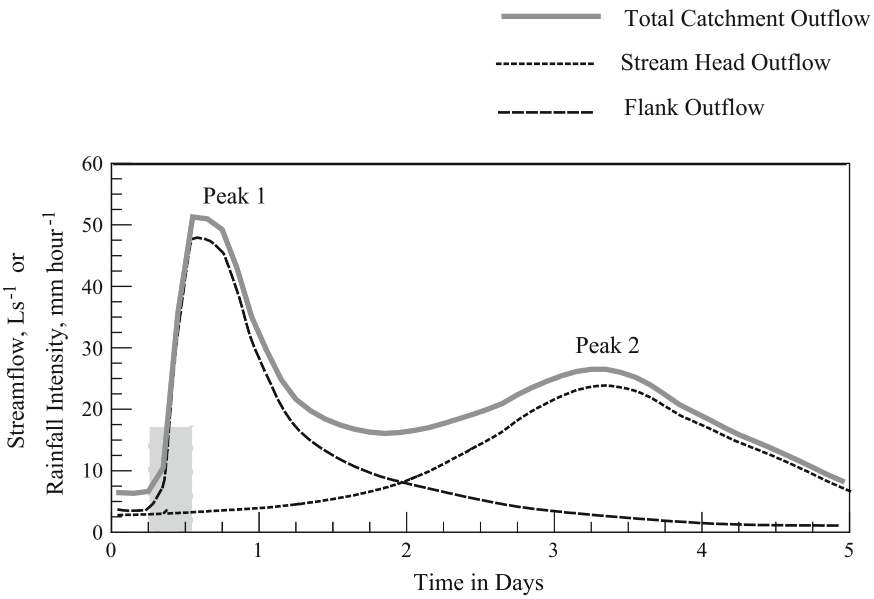

Fig. 3.9 The catchment flanks (parallel components) and divergent components reach a peak in conjunction with rainfall. In contrast the stream head may achieve its peak flow 2 or 3 days after rainfall, reflecting the convergent groundwater geometry and groundwater transmission times. Outflow hydrographs are the sum of the two outflows and hence often exhibit a *double peak* as shown here

collection of concave, parallel, and convex elements, and to consider how each of these contributes to the overall catchment response.

3.11 Similitude and Scaling of Catchment Processes

The relation between smaller and larger versions of the same thing is called similitude. Thus, in hydraulics, models of ships and aircrafts are used to determine the behaviour of the real thing. Measurements taken on models are scaled up using “similitude laws.” These are usually couched using dimensionless groups of variables which help remove “size aspects”. The process can give surprisingly accurate estimates of behaviour of the full-size versions. Although catchments can be viewed as having a systematic basis, development of “similitude” relations between small and large catchments is a largely unexplored field.

Black and Cronn (1975) used a rainfall simulator to “rain” water on small physical models of catchments to examine the effects of catchment size on various hydrograph parameters. It was shown that the model-size/maximum peak relationship was as predicted for real catchments, that relationships derived on the model were similar to those for a real catchment, and that the technique had potential.

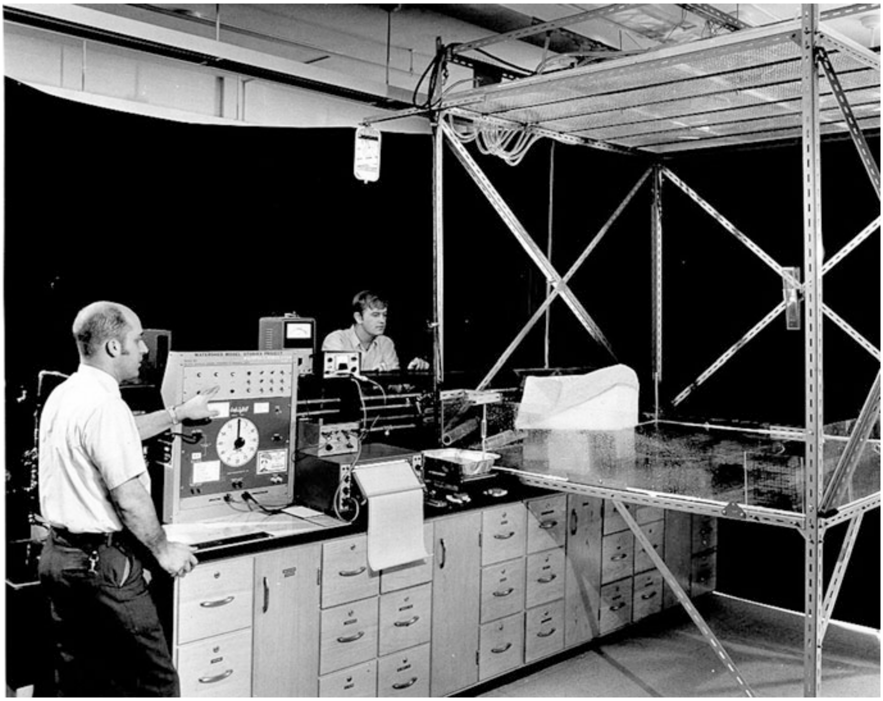

Fig. 3.10 It's the 1970s, there's not a computer in sight, and Professor Peter Black and graduate student James Cronn are working on their catchment similitude study in Syracuse, New York State (Black 1970; Black and Cronn 1975). The model catchment sits under a rainfall simulator. Runoff is continually weighed and an electronic differentiator gives a hydrograph. Physical modelling can give great insight into behaviour and avoids the issues associated with coding mistakes and computer underflow/overflow issues. However it is very demanding in time and has its own set of problems

Figure 3.10 illustrates this type of work. At the time of writing this approach appears to have been superseded by digital modelling. Amongst other advantages, physical modelling gives an excellent "feel" for the processes involved and avoids the issues of programming mistakes.

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Chapter 4
Dynamics of Catchment and Slope Processes

Abstract Dynamic processes are the factors that act on rainfall once it hits the catchment, leading to outflow varying over time. The Chapter examines the knowledge of these processes within the catchment slopes. Of particular importance is the role of groundwater and how groundwater outflows are influenced by catchment shape. Comparisons between observed results and mathematical groundwater simulations suggests that the concepts of rigorous boundary conditions and single-valued parameters are not met, and that hence groundwater theory can, at best, provide insight into behaviour but cannot simulate outflows. The observed behaviour is interpreted in terms of Hewlett's Variable Source Area model.

4.1 The Role of Science and Maths in Slope Dynamics

Famous scientist Galileo Galilei noted that "I can foretell the way of celestial bodies, but can say nothing of the movement of a small drop of water" (Eagleson 1970). We can do better today but our relative precision of forecasting the movement of the drop is still low compared to forecasting astronomical bodies. Why is this so?

Historically, two major texts underpinning hydrology have been Bear's "Hydraulics of Groundwater" (Bear 1979) and Eagleson's "Dynamic Hydrology" (Eagleson 1970). Even the briefest perusal will show them as replete with partial differential equations and diagrams showing initial and boundary conditions defining slope hydrology processes such as surface flow or groundwater flow. Underpinning this was how these equations might be solved, using methods we would now characterise as either archaic or "quaint." Since they were published, the equations may not have changed but the solution of them has become simply a matter of the scientist generating half a dozen lines of "*Matlab*" or "*Mathematica*" input and pushing a button rather than having to learn advanced mathematical methods. Why, then, is a book such as this not also littered with double integrals, double differentials, and lots of obscure Greek letters?

The answer goes to the heart of the science of forest hydrology. The discipline arose from the concept and observation that streams behave systematically and should obey physical laws. In fact the only "law" found in most hydrology books is "Darcy's Law" and this is only an empirical linear relation between the hydraulic head gradient across and flow through a column of sand. Even this only works over

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a narrow range of head gradients and low fluid velocities (as any experimentalist will tell you, there are many ways that infiltration through a sand column will or can be made to deviate from Darcy's Law). Study of the formulations of Bear (1979) and Eagleson (1970) and other theoretical texts is indeed worthy in that these help to interpret field observations. However, under the best conditions in a forest these solutions are only crude approximations to data obtained.

Consider a simple groundwater transmission through the forested slopes of a catchment to a stream. Assume that there is a tractable partial differential equation such as the Boussinesq/Dupuit approximation of groundwater flow reasonably applicable. Issues will be:

1. Such an equation is based on a continuum assumption (See Bear (1979) and Sect. 3.9 for a discussion of this). It is doubtful that this assumption holds at workable scales on forest slopes, and, for all we know, may not hold at all.
2. Basic parameters such as hydraulic conductivity are usually essentially unmeasurable (see Sect. 3.9). At a minimum the soil is anisotropic (i.e. properties differ in different directions), and any parameters have a stochastic distribution in all directions. Thus use of one number will be a gross approximation. We usually have no practical methods for measuring these at a point, much less the anisotropy or the distribution of values.
3. Any solution will involve assumptions of "boundary conditions" such as impervious boundaries or no flow across ridges. Sometimes these are approximated, but more usually not. Thus most catchments have diminishing permeability with depth but cracks and fissures will still give permeability and storage many meters below the ground. This is not the same as the usual assumption of an impervious "base" which is something akin to a concrete floor.
4. The geometry of a catchment at any point rarely conforms very closely to the usual Cartesian or cylindrical coordinates beloved of mathematical hydrologists.
5. There will be many other uncontrolled factors such as water temperature, air trapped in the soil mass, the fractal nature of boundaries, compacted soil surfaces, and masses of surface vegetation.

The net result is that any simple model can only reproduce a few features of the dynamic behaviour. This observation is borne out by the endless (but not unpleasant) study of stream hydrographs over many years looking for variations over time that somehow reproduce the behaviour predicted by the above texts. The study has been interesting but the results have generally been disappointing. The author believes that study of the mathematics of saturated and unsaturated flow in forest slopes may indeed give considerable insight into the process (and, for that alone, is well worth-while) but its ability to accurately reproduce the exact behaviour hardly exists. The result is that many elegant ("classic") solutions of infiltration equations or transpiration of trees are hardly useable in forest hydrology because of breakdowns of the above assumptions. This is mirrored (in this text generally and this Chapter specifically) by the unenthusiastic embrace (or, in this case, omission) of "classic" formulations such as the Philip Equation (Philip 1957) or the Green-Ampt Equation (Green and Ampt 1911) for infiltration, or various equations for computing evapotranspiration.

The net result is that forest hydrology tends to be an empirical science (but still a science). However the history of science shows that fields that are now viewed as "well-explored" were once similar empirical areas. A recent example is the work of Mandelbrot (1983) who cast light into a class of empirical issues (some of which impinge on material in this book) with his concept of the mathematics of "fractals." Thus it is to be hoped that a similar innovative and different approach will, in time, applied to forest hydrology to give it a less empirical and more theoretical basis. For the moment, the student and practitioner has to live with empiricism.

4.2 Overview of Dynamics of Slope Processes

Definitions of dynamics vary but usually refer to study of forces at work and their relation to motion and change. Dynamics of catchment and slope processes refer to the movement of water from the air through the catchment material into the stream, into deep-underground aquifers, or back into the air. In general water enters the catchment as rainfall at a (relatively) high energy. This energy is then dissipated (mainly as heat) by the passage of the water through various media until it either passes into the stream, into a "deep" aquifer, or into the atmosphere.

Forest management is about managing the slopes of small catchments, and it is mainly the slope hydrology which distinguishes forested catchments from agricultural catchments. Figure 4.1 shows a schematic cross-section of a forested slope and

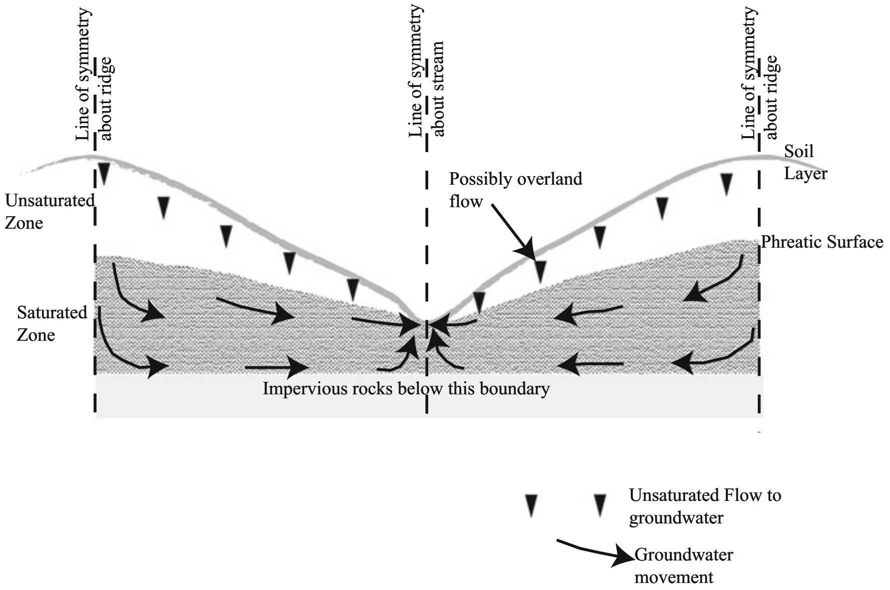

Fig. 4.1 Schematic of a forested slope cross-section illustrating surface and subsurface processes and assumptions commonly made in groundwater theory

illustrates some processes and assumptions often used in simulations. At the toe of the slope is the stream which carries water away from the slope; once the water enters the stream it plays no further part in the slope hydrology. The stream can be viewed as a source or sink of water at a low energy level. In a low order stream, the vertical movement of the stream water surface is almost negligible. Hence processes such as bank storage in which vertical movement leads to groundwater inflow and outflow from the stream bank are negligible.

The dominant source of water to the interior of the slope is precipitation. In Australia this is usually rainfall. Some of this water is lost to the catchment by interception (see Sect. 6.2). Most water passes through the ground into the soil. Two processes are commonly recognized as passing water from the slope to the stream – overland flow and groundwater flow. Each is detailed below. Overland flow is usually negligible for forested catchment slopes but can occur on compacted roads and tracks and a variant may occur after fire.

The major source of loss of water from the slopes is evaporation and transpiration; sometimes attempts are made to separate these processes. Transpiration is the passage of water to the atmosphere through living tissue, whereas evaporation is the passage of water through non-living material. However most studies have found these processes difficult to separate and refer to "evapotranspiration" as the joint processes.

An additional source of loss of water is "deep seepage" in which water effectively passes out of the bottom of the catchment. This generally involves recharge of deeper aquifers and is an important process in many uplands in which the high rainfall in mountains leads to groundwater recharge for important aquifers substantial distances away. However there is no known general method of assessing this.

These processes can all be replicated in laboratories and usually demonstrated in the field in a variety of ways. For most processes there is a body of theory describing the process under idealised conditions. However it is often difficult to apply these theories to specific field cases because of the wide heterogeneity of materials, the irregular geometry of individual items, the non-constancy of conditions such as temperature, the large minimum continuum level if assumptions of continuity are to be applied, and the difficulty of access to deep areas within the catchment slopes.

The processes have all been brought together in the "Variable Source Area" conceptual model of Hewlett and Nutter (1969) and others. At the time this was promulgated it was controversial because it disagreed with the findings of agricultural hydrology. Those differences in view have long since faded away.

4.3 The Stream Channel as a Connecting Link

From the point of view of hydrology, the stream channel is everything. It connects the slopes and the head of the stream. It acts as a reference energy point, with the lowest point in the stream often being the point of lowest water energy in the catchment. The stream acts as a "sink" to the catchment slopes in that once water has entered the stream it is lost to the slopes and, soon after, to the catchment as it passes downstream. Most forest hydrology projects ultimately end up measuring the flow in the stream. Forest management usually involves some consideration of stream protection from works in the catchment.

For first and second order streams, the channel is complex, shallow, and wide relative to the flow carried. Like so much in forest hydrology, the streams do not sit well with hydraulic theory of channel flow. Parameters such as cross-sectional area and "perimeter" are essentially unmeasurable because of the fractal nature of the solid-water interface. The stream hydraulic behaviour is well-described by the kinematic theory of overland flow (see, for instance, Lighthill and Whitham (1955); Henderson and Wooding 1964; Wong 2012). Bren and Turner (1978) applied this to examine flow behaviour at Clem Creek and found that the flow was related to the storage in the channel by the relation:

$$q = 0.003077\ h^{1.81} \tag{4.1}$$

where q = Volumetric flow rate (Ls^{-1}) and h is a measure of the depth of water across a cross section (m). This is illustrated in Fig. 4.2. The measurement technique is described in Bren (1979), and allowed isolation of a 30 m reach of channel from flow emanating from upstream. This could be used to generate a "pulse" of water in the channel; to our surprise these were surprisingly stable and could be followed downstream. Figure 4.3 shows how a pulse of water travels along. It can be seen that:

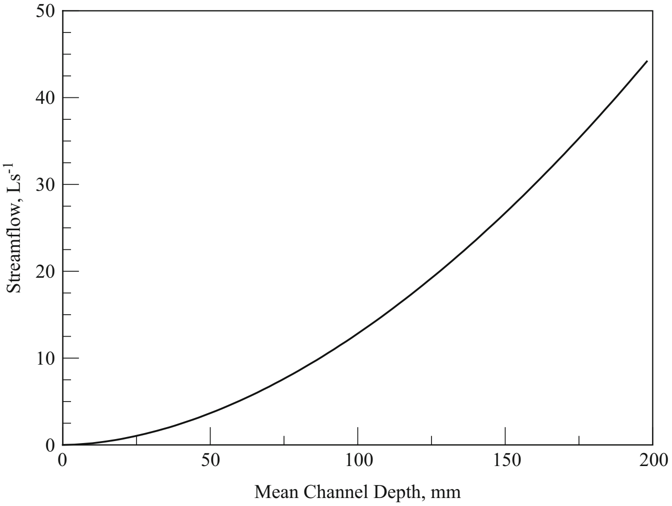

Fig. 4.2 Relation between mean channel depth and streamflow derived by field measurement on Clem Creek (From Bren 1979). For a plot like this, it is arguable as to which is the independent variable

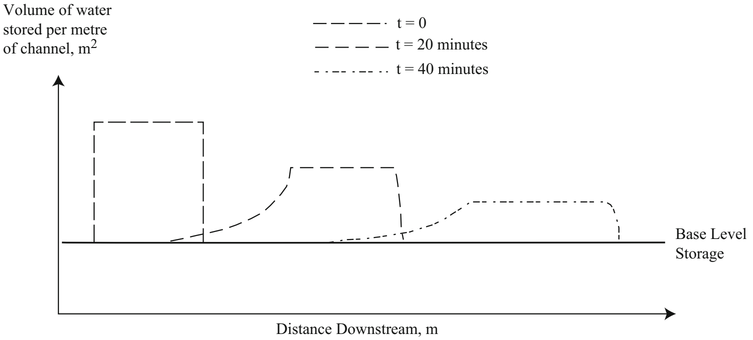

Fig. 4.3 Schematic showing how a water pulse travels along a small-stream channel. For Clem Creek, the speed of passage was a little slower than walking pace

1. The leading edge of the discontinuous increase in flow travelled downstream as a discontinuity. This effect has become of some importance as an effect in fire hydrology considered in Chap. 8.
2. The trailing edge was a recession in flow passing downstream.
3. The changes were effectively moved along the channel at the mean channel velocity, and only moved downstream.

The amplitude of the pulse was diminished because the leading edge travelled faster than the trailing edge. The technique was used to measure the time of travel of hydraulic effects along the stream. Typically these travelled at about 1 km h^{-1}, reflecting the very rough hydraulic conditions of the streambed. Travel speed increased with increasing storage of water in the channel.

Overall the behaviour is characteristic of a flow in which the flow is “critical” (i.e. “Froude Number” close to 1). Detailed observation of the flow suggested that, for most of the time, it was closer to a series of “micro-pools and riffles” formed by rocks and vegetation rather than a continuous moving body of water to which such hydraulic parameters can be applied. Passage through such riffles ensured excellent mixing and oxygenation. Estimation of Reynold’s Numbers as an indicator of turbulence always showed flow was highly turbulent.

For practical purposes, the stream can be viewed as something analogous to a conveyor belt moving downstream and carrying the outflow from slopes, with the velocity increasing with increasing flow. In the studied catchment, the time taken for an effect to travel from the uppermost point of channel flow to the weir (about 460 m) varied from about 30 min to 2 h. In hydrograph modelling, classic “routing techniques” can be applied to improve accuracy (e.g. Ladson 2008), but the error induced by ignoring the time taken to pass along our small catchment was small.

4.4 Overland Flow and Slope Infiltration

In overland flow, water passes across the catchment surface along the most downward path to the stream. Although such a flow rarely (if ever) occurs on most forested slope it is embedded in public consciousness as the model of stream generation; the term “runoff” implies this. The concept was particularly popularised by the works of Horton (1938) and became the basis of work in agricultural hydrology developed on cultivated slopes. There is a wide body of mathematical solutions of cases of overland flow, mostly based on “kinematic wave theory” of flow propagation (see Wong 2012 for a modern synthesis).

In the classic mathematical model of generation of overland flow on catchment slopes, the rainfall intensity exceeds the soil infiltration capacity. The result is some sort of sheet flow passing down-slope. The process can be commonly observed in large paved areas, on compacted farmland, on forest roads (Figs. 4.4 and 4.5), or occasionally on saturated lower portions of slopes (referred to in Sect. 4.6 as the “source area”. Figure 4.5 shows an overland flow hydrograph generated by a substantial storm on a reach of forest road at Croppers Creek (taken from Bren and Leitch 1985). The hydrograph was extremely “jagged” and the water very turbid compared to that from a nearby forested catchment. This is a general characteristic of overland flow hydrographs, and reflects the strong buffering role of forest cover on slopes.

In most forest soils the infiltration capacity far exceeds the intensity of commonly-encountered rainfall, and hence true overland flow does not occur. However occasionally inadequate slope water storage capacity may lead to exfiltration (i.e. coming to the surface) of slope groundwater at upper slope positions, leading to a sort of overland flow (usually this water again infiltrates at a lower position). In general, most forest surfaces are so hydraulically rough that true

Fig. 4.4 Road runoff. The photograph to the *left* is a stretch of forest road. The box is a streamflow measurement structure mounted on a culvert. The photograph on the *right* shows the measurement weir. Water passing out of this was distributed over the slope. A second measurement weir downslope estimated slope infiltration. The work is detailed in Bren and Leitch (1985)

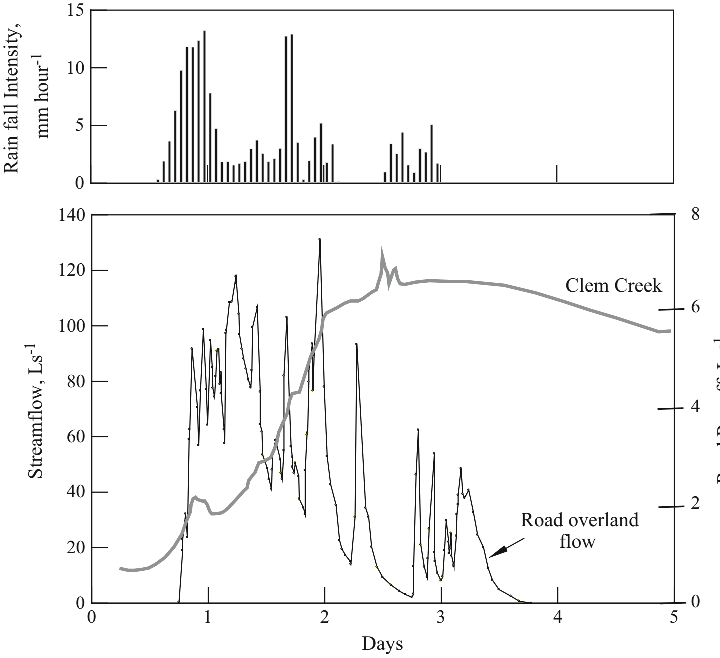

Fig. 4.5 Overland flow hydrograph generated on a forest road. The *left-axes* shows the flow in Clem Creek. The *right axis* shows the flow from a section of forest road. The jagged nature is typical of overland flow hydrographs

overland flow cannot occur. Figure 4.6 (taken from Bren and Turner 1979) shows a comparative hydrograph of runoff from an impervious metal surface and an area of forest of the same size, side by side. There was some downslope water movement on the natural forest slope but it appeared to be mainly raindrop splash preferentially passing downhill because of the slope angle (see Miura, Hirai and Yamada 2002 for a quantification of this).

Occasionally, in extremely intense rainfall the rainfall intensity may exceed slope infiltration capacity in a forest and generate true overland flow. When this happens the flooding is, indeed, spectacular, and intense and destructive erosion may occur. Orr (1973) gives an account of such a storm in the Black Hills of South Dakota. Preceding rainfalls had effectively filled up the slopes to near their maximum storage. Rainfalls over 6 h on the night of June 9th, 1972 were described as “immense” and ranged from 100 to 400 mm. The infiltration capacity of the hillslopes was exceeded. Flow on the hillslopes then moved through the thick leaf litter unit it was diverted or ponded by stones. When this happened the litter floated and moved downslope, leaving a small patch of bare mineral soil. Many such spots could be seen on some slopes. Sometimes a point of “flow-stagnation” behind a tree would lead to accumulations of leaf litter. The particular storm caused a major (and famous) flood at “Rapid City” with an official death-toll of 238 (Carter et al. 2002).

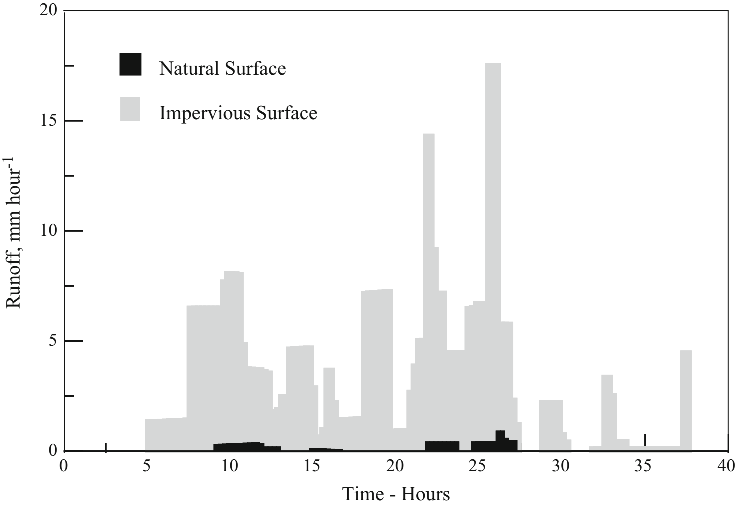

Fig. 4.6 Comparison of runoff generated on a sheet of impervious steel and a forested surface of the same size at Croppers Creek

In such a case, the entire catchment becomes a "source area". Orr (1973) noted in this flood that the catchment slopes acted as an efficient water conveyance but there was little transport of mineral matter or erosion on the slopes, showing the effectiveness of forests in protecting slopes surfaces from erosion in extreme conditions.

Overland flow on forested slopes may occur after wildfire in Australia and this process is described in Chap. 8. This generates extremely high flows for short periods, and is responsible for much erosion.

4.4.1 Measuring Infiltration

It is instructive to use a "sprinkling infiltrometer" (e.g. Burch et al. 1987) on both agricultural soils and forest soils (Fig. 4.7). In these, water is somehow "rained" onto a small, bounded area of soil surface, and runoff collected. The difference between the rate of supply and the rate of runoff is the infiltration over the bounded plot. On farmland and forest roads, this runoff is clearly proportional to the rate of supply for anything but very low intensities. When tried in a native forest, it is not so simple. Firstly, getting the equipment in place in an "undisturbed site" is almost impossible. Secondly, the density of litter. plants, and surface roots is so great that installing the infiltration plot boundary is both difficult and a major disturbance. Thirdly, within the limits of naturally occurring rainfall it is usually difficult to generate any runoff. Much of the water appears to be stored in the litter, and examination of the site usually suggest that most infiltration is occurring at one or more "preferential" sites (also referred to as "macropore pathways"). Burch

Fig. 4.7 Use of a sprinkling infiltrometer in a study of the impact of soil slaking on infiltration into a nursery soil. Water is pumped from a storage tank to the rotating disc on top, from where it "rains" onto a bounded plot. It worked well on agricultural soils but could not meet the high infiltration capacity of forest soils

et al. (1987) commented on the absence of these in non-forested sites. A common sampling strategy is to find a site with no such obvious surface hole, but this immediately biases the results statistically.

Section 3.9 quotes the experience of Davis et al. (1996) in measuring hydraulic conductivity by an infiltration technique; the work is cited as an example of the difficulties encountered when working at less than the minimum "continuum level." This work showed that, in general, the larger the sample size, the larger the infiltration rate.

Related to this is the agricultural concept of "wetting fronts" (e.g. Hillel 2004). Thus, after large rainfall in an agricultural soil, one can dig down and find a junction between the soil wet by the rainfall and the dry soil underneath. In a forest soil, it is firstly difficult to dig down because of roots. Secondly both excavation and work with a neutron soil moisture probe (e.g. Bren 1979) failed to show such a wetting front. Observation of the water–soil system suggested a two-part system in which a network of macropores associated with old tree roots and other disturbances passed water to substantial depths in the soil, without transmission through the capillary matrix of the soil. The mineral matter of this soil did show a general wetting and drying, but it was impossible to link this to a particular hydrologic event. Formal concepts of infiltration capacity can only be applied to forest soils with difficulty.

In forest soils the work of Auberton (1971) and many others since have shown that the infiltration is dominated by the porosity associated with tree roots, soil fauna, and larger fauna (see Box 3.1). These “macropores” may take water to many metres below the soil surface very fast and play an important role in the ability of forest slopes to store and release water. The presence of these also makes classical definitions of “soil water” difficult to apply to forest soils at a small scale, since water at different energy states may effectively coexist in the soil, with transmission limited by the low unsaturated hydraulic conductivity of the dry soil or impervious walls of the macro-pores.

Harr (1977) made detailed measurements of soil properties and water potential in the unsaturated and saturated zone, and rainfall on a steep forested slope in Oregon, USA. He found that although unsaturated flow predominated in the soil during 14 moderate-size winter storms, discontinuous saturation of upslope subsoil did occur at depths of 110–150 mm. This saturation persisted less than 20 h and can be viewed as a “temporary storage” of water on its way to greater depths. Analysis of data showed an abrupt decrease in the rate of water flux to the lower part of the slope about 10 h after the end of rainfall. This decrease corresponded with nearly complete draining of larger pores that had filled with water during storms.

Ranken (1974), also working in the mountains of Oregon, examined hydrologic properties of the soil and subsoil on a steep forested slopes at depths of up to 2 m. He noted the extreme permeabilities and high porosities of the samples caused many difficulties. He found little variation of porosities and bulk density with depth but that permeability decreased in the soil matrix. He also found evidence of temporary saturation occurring during storms, with this water draining away on the cessation of rainfall.

Perusal of scientific literature in this field shows that the peak of work appears to have been between about 1970 and 1990 and that there is a scarcity of new work (and conceptual advances) in the field since then. It is to be hoped that newer studies using modern data-logging technology can help resolve issues.

4.5 Saturated (Groundwater) and Unsaturated Flow

Consider our slope of Fig. 4.1 in a moderately steep catchment with a well-developed soil. Suppose one moves a few metres to one side of the stream and augurs a hole during a period without rainfall. This will pass through dry (or at least unsaturated) material but ultimately will pass into wet material and the bottom of the hole will fill with water. Suppose this is repeated a few metres further upslope. The hole will be deeper before it starts filling with water. This can be repeated ad infinitum (Fig. 4.8). Doing this in practice is limited by the holes becoming many tens of metres in depth, with a consequent need for large drilling equipment and earthworks to allow drilling-rigs access to the slope.

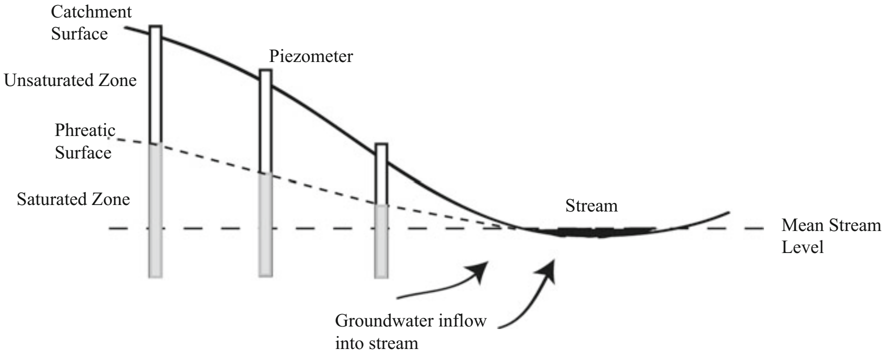

Fig. 4.8 Concept of groundwater depth and the phreatic surface in a forested slope

In our hole, the area above the water level is the unsaturated zone, in which water is held by capillary soil forces at less than atmospheric pressure. The water below the water level is the saturated zone, and hence will fill with water. In Fig. 4.8 the hypothetical line joining the water levels marks the line of water at atmospheric pressure and can be called a "phreatic line" or "groundwater line". In the three-dimensional case this would be the "phreatic surface", the "groundwater surface", or the "water-table surface." If one imagines a small, triangular element of this phreatic surface, it will go up and down, and tip and tilt as groundwater pressures change during periods of rainfall. The work of Harr (1977) showed that sometimes, above this there may be transient, discontinuous pockets of saturation but these eventually drain to the phreatic surface. Because of the existence of the transition from unsaturated to saturated soil the slopes can be viewed as a "water-table aquifer" or "phreatic aquifer" (Bear 1979) in which the lower boundary is an impervious zone in the catchment and the upper aquifer boundary is the water table.

Figure 4.1 presents a cross-section of our first order catchment and illustrates assumptions of such a model. In this the lower boundary of the aquifer is taken at a substantial but indefinite depth below the stream. Of note are:

1. The stream and the ridges have elements of symmetry about them. Thus, to a first approximation, the left side of the stream can be viewed as behaving as the mirror image of the right hand side of the stream. This imposes a "no flow" boundary along this line of symmetry as indicated.
2. If we assume a finite "bottom" of conducting material, then the mathematics and various field studies show that we get a pattern of streamlines something like that shown in Fig. 4.1. Streamlines near the boundary reflect the shape of that boundary. Thus water which passes to groundwater may then pass through considerable depths in its passage to the stream. This passage may take considerable time, and hence water issuing into a stream may enter the stream as a direct result of a hydraulic gradient induced by a storm, but the actual molecules of water entering may have been taken many months to travel from the catchment surface to the stream.

3. The slope of the phreatic surface, in this catchment, is substantially less than the land slope. Thus the depth of the unsaturated zone increases with distance from the stream.

A number of issues limit the application of such a simple model. Particularly difficult is the assumption that the catchment slopes are spatially homogeneous in their transmission properties. In fact the permeability usually decreases with depth; it has been often been shown (e.g. Marechalm et al. 2004) that fracture properties of the rock dominate the permeability at depth. Hence the simple streamlines shown in Fig. 4.1 can be demonstrated in models using homogeneous aquifer material but not in real catchments. This zone of transmission is sometimes called the regolith, and is defined as a layer of loose, heterogeneous material covering solid rock. For real slopes the distinction between rock and soil is not always clear, and the “solid rock” may be permeable because of fractures. Secondly, response of groundwater involves movement of both water and gases in the soil. This two phase flow is very damped and slow to occur. Observation of air compression in soils goes back to the origins of soil physics (see Bevan and Germann (1982) for a review of this) but we still have no easy way of dealing with the effects.

Study of groundwater response in catchment slopes is an interesting area of study. Near the stream the groundwater levels usually exhibit a diurnal variation in summer (Fig. 4.9, from Bren 1979) and this has been occasionally used to estimate evapotranspiration (e.g. Loheide et al. 2005). It can be shown that the groundwater recharges very fast after heavy rainfall, and that the stream recession is effectively a period of groundwater falling in the slopes, leading to diminishing stream inflow; Fig. 4.10 shows a the relation between groundwater depth and streamflow from measurements of three bores upslope from Clem Creek Weir over 10 years. Over the years, many attempts have been made world-wide to link slope groundwater properties to detailed hydrology, but the difficulty of obtaining good groundwater

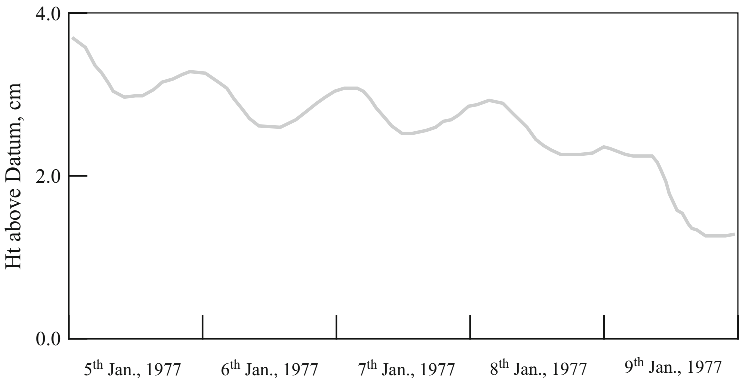

Fig. 4.9 Example of groundwater diurnal variation in a groundwater bore close to the stream at Croppers Creek

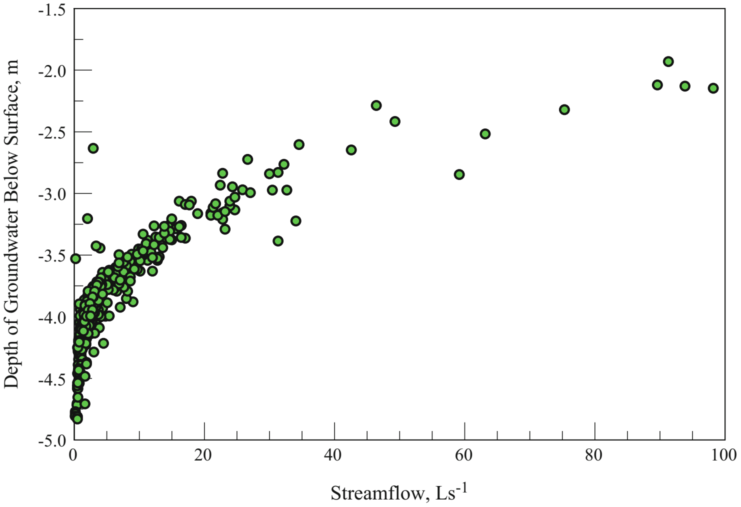

Fig. 4.10 Relation between groundwater depth and streamflow at Clem Creek. Each point is the mean of three bores located approximately 30 m upslope of the weir. Bores were read weekly over a 10 year period

and outflow data and measuring sub-surface parameters have not made this a fruitful field.

4.5.1 Applications of Groundwater Theory to Model Forest Slopes

There is a well-developed mathematical groundwater theory for water-table aquifers, generally based around Dupuit-Forcheimer theory and variants of the Boussinesq Equation (e.g. O'Loughlin 1981). In these, flow is proportional to both the thickness and hydraulic gradient of the aquifer, with hydraulic conductivity and storage per unit volume of the aquifer being specified. The theory can be most useful at an explanatory level and for showing aspects of catchment shape (see Sect. 3.10). Readers are referred to texts such as Lu and Godt (2013) for an excellent presentation of the governing equations and the derivations of various equations including the Richards Equation for unsaturated flow and the Green-Ampt infiltration model. Workers such as Beckers and Alila (2004) have used such relationships to model aspects of hillslope runoff contributions to peak flows in heavily forested settings and to interpret the results. Thus their results suggested that storm flow runoff was dominated by macropores, but as these became drained the hydrograph outflow was formed by flow through the mineral soil matrix. The relative importance of these sources was functionally dependent on storm size.

Attempts to use equations based on groundwater theory for detailed prediction on forest slopes usually face the following difficulties:

1. Because of the mixed organic/mineral nature of the aquifer material, there is an unusually wide range of variability in parameters such as porosity and hydraulic conductivity from point to point.
2. Most groundwater formulations are ultimately based on "Darcy's Law" (Bear 1979) in which flow is proportional to hydraulic gradient. For soils with a large macropore component this may be a particularly difficult assumption.
3. The high hydraulic gradients encountered in forested catchments often invalidate assumptions made in the theoretical development.
4. "Initial conditions" and "boundary conditions" necessary for successful simulations can be unusually difficult to specify and probably only approximately apply.

4.5.2 "Perched" Groundwater and "Deep" Groundwater

Classically the Australian groundwater cited in many hydrologic studies are "regional aquifers" which underpin water-supplies and agricultural development. These aquifers are usually deep and extensive, often confined (i.e. bounded at the top and bottom by impervious layers) or semi-confined, and may be at a high pressure (e.g. the "Great Artesian Basin, or the "Mound Springs" of Central Australia). In contrast to these, the water-table aquifers of catchment slopes are small, discontinuous, shallow (by groundwater standards) and, by definition, are not confined. Sometimes differentiating the two types of aquifers has caused some confusion in terminology. The surface groundwater system is sometimes called a "perched aquifer" with the name suggesting it is perched above a regional aquifer. Deep drilling will often pass through banded aquifers separated by impervious rock, so the terminology of multiple aquifers vertically overlaid but not necessarily connected hydraulically can become confusing. There is usually no clear evidence to support linking of the surface groundwater systems of small catchments with deeper groundwater systems, although the deeper systems must ultimately get their water from somewhere. This is sometimes referred to as "deep seepage" and has occasionally been a worry of experimental hydrologists (e.g. Daniels and Kulik 1987).

Occasionally, the movement of water through the catchment slopes to the stream is called "interflow" (see, for instance Jackson et al. 2014). This may deliver water to the saturated riparian zone or riparian areas almost at saturation (sometimes called the "vadose zone"). As commonly used, the term interflow may include both saturated and unsaturated flow. The magnitude of the former far exceeds the latter. For water to pass spontaneously into the atmosphere from the soil, it must be at a pressure equal to or slightly greater than atmospheric pressure, and hence is best classed as groundwater movement. If the slope consists of soil overlying rock then the terminology is straight-forward. If there is stratification of materials in the slope then the question of whether the material is saturated or unsaturated becomes difficult to resolve. Resolution often requires strict definition.

4.5.3 Does a "Wave" of Groundwater Recharge Occur?

The model that has been presented is that, across a cross-section of the catchment, the phreatic surface is at the stream level near the stream, but increasingly below ground level with increasing distance upslope. It then follows that the further upslope one is, the longer groundwater recharge takes to pass through the unsaturated zone to groundwater. Effectively this means that in a large storm, a "wave" of groundwater recharge passes from the stream to the ridge. This concept is illustrated in Fig. 4.11. The rainfall recharge moves downwards through the unsaturated zone at a uniform penetration rate, thereby recharging the groundwater closer to the stream first. The concept was teased out in mathematical simulations for Clem Creek catchment by Bren (1979). It was noted the concept effectively led to groundwater flowing back towards the ridge until the recharge from the neighbouring catchment stopped this. Interestingly, the simulated hydrographs suggested this would lead to a change in recession gradients which were often observed in measured hydrographs on this catchment.

We are not aware of any actual measurements showing the existence of such a recharge wave, and hope that technology will allow exploration of this in the future. The concept of a "recharge wave" sits very well with Hewlett's variable source area model described below.

4.6 Slope Evaporation

The major fate of water infiltrating into the slope of an Australian catchment is to be evaporated or transpired back into the atmosphere. In general, the greater the proximity of the tree to groundwater, the greater the tree growth and the greater the transpiration. In particular:

1. Trees in the riparian zone have the greatest access to water and nutrients and are also highly sheltered. Hence they grow faster and achieve greater heights.
2. As one moves upslope, the distance of the tree root zone above the phreatic surface increases. Hence the energy needs of the tree in lifting water become greater.

The usual model applied to this is the "SPAC" model ("Soil, Plant, Air, Continuum" – see Hillel 2004). This postulates that the water flows upwards to the tree due to an energy gradient created by the presence of the leaves in a vapour-deficient atmosphere. Hence an upslope tree is faced with a far greater capillary lift than a downslope tree; this partly reflects that the upslope trees in small catchments

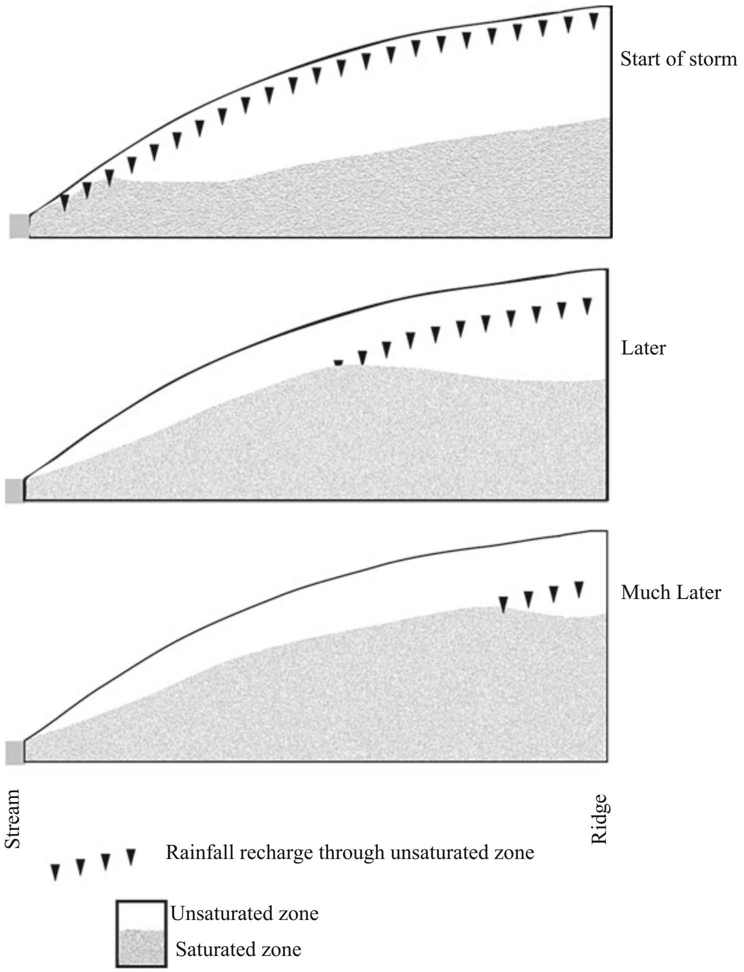

Fig. 4.11 Concept of a wave of groundwater recharge (From Bren 1979)

are usually smaller and carry a smaller leaf crown. Modelling of single tree survival using these concepts (e.g. Kowalik et al. 1988) has shown good agreement of theory and actual tree survival. Thus, in this study the authors concluded that "even with dry soil, shallow rooting depth, and high evaporative demand, trees did not show evident water stress." This corresponded with our observations at Croppers Creek in which we were continually surprised at the healthy crowns of trees in upper-slope positions during long summer periods without rainfall.

Direct measurement of evaporation is usually made by sapflow measurement (e.g. Roberts et al. 2001). Less commonly, more exotic methods such as weighing lysimeters can be used (e.g. Dunin et al. 1985). These are specialised methods beyond the scope of this text. At the time of writing a number of satellites either existing or about to exist offer the potential of some form of direct instantaneous measurement of variables which are directly correlated with evapotranspiration. This should open a whole new field of forest hydrology studies.

Considering much of hydrology is concerned with evapotranspiration loss, there is a shortage of workable methods to recommend to compute slope evaporation. A number of evapotranspiration equations are commonly cited for this task. “Classic equations” include the Thornewaite method (Thornewaite 1948), the Penman method (Penman 1948), or the Penman-Monteith method (Jensen et al. 1997). In general, these all require a large number of parameters, may involve assumptions which are not very applicable to Australia, and are enigmatic to use. They do not engender enthusiasm in Australian forest hydrologists. With practice and discipline they can be made to give reasonable answers for Australian forests. The reader is referred to texts such as Black (1996) for an explanation of their theoretical background and use in practice. Often these equations are embedded in catchment computer models, but obtaining values of the necessary parameters has proven to be a formidable issue.

4.7 Hewlett’s Variable Source Area Concept of Stream Runoff

Hibbert and Troendle (1988) present an overview of the development of this concept and some of the passions which were associated with it. A group of forest hydrologists at Coweeta Hydrologic Laboratory led by John Hewlett (Hewlett and Nutter 1969) developed the “Variable Source Area concept” (VSA) of runoff. This had its origins in dissatisfaction with application of hydrologic theory developed on agricultural catchments with low infiltration and subsurface transmission capacity. Over the years, many forest hydrologists had observed few if any episodes of “overland flow” in forests, although this was the paradigm for fast response of streamflow. Their alternative hypothesis/explanation was that runoff was generated by rain falling on a saturated area near the stream – the “source area”. As the storm size increased the source area increased until, ultimately, it became the entire catchment. Figure 4.12 illustrates this concept. O’Loughlin (1981) noted that runoff from the saturated areas shown in his hypothetical analysis (see Fig. 4.13) would correspond to the “source area” of Hewlett (1974).

Intrinsic to the hydrology thinking of the time was a separation between “base flow” and “storm flow”. Base flow was viewed as a sustaining flow with its origins in groundwater, and is the streamflow occurring for long periods in the absence of rainfall. Stormflow was the streamflow which occurs in rapid response to rainfall, and was viewed as having a different origin. At the time the concept was first advanced, the view was that groundwater was too deep and unresponsive to generate fast stormflow response. Subsequent work has shown that virtually all

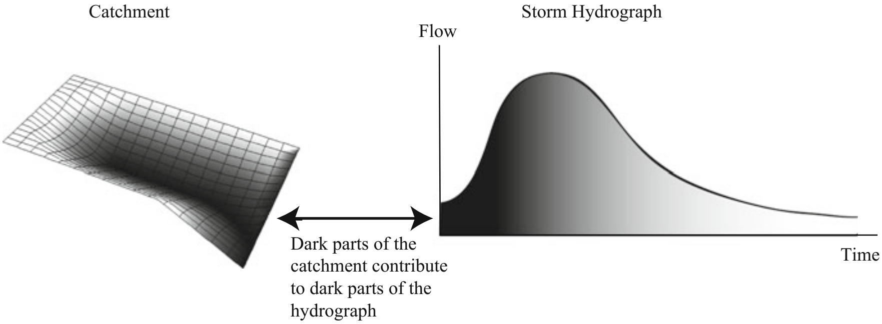

Fig. 4.12 Illustration of the variable source area concept. The darker parts of the 3D representation of the catchment contribute water to the darker parts of the hydrograph

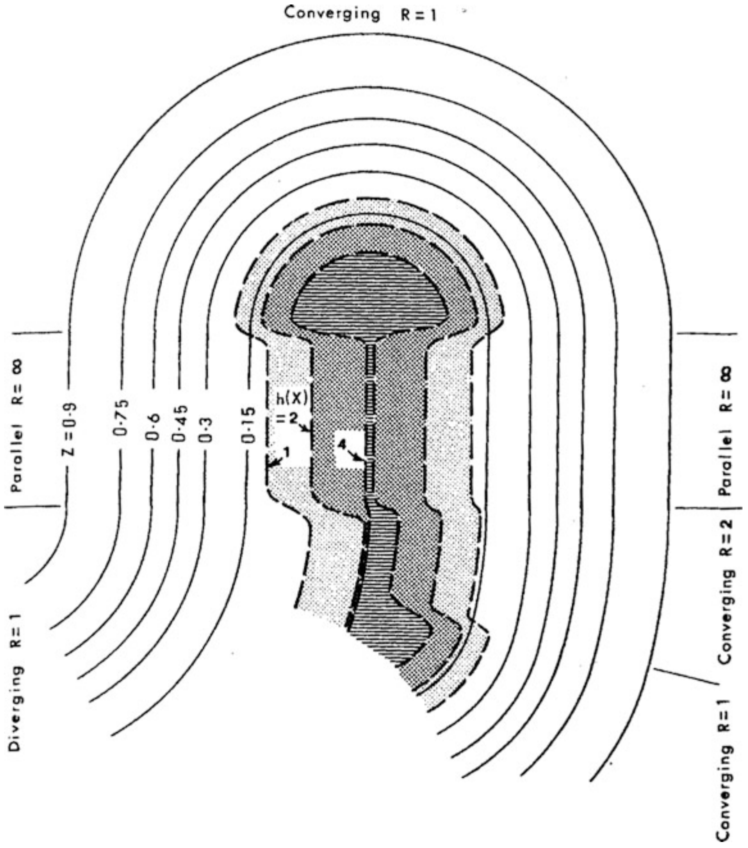

Fig. 4.13 From O'Loughlin's (1981) analysis of wetted areas as a function of catchment geometry. The hatched areas show the location of groundwater seepage zones in different portions of a catchment as a function of flow – for higher flows these expand outwards. The geometry is similar to that of Fig. 3.1. The hatched areas can be viewed as representations of Hewlett's variable source area

runoff in a forested catchment is groundwater, and that the water-table aquifers that comprise forest slopes are both fast transmitters of water and responsive.

The key features of the concept were that:

1. The area of a drainage basin contributing directly to streamflow from a period of rainfall varies with time. Initial storm runoff comes from rain falling on the stream and near surrounds. As the storm progresses, runoff is generated by rainfall falling on the catchment slopes which had infiltrated to groundwater and passed back to the stream.
2. In vegetated basins, subsurface flow supplies all baseflow and is also a major contributor to stormflow.
3. Groundwater recharge increases slope outflow. A key determinant of hydrologic response is the amount of groundwater stored in the catchment slopes, of which "antecedent flow" (the flow in a stream before the start of rainfall) is a measure.

Subsequent work (e.g. McDonnell 2003) has pointed out that although the "new" infiltrating rainfall may lead to increased runoff, the water that emerges is pushed out by the new water. It is not the "new" water which enters the stream.

As presented, it was and is essentially a conceptual model implying groundwater recharge and discharge as the dominant slope processes. At the time of development, the stream flow response to rainfall was usually viewed as some variant of overland flow. Pressure was sometimes exerted on hydrologists to conform to the overland flow model (this pressure typically manifested itself in rejection of papers which rejected the overland flow model). Subsequently this led to a wave of work around the world between about 1960 and 1990 which confirmed that overland flow was hardly a factor in forest hydrology, that the water-table aquifers of forested slopes were fast and responsive, that hydraulic conductivities of the upper layers of forest soils were very large when compared with those of deep aquifers, that the "classic" models of groundwater behaviour needed modification, and that the properties of the catchment materials were "complex".

McDonnell (2003) revisited this model some 40 years after Hewlett and colleagues articulated it. He notes that numerical models of small catchments usually implicitly use a structure based on the VSA concept, but notes a "disconnect" between the modellers and field investigators which has slowed down attempts to link numerical modelling and VSA concepts. Although field observation supports the VSA model, there is little numerical development of the concepts.

Dahlke et al. (2012) provide an interesting and more modern examination of the concept using an instrumented agricultural hillslope in New York State. During events with dry antecedent conditions, infiltrating rainwater was found to percolate to deeper soil layers through a "fragipan" (i.e. restricted permeability) layer. During storm events with wet antecedent conditions and large rainfall amounts, shallow lateral flow of event and pre-event water above the fragipan occurred and was one magnitude greater than the deeper water flow contributions. Spatial observations indicated that groundwater from a distance of up to 56 m from the stream contributed runoff from the hillslope during storm events.

The Variable Source Area model is a useful conceptual aid and met a clear need at the time that it was introduced because it presented an alternative theoretical framework to that of Hortonian overland flow derived from agricultural studies. Like most such models it is an abstraction from a more complex reality. Although there has been some embellishment of details by work such as O'Loughlin (1981) or Aryal et al. (2002), it is disappointing that there has been no more numerically-based "universal" theory to replace it.

4.8 Use of Hydrographs to Examine Dynamic Processes

To the hydrologist, the interpretation of hydrographs is a never-ending source of both joy and frustration. The joy is because many of the features discussed above are apparent to some extent. The frustration comes when one attempts to show this for some form of analysis; what appears to be so clear and unequivocal in the data record suddenly becomes anything but. Difficulties usually relate to the issue of measuring the parameters of mathematical models, that the hydrographs are influenced by a multiplicity of factors, the presence of changes of gradients that are not compatible with theory, and the difficulty of defining an event that is somehow "separate" from the events preceding and following it. We have illustrated some hydrographs through this book and provided comments relating to their interpretation.

Conclusion

Forest hydrology dynamics bears an interesting relation with "theory". This helps explains the catchment outflow behaviour and may offer means to predict certain outcomes. At the same time the necessary conditions for a theory to work – parameters that can be measured consistently and reproducibly, clearly defined initial and boundary conditions, and laws governing the transmission of water under energy gradients are either absent or approximated. Hence theory may help explain observations but usually follows the observations rather than allowing prediction. At this stage, forest hydrology appears to be something of an empirical science with some theoretical underpinnings.

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Chapter 5
Field Measurement of Water Use of Forests

Abstract In the absence of well-developed theory of forest water use, most measurements of changing water use of forests have come from field measurements. The most effective measurement strategy has been "paired catchment projects" in which two or more similar catchments are gauged and the statistical relationship between measures of flow are assessed. The forest type on one is then changed and the impact on the hydrology relative to the retained "control" is computed. The Chapter examines the basis of paired catchment projects including how "calibration" is achieved and how long this takes. Examples of two paired catchment projects are given. Other methods of gaining information such as single catchment projects and plot studies are also considered. All methods have their advantages and disadvantages.

5.1 Why Study This?

Traditionally, forested catchments have been viewed as the standard for delivering high quality water. As we have moved away from entirely "natural" forests, land-managers and society have been keen to define the changes we are making in water outflow. This has become more pressing as the world's water resources are increasingly allocated. Sometimes there is resentment that forests are transpiring water which might otherwise be sold to cities or irrigators; this in turn can lead to demands for information on the water use of new forest developments. The methods described below are used around the world to accurately characterise the water use of forests.

Quantifying hydrologic variables allows fast elimination of often outlandish claims concerning the relative water use of plantations and other land uses. By pricing the water and applying appropriate interest rates the value of any change can be costed and compared with other inputs. Although new remote-sensing measurement techniques are on the horizon, there seems to be little alternative to traditional field measurement at this time if we wish to quantify the relation between forests and streamflow and make comparative studies between forests and other plant communities.

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5.2 Paired Catchment Experiments

5.2.1 What Is a Paired Catchment Project?

The basic idea is to have two or more catchments located close together, measure how similar the outflow is, and then change the land-use on one and observe the differences in streamflow which result. The catchments should be "similar" (a vague but useful concept) in size, shape, aspect, geology, and topography. One of these ("Catchment A") is designated as a "control" catchment and will remain unchanged (or as unchanged as one can manage) for the life of the project. The other ("Catchment B") is designated to be "treated" after a period of calibration. Flow measurement structures (usually weirs) are built, rainfall and streamflow are measured, and the development of the catchment calibration is monitored. When a satisfactory "calibration" is obtained, the experimental treatment (usually some form of logging and/or reforestation) is implemented. By using flows from the control catchment as input into the "calibration model" the "natural flow" in the treated catchment is estimated. By differencing this and the observed flow, the change in flows due to the treatment are estimated. By comparison of the post-treatment change with the errors in the pre-treatment "calibration", statistical limits on the magnitude of the change encountered can be computed. Thus the impact of a given land use in both relative and absolute terms can be estimated.

Although rarely articulated, there is a substantial personal and organisational cost associated with this form of experimentation. They are usually located a long-way from head-office, often in remote and difficult environments, and usually require substantial overheads (particularly roading) just to allow access to sites alone. The life of the project may well transcend the working life of individuals working on it and sometimes the organisations that install the project. Despite or because of these issues, many workers greatly enjoy the experience of paired catchment experimentation.

This is probably the one experimental technique that has passed out of forestry into the wider world. The technique is about the simplest "true" experimental technique one can get and incorporates the experimental concepts of a control and a measure of error. The concept of replication and "blinding" (in which the analyst has no knowledge of the treatments) is less applicable.

Although water yield is usually the key variable, the method may be extended to any other water–related variable such as nutrient or sediment load and various measures of water quality. The method has gone in and out of fashion around the world, but has been one of the most successful method of producing hydrologic information. Hewlett and Pienaar (1973) and Hewlett et al. (1969) give interesting and still relevant discussions of the pros and cons of the methodology. Whether a point is a pro or con often depends on the contexts and the needs of the organisations and individuals. These include:

1. The method is necessarily long-term because the length includes the calibration period plus the length of the treatment, with the sequence of forest growth being measured "in series" (i.e. in real time). Other methods such as plots may allow sampling of different age classes such that the information about different ages is gained "in parallel". In either case, the error of measurement is important. Plots may allow a better estimation of error; equally the error induced between plot sites may be enough to obscure the differences between successive age classes being sampled. Commitment to a paired catchment project is commitment to a project that might extend from 5 years to a century or more.
2. There is an immediate gain of information on the hydrology from the flow of data collected from the first day of measurement. This is immensely valuable and often leads to substantial and useful modifications of the research questions being asked. For young hydrologists, this is a valuable educational experience in itself. Processing of data and dealing with "missing data" gives a realistic appreciation of errors inherent in hydrology.
3. The method allows collaboration between short-term and long-term data collection. Short-term studies provide supplementary information on the processes involved. Long-term work allows this to be put into perspective. Paired catchment projects provide ideal venues for combining the two types of work, to the mutual benefit of one-another.
4. The method demands ownership of the catchment areas, and a substantial investment in instrumentation (weirs, rainfall measuring equipment, on-site buildings, etc.). To install and maintain this requires good forest roads, access to a skilled work force, and a continued site commitment. However, after installation the projects are (relatively) inexpensive to maintain, and this can often be coordinated with other routine forest work. This has proven to be advantageous in Australia where funding for the capital investment is sometimes easier to get than funding for routine maintenance. Thus the method works well for stable forest owners with the land and resources (including scientists and equipment) to bring such projects to fruition.
5. The sequence of long-term data produced is a real asset in the changing fortunes of time, both to the hydrologists working on the project and the organisation. The information often serves to "dampen" wide or outlandish claims sometimes made. The data has often become the feedstock of the work of theoretical hydrologists and modellers who, to the dismay of the data collectors, often ignore the caveats on data accuracy. The author's experience in courtrooms is that results based on paired catchment experiments are more readily accepted than those based on modelling or plot work, and that the projects result are difficult to "attack" by opposing lawyers.

A number of scientific questions arise:

1. There is no real replication in an experimental sense. Hence it is hard to ascribe the error in the sense of "if we had given this treatment to two identical catchments, how might the results obtained have varied?" Although, in principle, the experiment could be repeated on another catchment, the variability

between catchments tends to reduce the elements of "replication". More usually, the logistics and cost of the treatment preclude even this type of partial replication.

2. How long should the period of calibration be? A reasonable period would appear to be 3–5 years if daily or monthly data are used. See below for a discussion on this.
3. How general are the results, and how can the results be generalised to a wider environment? Thus, is an experiment carried out in a high rainfall area in Victoria applicable to a lower rainfall hill environment in South Australia? This has been, is, and will remain as a contentious question. In Chap. 7 we demonstrate that combining results from four paired catchment projects gives very strong information across the range of planted environments of radiata pine.

Piece by piece, such questions have been and are being answered. Technical advances in paired catchment work include the technology of data logging, improved calibration modelling, and use of remote-sensing and LIDAR for improved measurement. A new generation of remote-sensing measurement of hydrologic variables is about to ensue. Paired catchment projects are often used to assess the utility of such new measurement techniques.

5.2.2 An Example of a Paired Catchment Project: Croppers Creek

The project had its origins in the development of radiata pine plantations in the 1960s in Australia. These involved clearing of native forest and planting of the cleared sites with pines. At the time there was disquiet from downstream landholders about "excess flows" causing flooding and erosion on downstream properties. The managing agency (the then "Forests Commission-Victoria") concluded that there was little data about forest hydrology. After some unsuccessful forays in "joint projects" with other agencies, they decided to initiate a paired catchment project using pine conversion of native eucalypt forest on steep catchments to develop their hydrology knowledge.

After a long search, three small catchments were selected 22 km south-west of Myrtleford (Victoria). These were Clem Creek (46 ha), Ella Ck (113 ha), and Betsy Creek (44 ha). The catchments were steep, well-defined, and near existing plantations. Figure 5.1 gives a view of the catchments, and Fig. 5.2 gives a view looking down the "just-treated" Clem Creek catchment. The project involved road construction to allow access, weir construction, clearing for rain-gauge sites, and a network of instrumentation for various studies including nutrient input and output, studies on hydraulic properties of channels, limnology sampling, tree water potential, sap-flow studies and slope groundwater studies.

Figure 5.3 shows a project timeline. Installation of the project took 2 years. The first data were measured in May, 1975. In 1979 it was decided that Ella Creek was to be the "control" and that Clem Creek catchment was to be "treated". This

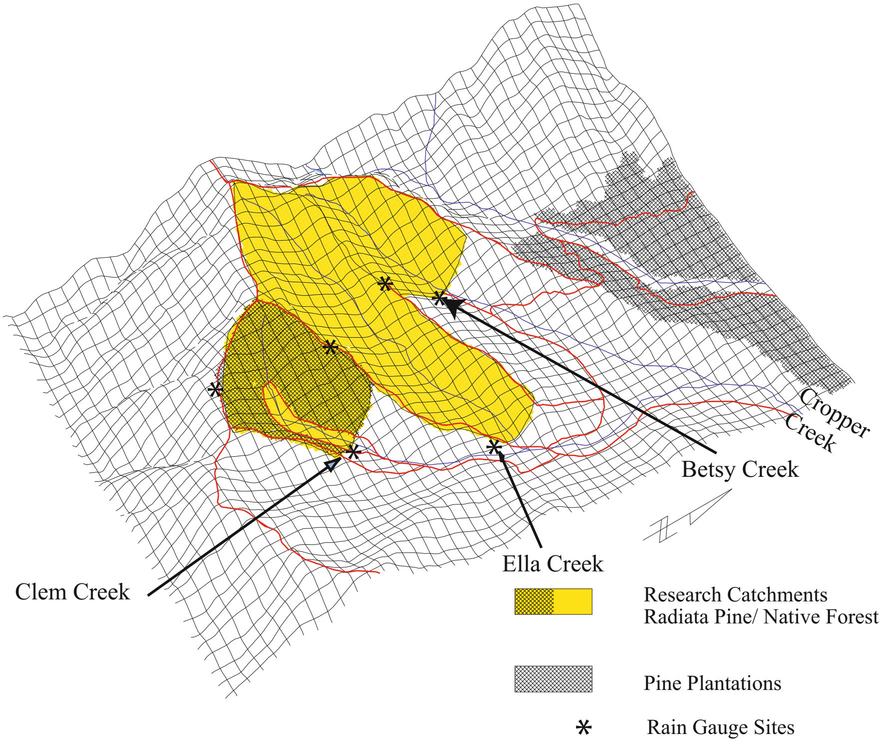

Fig. 5.1 Oblique view of Croppers Creek research catchments

decision was partly due to the lower cost of conversion of the smaller catchment, and partly that Clem Creek was never known to "dry up". Thus it was felt that if the catchment did "dry up" under the influence of the pines then there would be a direct comparison of the water use of the native eucalypts and pines (in fact, the stream has always flowed). A study of the data suggested there was a good calibration available. In December 1979 the catchment slopes were cleared using heavy crawler tractors and in June 1980 the catchment was planted with radiata pine. Data collection ceased in 1987 when the then managing agency decided that all that was necessary was known about the hydrology. A bald account such as this makes the process seem logical and inexorable. However, for those involved there were many complexities of project installation, administration, considerable learning (some hard), discussions on the worth and advisability of such ventures, and issues of equipment reliability.

In the mid-1990s water issues become important because of recurrent drought and the plantation industry argued for a recommencement of measurement. This commenced in 1997, and continues to the present. In 2006 planning for the harvesting of the first pine crop in 2008 commenced. However nature got in first and the area was burnt in a major wild-fire in late 2006. This caused destruction of

Fig. 5.2 View looking down Clem Creek catchment in January, 1980. The native eucalypt vegetation has been pushed over preparatory to burning and planting with radiata pine. A 30 m (either side of the stream) riparian strip has been retained. The weir is about 50 m upstream from the cleared forest edge. This treatment increased annual streamflows by about 200 mm

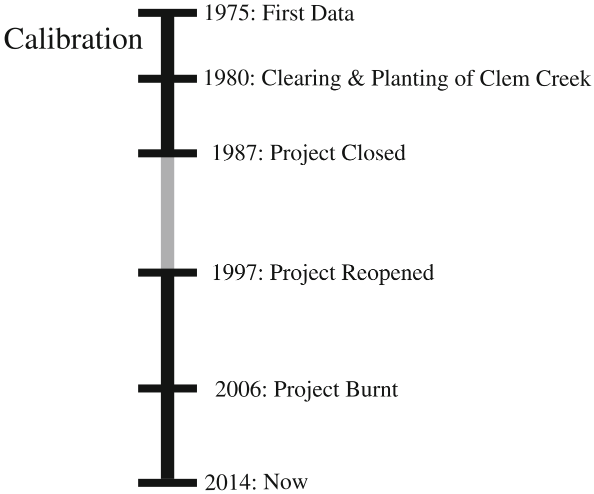

Fig. 5.3 Croppers Creek hydrology project time-line

the measurement network. In the next year this was rebuilt, and measurement resumed. The burnt plantation was salvage-logged and replanted. Measurement is now continuing through the second rotation; and analysis in 2011 (Bren 2011) showed that the first few years of the second planting more or less repeated the findings of the first few years of the first plantings.

The project was an early venture into paired catchment experiments in Australia, and has produced a continuing flow of information including water use and nutrient balance of plantation and native eucalypt forest. Data has been used internationally in comparisons, and has contributed to studies on theoretical aspects of paired catchment research. Interestingly, the project has survived despite large changes in forestry administration over the years. The privatisation of plantation forestry has led to the separation of ownership and management of the "treated" and "control" catchment – something that could not have been envisaged at the time of project planning. Similarly, because of reorganisation of forestry agencies the project and the data have had about five different owners.

Results from the project are given in many papers cited through this text. Briefly the results showed that there were real hydrologic effects of the conversion. Clearing led to a substantial increase in "runoff" (see Chap. 7) and had some short-term impacts on water quality. The water yield of the plantation always exceeded that of the native forest it replaced, but as the plantation aged, the difference diminished.

Reviewing the contribution of the project to forest hydrology development, one is struck by the usefulness of the venture in providing both data and enjoyable or memorable (sometimes both at the same time!) "on-the-job" training. At the time of installation, there was no view as to how long the project might last since it was known there would always be substantial uncertainly; in this respect the project surviving for approaching four decades has exceeded expectations. Although this is a respectable age, there are many far-older paired catchment projects continuing around the world.

5.2.3 Traditional Approach to Paired Catchment Calibration and Analysis

Table 5.1 shows data from the "control" catchment (Ella Creek) and the "treated" catchment (Clem Creek) for 12 years. We have used annual data because each year can reasonably be viewed as independent of the previous year. Two methods of analysis of this data are shown – the "double-mass" graphical method, and the calibration model method.

Double Mass Plot Method This is one of the oldest (and still most effective) methods of analysing paired catchment data. A good theoretical account of the method is found in Chang and Lee (1974). Its effectiveness is in its ability to subordinate detail to an overview of treatment results. The disadvantage is that no estimate of probability is given. Table 5.1 shows show how a double-mass plot is derived. The data in Columns 3 and 4 of Table 5.1 is accumulated (aka integration) by forming a running total for both Clem and Ella Creek annual yields in columns

Table 5.1 Annual yields measured at the Croppers Creek project, and accumulation for a double-mass analysis. Table shading shows pre-treatment data, although 1979/1980 may contain a small treatment effect

Period	Annual rainfall, mm	Ella Creek yield, mm	Clem Creek yield, mm	Accumulated Ella Ck, mm	Accumulated Clem Ck, mm	Residual, mm
May 1975–Apr 1976	1,996	784	952	784	952	−13
May 1976–Apr 1977	1,058	40	79	824	1,031	−10
May 1977–Apr 1978	1,083	99	148	923	1,179	−10
May 1978–Apr 1979	1,529	348	485	1,271	1,664	33
May 1979–Apr 1980	1,552	486	621	1,757	2,285	7
May 1980–Apr 1981	1,476	330	797	2,087	3,082	367
May 1981–Apr 1982	2,101	919	1,337	3,006	4,419	213
May 1982–Apr 1983	800	3	79	3,009	4,498	34
May 1983–Apr 1984	1,628	446	894	3,455	5,392	327
May 1984–Apr 1985	1,177	350	608	3,805	6,000	154
May 1985–Apr 1986	1,310	213	460	4,018	6,460	167
May 1986–Apr 1987	1,869	679	963	4,697	7,423	121

5 and 6. The accumulated flow in the treated catchment is then plotted as a function of the accumulated flow in the control catchment (Fig. 5.4). The individual points can be dated and the point of treatment marked on the double-mass plot. Then, by extending the line of the pre-treatment points (AB), the line of accumulated totals if no treatment had been given is derived. The vertical distance between the line given by the treated catchment and the extended AB line is a measure of the accumulated

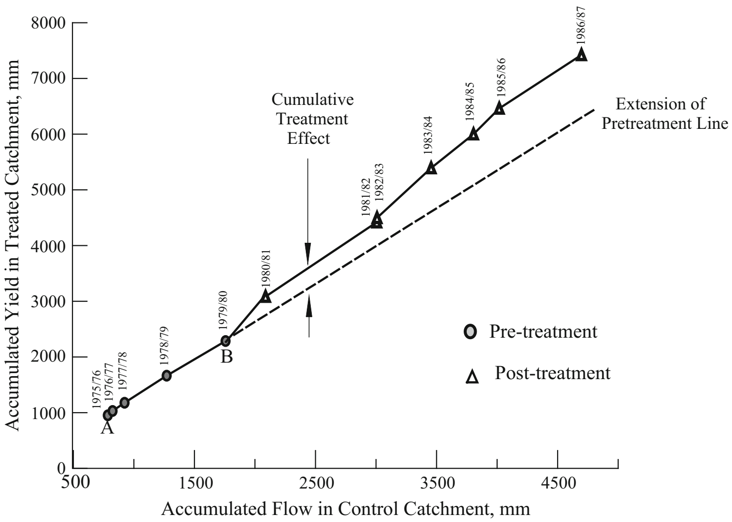

Fig. 5.4 Double mass plot generated from the data of Table 5.1

treatment effect. The 1979/1980 year has been included as pretreatment but may contain a small treatment effect.

Double mass plots are fast to generate on a spreadsheet and probably the best single tool for coming to grips with the results of an experiment. In the example above we have used annual data but it could equally as well have used daily or monthly or any other time division (the author's preferred choice is daily data). The method is particularly well suited to spreadsheet analysis. Subsequent analysis using more sophisticated regression analysis to form a calibration model usually only manages to set probability limits on the results inferred from double mass plots.

Calibration Model Method The calibration model is an estimate of the flow in the "treated catchment" as a function of flow in the "control catchment" using the pre-treatment data. Figure 5.5 shows the four pre-treatment points plotted (1979/1980 has been excluded because there is a treatment component) and a line fitted (by regression) through these. This line is the equation:

$$C = 1.177E + 41.86 \tag{5.1}$$

where C and E are the annual flows from Clem and Ella catchments (in mm) respectively. An alternative would be to draw a "best-fit" line; the difference in results is minimal. The vertical distance between each point and the line in the derived equation is a measure of the calibration model error. As before, the control catchment is viewed as the independent variable and is on the bottom axes. The vertical distance between each point and the line fitted in post-treatment data are a

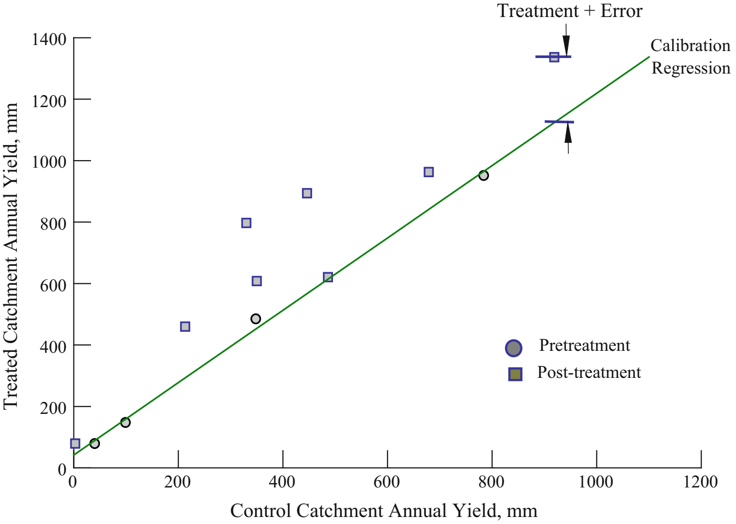

Fig. 5.5 Derivation and use of a calibration relationship to compute treatment effects

measure of “treatment + error”. The results have been gathered in the far-right hand column of Table 5.1 as “Residual” (treatment plus error). Box 5.1 lays out the calculations in some detail for one particular year. These show the impact of the clearing of native forest to plant with radiata pine.

This method is the core of paired catchment experiments. In real life a more complex model than that of the simple equation may be used (see Example in Sect. 5.2.4). This might incorporate additional variables such as annual rainfall. Complex methods may be used to characterise error, and transformations may be used to improve statistical behaviour of the data.

In some cases the pre-treatment “errors” can allow estimates of the probability of obtaining the treatment effect errors by chance. Usually this assumes that the pro-treatment residuals are normally distributed and have no serial correlation. It is rare for such conditions to be met and this is a current area of research. We have commented on this more fully in the next section below.

Covariance Analysis Method If there is a “traditional approach” to paired catchment experimentation, it probably goes back to Wilm (1944, 1949) at Coweeta (North Carolina). This uses a covariate approach in which the response of both the control and the treated catchment is assumed to be functionally dependent on the covariate of rainfall. Covariance analysis was, for many years the favoured analytical method for paired catchment projects but is less-commonly used now. The limitations of this approach are:

1. The use of annual data, which means that partial-year data (e.g. 1979/1980) is not useable.

2. The assumption that the pre-and post-treatment regression lines of streamflow on rainfall have the same slope (or that the effect of pine formation is a constant difference between the pre and post-treatment catchments). This is an inherent assumption in covariate analysis.
3. The possibility that assumptions about normality of error and independence of events are not true.

For these reasons it would usually only be used as one of a battery of statistical analytical approaches.

Box 5.1: How the Calibration Computations Are Done

Consider 1980/1981. This is the first full year after treatment. Regression using the first 4 years of the pretreatment data (Eq. 5.1) suggests that the calibration relation is

$$C = 1.177E + 41.86$$

where C and E are the annual flows from Clem and Ella catchments respectively. In 1980/1981, the annual yield from Ella Creek was 330 mm. Then, if there had been no treatment, the annual yield from Clem catchment would have been (1.177*330 + 41.86)mm = 430 mm. But observed water yield from Clem catchment was 797 mm. Hence (treatment + error) = 797–430 = 367 mm.

5.2.4 A Modern Example of Paired Catchment Statistical Treatment

The Coranderrk paired catchment project was the first one in Australia, with data collection commencing in 1956. However, for this phase of the work data collection commenced in 1966 when a new weir was constructed on the control catchment, Slip Creek. The “treated” catchment, Picaninny, had its old growth mountain ash forest logged in 1971 (Fig. 5.6). The project was and is following changes in water use. This work was published in Bren et al. (2010) and has been updated to 2011.

Figure 5.7 shows the project results as a sequence of “daily residuals” using a logarithmic transform; the latter introduces some better statistical behaviour in the model (see Watson et al. (2001) for an excellent discussion of this). The model ultimately adopted was:

Fig. 5.6 View of the Picaninny Creek catchment at Coranderrk paired catchment project in 2011. This was clear-felled in 1971. The finer texture of regrowth crowns is evident compared to the coarser, older-growth crowns on the spur

$$Log(\hat{p}_t) = a_1 + a_2{}^*r_t + a_3{}^*Log(s_t) + a_4{}^*Log(s_{t-1}) + a_5{}^*Sin\left(\frac{2\pi d}{365}\right) + a_6{}^*Cos\left(\frac{2\pi d}{365}\right) \tag{5.2}$$

where

p_t = Daily flow from Picaninny Creek, mm.

$\hat{p}_t$ = Estimate of daily flow from Picaninny Creek, mm.

r_t = Daily rainfall in the lower gauge, mm.
s_t = Daily flow from Slip Creek, mm.
a_1 to a_6 = regression coefficients.
d = Day number in water year.

The use of logarithms reduces errors associated with heteroscedasticity (see Watson et al. 2001). Two residual sequences were computed. These were:

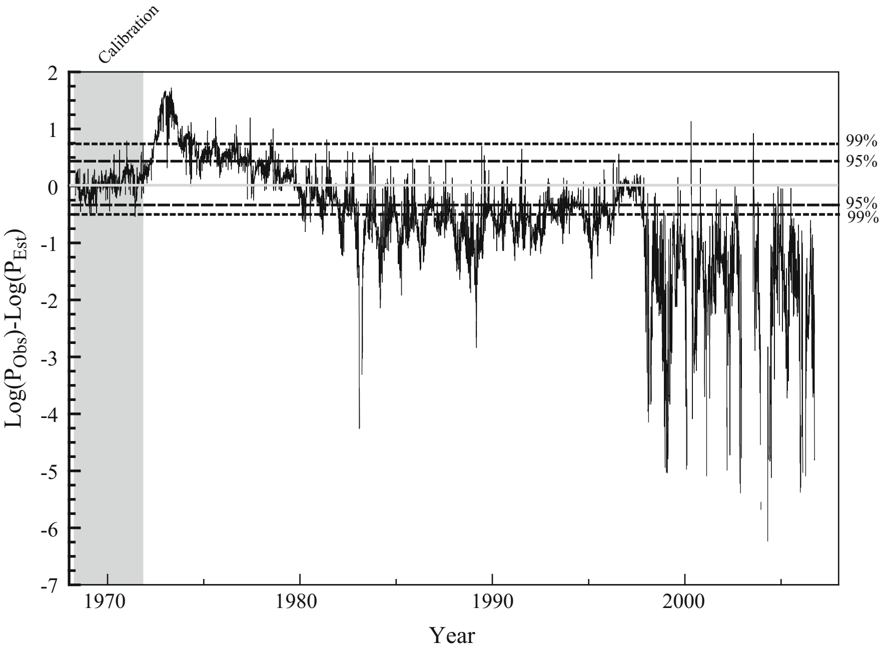

Fig. 5.7 Treatment plus error results of the Coranderrk paired catchment project, expressed in logarithmic units. The long tails to the right represent the effect of a major drought

$$\text{Logarithmic difference}: Log(p_t) - Log(\widehat{p}_t) = Log\left(\frac{p_t}{\widehat{p}_t}\right) \tag{5.3}$$

$$\text{Real Residual}: R_t = p_t - \widehat{p}_t \tag{5.4}$$

The residual can be viewed as comprised of a measure of error and of the treatment

$$R_t = \varepsilon_t + T_t \tag{5.5}$$

where ε denotes the error and T denotes the treatment effect. During the calibration period, T is zero by definition, and hence we can gain some measure of the error alone. The error residual sequence usually does not have a normal distribution and may show autocorrelation, rendering statistical testing of hypothesis difficult. The importance of this appears to depend to some extent on the observer. Thus Hewlett et al. (1969) observed that many hydrologists are unconcerned about the statistics compared to the magnitude of the change, and that comment still seems valid. Others feel that this is an abrogation of the "scientific method".

Figure 5.7 shows the logarithmic difference in residuals on a daily basis from the logging and regeneration of mountain ash (*Eucalyptus regnans*). The logarithmic difference suppresses the increases in flow for some years after logging but highlights the low flow periods during the “millennium drought” during this period of measurement. The results show:

1. A measure of experimental error during the calibration period. Error limits of the calibration data are also shown. Values outside these can be viewed as statistically significant.
2. A treatment effect for about 6 years after the logging in which streamflow increased, and
3. A longer period of decreased flows. The long “tails” marked during the drought reflect very low flows in the logged catchment during the drought; the use of logarithmic transformations suppresses the high flows after logging and accentuates the low flows.
4. An occasional return to “no treatment effect” during wet periods. At this time the catchment flow is more influenced by the properties of the catchment material than the influence of the overlying vegetation.

Figure 5.8 shows the real residuals with the results integrated over periods of 1 year, and expressed in normal units; for added clarity calibration data are not shown. Arguably there is less information in this but the information is more useable for most readers. The results are discussed in some detail in Chap. 6.

It should be noted in the example that the calibration period lasted for 3.5 years, but the post-treatment phase is, at the time of writing over 43 years in length. The validity of a calibration model over such long time periods is unknown. An inherent assumption in this work is that the “control” is “stationary” in the sense that the relationship between rainfall and streamflow remains unchanged. There is no

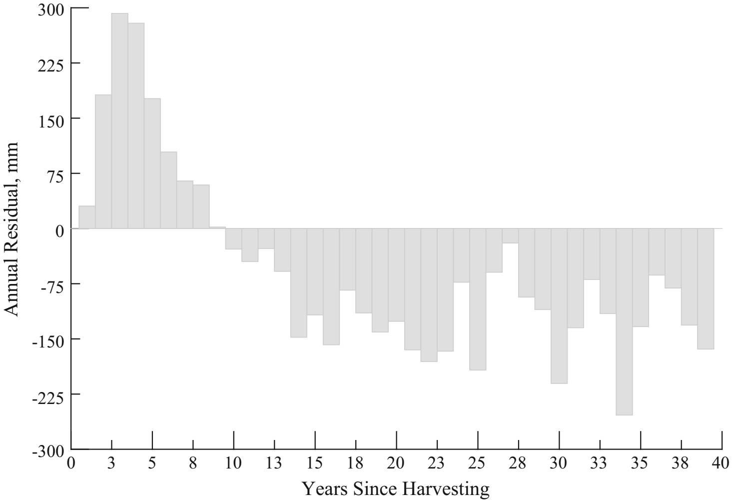

Fig. 5.8 The results of Fig. 5.7 expressed in real units and integrated over a water year (May to April). The “residual” is effectively the annual change in flow by replacing an old-growth mountain ash forest with regrowth mountain ash

evidence of any gross violation of this assumption. However an examination would require reference to some truly stationary catchment. It may be possible to conceive of such a reference (real or synthetic), but we have no knowledge of one. Hence the land use effects of paired catchment results are referenced to a land use we view as “reasonably constant”. As some paired catchments projects are approaching a century of data measurement, this point is becoming of more concern. In general paired catchment projects were usually installed with the expectation of giving a decade or so of data; however pressures for information from such studies have meant that they have often lasted much longer so that assumptions on the stationarity of the “controls” can become questionable.

Bren and Lane (2014) examined the properties of residuals generated using both Coranderrk and Croppers Creek data and found that the method of Watson et al. (2001) overcame autocorrelation issues but that the calibration residuals usually had a non-normal distribution; this is discussed below. A range of non-parametric techniques is available for hypothesis testing but these are often viewed as less satisfactory than distribution-based techniques.

5.2.5 *What Time Units to Use?*

“Natural cycle” subdivisions of hydrologic data are days (rotation of the earth on its axis) and years (rotation of the earth around the sun). In Australian studies daily, monthly, quarterly, and annual data has been used. The selection of units is a matter of user preference, but if shorter time units are used, more information is potentially gleaned from the data at the expense of some complexity of computation and redundancy in information. Shorter time units also give the potential of shortening the calibration period of the project, allow better monitoring of the development of calibration, and involve less “truncation error” when an activity means that only part of a period is available. Bren and Lane (2014) found that workers in Australia had used units from daily flow to annual flow in their analysis of paired catchment projects.

Bren and Lane (2014) looked at the methodology of paired catchments and found that, not unexpectedly, you achieved the same answer in your chosen units using shorter-time units. Thus, for the same data set, using a daily regression and integrating the residuals to give yearly data gave the same answer as working in years directly. However this tended to be rendered less clear because of the variation in the number of days in different time periods. Thus, most years have 365 days but occasionally a leap year has 366 days. Similarly day number of months and seasons vary. Their recommendation was that, irrespective of the time unit chosen, the unit of flow should be mean volume per day or mean depth of flow per day to overcome the varying number of days of time units based on months, seasons, or years.

5.2.6 How Long Does Calibration Need to Be?

Other than the work of Wilm (1944, 1949) and follow-up work by Kovner and Evans (1954), this has received surprisingly little attention. Their work used a covariate model and examined how many years of calibration data were necessary to keep the error bounds within limits. There appears to be a consensus in hydrologic literature that "the longer the better" but we can find little quantitative consideration of this point. It is noted that South African worker Wicht (1967) intended to use a 32 year calibration period for one of his projects (Kruger and Bennett 2013). This would be viewed as impossibly long in the modern age since it would transcend the working life of most researchers.

Bren and Lane used (2014) used a 13 year sequence of daily data collected between 1958 and 1971 for the Coranderrk project and the 5 year calibration sequence for the Croppers Creek project to examine the rate of information gain in a paired catchment project. In each case the pre-treatment data were broken into a longer "calibration period" and a shorter "verification period" was defined. The aim was to reproduce this verification set by using data from 1 to n days of each calibration data set, where n was the calibration length. The criteria of fit was the Nash-Sutcliffe coefficient of efficiency (NS). This had its origins in the work of Nash and Sutcliffe (1970). A good description of this is given in Krause et al. (2005). The coefficient is commonly used in hydrology for evaluation of hydrologic models. It is calculated as:

$$NS = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - \bar{O}\right)^2} \tag{5.6}$$

in which O_i is the i-th observation and P_i is the corresponding prediction of that observation. The range of the coefficient lies between 1 (perfect agreement) and minus infinity. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model.

Figure 5.9 shows the results obtained as a function of n using a simple regression model. The results show a surprisingly rapid gain in information, particularly with the simple regression model. Thus as little as 60 days of calibration would give a reasonable calibration regression using daily data. With appropriate consideration of units, this could be converted to an annual relationship. Similarly, when the Watson model (see Eq. 5.2) was used, 200 days of calibration gave a reasonable relationship. Similar results were found at Croppers Creek. Figure 5.10 shows the corresponding residual plot of Fig. 5.6 derived with a calibration length of 60 days 100 days, 200 days and 1,100 days calibration; the plot of Fig. 5.6 corresponds to the 1,100 day plot. It can be seen that there is not much visually to distinguish the 200-day from the 1,100-day calibration residual plot.

The study concluded that using daily data, there was a rapid build-up of information. This was the same with monthly, quarterly, and annual data, but the

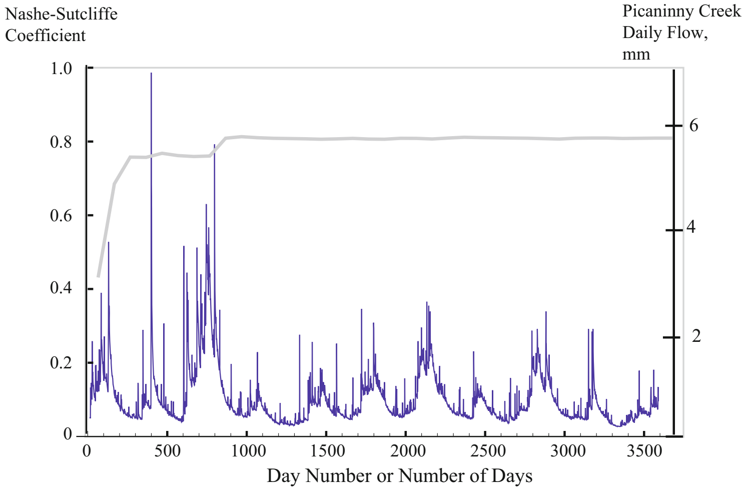

Fig. 5.9 Calibration results as a function of number of days of data using data from the pre-treatment Coranderrk project. For reference, flow in Picaninny Creek, which was used in the data analysis is also shown. Results from Bren and Lane (2014)

degrees of freedom were less. The authors concluded that the similar relationships were delivered after 1–2 years of calibration, that 3 years of calibration gave almost all the information, and that there was little to gain in extending the calibration after 5 years (unless the 5 year period had an unusual characteristic such as being in the midst of a long drought). The results were surprisingly unaffected by whether the calibration period was viewed as "dry" or "wet". The results also showed how strong the predictive ability of the calibration model applied using the control catchment as data. Again this appeared to be irrespective of the climatic nature of the period.

The results also showed that the use of autoregressive models as espoused by Watson et al. (2001) to reduce autocorrelation was very effective, but that residual sequences usually did not meet assumptions of normality irrespective of whether a logarithmic transformation was used. This conclusion appeared to be valid whether daily, monthly, quarterly, or annual data were used. One strong advantage of the use of shorter-term data were that the degrees of freedom were adequate to allow examination of such hypotheses,

5.2.7 Where Do Paired Catchments Sit in the World of Experiments?

"An experiment is an orderly procedure carried out with the goal of verifying, refuting, or establishing the validity of a hypothesis" ("Wikipedia" 2013). In

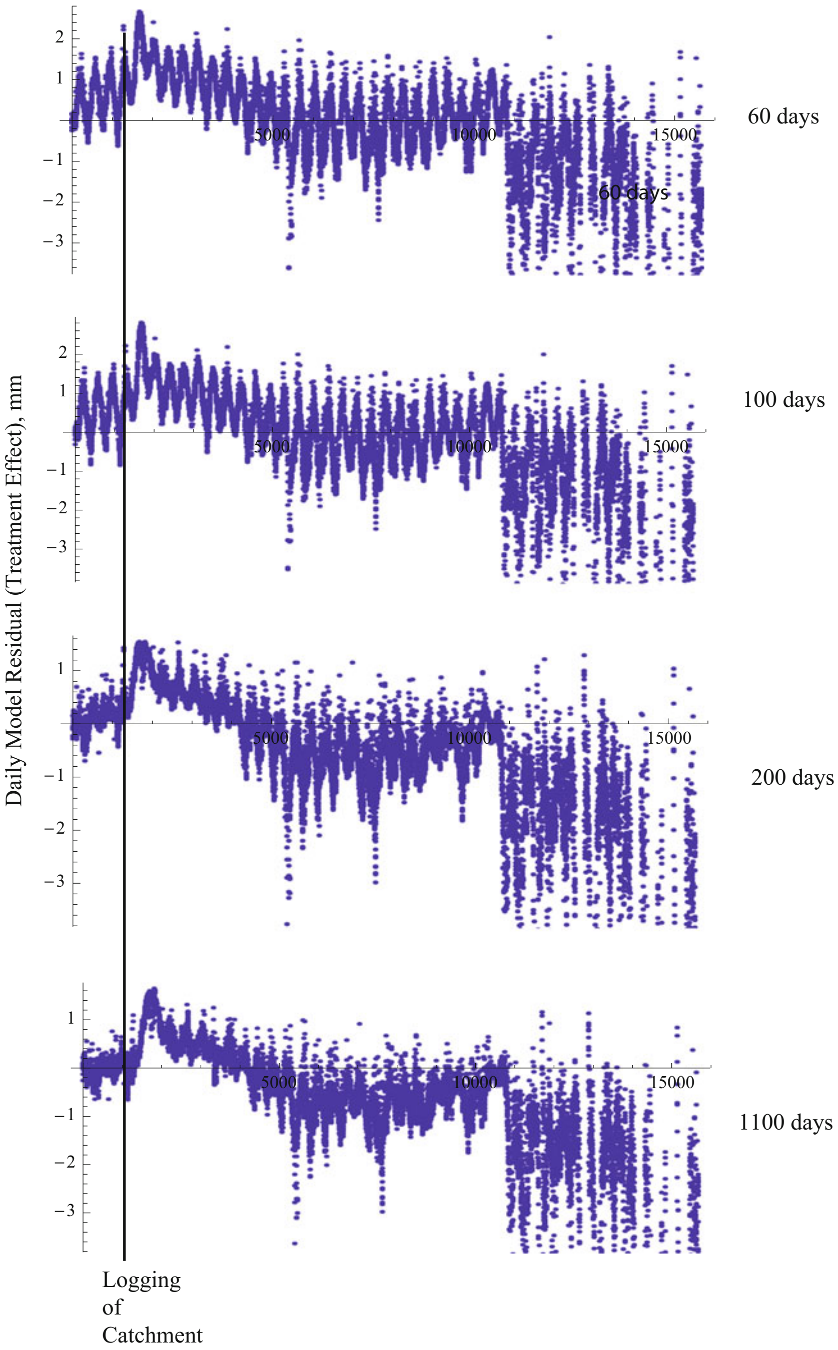

Fig. 5.10 Calibration plot of Fig. 5.7 derived with different calibration lengths

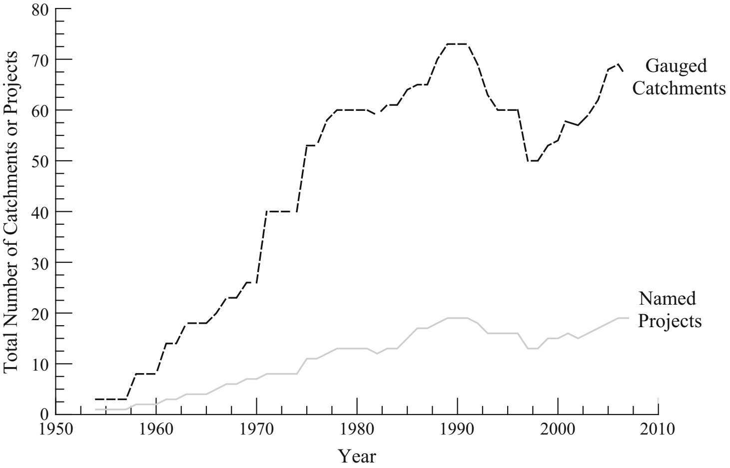

Fig. 5.11 Australian paired catchment projects and gauged catchments over time (From Bren and McGuire 2011)

physical sciences experiments are a primary component of the scientific method. Ideally, replication may be an inherent component in the hope of producing identical results in each replication, thereby strengthening faith in the result. Non-identical results give some indications of the errors inherent in administering and measuring the treatment. An experiment should control possible confounding factors – factors that mar the accuracy or repeatability of the experiment or confuse the ability to interpret results. This is mainly done by use of a scientific control and/or random assignment of treatments.

Paired catchments appear to sit reasonably comfortably within this taxonomy of experiments. Randomisation of the control and treatment is rarely attempted because of operational constraints. Replication in space is usually not possible because of site variability but may sometimes be adopted. Replication in time can sometimes be attempted (e.g. Croppers Creek observation passing through two rotations of radiata pine). Probably the one common weakness is the involvement of the experimenter with data analysis; the concept of "blind" analysis in which the analyst is not involved with the field implementation and may not even know which catchment is which in the analysis has yet to be explored.

5.2.8 Paired Catchment Projects in Australia

The technique has been first used in Australia from the mid 1950s, and has waxed and waned in popularity through that time. Figure 5.11 (from Bren and McGuire 2011) shows the number of named projects and gauged catchments as a function of

Table 5.2 Breakdown of paired catchment projects by states, and classification of research objectives

State	No of projects	Classification[a]		
		Native forest	Plantation	Deforestation
Victoria	9	6	3	
NSW	12	8	4	
ACT	1	1	[a]	
South Australia	0			
Western Australia	11	5		6
Tasmania	1	1		
Queensland	3	2	1	
Total	37	23	8	6

Native forest logging, thinning, and regrowth water use
Plantation water use
Vegetation clearing, salinity and mining rehabilitation
[a]Classifications

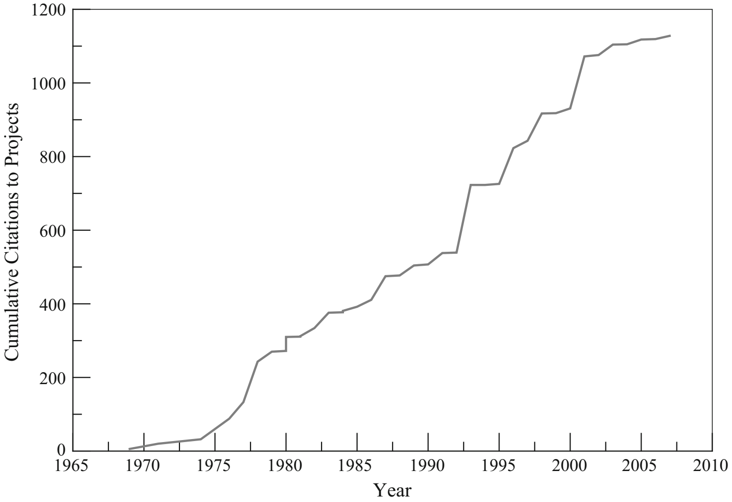

Fig. 5.12 Cumulative citations from Australian paired catchment projects as a function of time (From Bren and McGuire 2012)

time. Figure 5.12 shows the cumulative citations from Australian paired catchment projects – there is about a 20 year time lag between the initiation of projects and the "embedding" of the knowledge in the scientific literature. Bren and McGuire (2011) give a list of the paired catchment projects; a summary of this is given in Table 5.2.

5.3 Single Catchment Studies of Water Use

"Single catchment" studies are usually viewed as the "poor cousins" of paired-catchment research. The concept of a "control" was a fundamental development of experimental techniques and is a "must" in sophisticated methodology. Since having a control more or less doubles the resources needed, they can be costly to implement and maintain. Sometimes there is no second catchment that can reasonably act as a control. It has occasionally been argued that the role of a control catchment could or should be filled by a "calibrated computer model". Additionally it can be argued that a "single catchment approach" can be used to determine complex cumulative effects on larger catchments for which the paired catchment approach is not applicable.

Nik et al. (1983) tested the hypothesis that climatic data could be used to develop a watershed model to replace the control catchment. Measured independent variables were precipitation, daily maximum and minimum temperature and concurrent relative humidity. They found that when 10, 15, and 20 years of data were used to develop the regression equations, error of prediction was within 17 %, 12 % and 10 % respectively of the measured means. Perusal of their work suggested that collection of data to replace the control catchment involved much meteorological data handling, which negates the advantage of not having a control. They concluded that climatological calibration appears to be a viable approach under special circumstances such as when only one watershed is available for study. They noted that the paired watershed approach is expected to remain the preferred method for determining the effects of forest management on the water resource because of simplicity and accuracy. This echoed an earlier experience of Reigner (1964).

More modern hydrologic modelling does appear to have the capacity to provide effectively a "synthetic control" using models. However in the work of Bren and Lane (2014) we were surprised at the high level of prediction gained by control catchments with a short period of calibration. The Nash-Sutcliffe coefficients of efficiency gained were commensurate with excellent modelling. Thus there would seem to be little gain in avoiding controls except in the special circumstances mentioned above.

5.4 Plot Measurements of Water Balance

Plot measurements can measure virtually all hydrologic flows with the exception of streamflow; the absence of this measurement is a big drawback in hydrology work. The accuracy of the measurements varies, some quantities are exceedingly difficult (or expensive) to measure, and the questions of estimating streamflow from the water balance data are always problematic.

In their fullest forms, plots may produce a huge flow of data which can illustrate the physiology or the physics of various processes. A common use of plots is to supplement the program of measurements on paired catchment projects, since this includes measurements of streamflow as well. Plots are particularly useful when streamflow does not arise – a fine example being the work of Benyon et al. (2006) quantifying plantation water use on the limestone plains of South Australia. In this case there is no streamflow and the question was whether the plantation water use was increased by the proximity of groundwater.

We have chosen to illustrate the use of plots in hydrology research with a case study, illustrating their utility. Studies such as this provide insight into the environment but have their own share of problems and issues.

5.4.1 Case Study: Rachel Nolan and Impact of Fires

Fire has become a major factor in the management of Victoria's forests. However the impact of forest fire on measures of forest water use are largely unknown The aim of this work was to examine the impact of forest fire on the water balance of burnt, mixed species forest. This type of forest, when burnt, recovers by formation of buds which, in turn, leads to epicormic leaves. These cover the stem and branches (see Fig. 8.10).

Rachel Nolan undertook this work as her doctorate; this was subsequently published (Nolan et al. 2013, 2014). Monitoring was undertaken at burnt and unburnt sites in Melbourne's water catchments for 1–3 years after the major "Black Saturday" 2009 fires. Plots were typically circular, about 20 m in diameter, and were located in a range of ecosystems including dry mixed species forest and wet rainforest. Measurements included sapwood area, leaf area index, soil moisture content, temperature, photosynthetically active solar radiation, rainfall, forest floor evaporation, and sapwood flux using heat probes in 2–4 trees per plot (2–8 sensors per tree). Such a series of measurements rapidly builds up a formidable data base.

The results showed that topography, through its effects on forest structure, aspect exposure, and fire severity was a strong determinant of evapotranspiration. Thus, Et was 41 % lower in forests burnt at high severity compared to unburnt forest. However Et from forest burnt at moderate severity was 9 % higher over 2–3 years post fire. Plots located in high severity burn areas had substantially lower Et rates than either moderate or unburnt plots. Nolan et al. (2014) also showed many physiological differences in the transpiration behaviour of epicormic leaves compared to the unburnt leaves. These tended to promote higher rates of transpiration per unit leaf area. These changes tended to promote the rapid return of tree transpiration to pre-fire levels. Table 5.3 is reproduced from Nolan et al. (2014) and shows the difference between burnt and unburnt messmate (*Eucalyptus obliqua*).

Studies such as this show how that whilst plot level work cannot provide streamflow measurement, it can provide valuable insight into the processes at work.

Table 5.3 Differences in messmate water use per unit leaf and sapwood area for burnt and unburnt trees (From Nolan et al. (2014)

Parameter	Unburnt trees	Burnt trees
Water use per unit sapwood area, L m^{-2} day^{-1}	3,118	1,939
Water use per unit leaf area, L m^{-2} day^{-1}	0.46	1.33
Sapwood area, m^2	0.0249	0.0296
Leaf area, m^2	182	69

5.4.2 Advantages and Disadvantages of Plot Hydrology Work

The transience of plots is their greatest strength and greatest weakness. Unlike paired catchment experiments, plots tend, by their nature, to be temporary and transient, and do not always lend themselves to permanent infrastructure or incorporation into organisational routines. Issues of land ownership are always present. A particular problem is always safe-guarding plots from the regular assault of land management including burning, clearing, weed control, logging, roading or a myriad of other disturbances. Clear marking of plots helps distinguish them but attracts curious (and unwanted) visitors and may lead to the plots being treated differently from the surrounding forest.

By their nature, plots always have many "sampling issues", including plot and sampling element size, and the number of plots. Plot "campaigns" involve many logistic issues including the installation of equipment and provision of power to automated equipment. Hydrology researchers have found from long experience that working in a forest is a damp, corrosive, biologically-rich environment. Thus, adequate moisture control in instruments, prevention of corrosion on terminals and equipment, and exclusion of larger and smaller biota becomes an on-going issue. The larger biota chews cables or breaks things by walking through the equipment. Smaller biota makes a comfortable home in whatever openings they can find in equipment. Provision of electrical power is always an ongoing difficulty, with the usual choice being heavy rechargeable batteries or solar panels (fragile, easily shaded, sometimes stolen). Often work must be done in the rain, with issues of electrical leakage or potential shock to be overcome. More permanent installations usually develop some sort of equilibrium with these factors.

Notwithstanding all of these issues, plots are a most effective way of gaining data. They particularly lend themselves to creativity in formulation of hypothesis and the design of equipment. Plots often tend to be "personal" in the sense that their life is associated with one person in the organisation; when that person moves on the plots are no longer maintained.

5.4.3 Where Do Plots Sit in the World of Experiments?

Plots allow a closer approach to replication and randomisation, and hence give direct estimates of error in measurement. Their flexibility allows them to be installed to monitor and measure experiments. Hence, in this sense, they are closer to the "experimental ideal". However their weakness in regard to streamflow measurement is that they do not allow direct estimation of streamflow; rather it has to be inferred from the water balance. It is reasonable to regard paired catchments and plots as complementary in the pursuit of hydrologic experiment ideals.

5.4.4 "Closing the Water Balance" on Plots

The water balance of anything is that, over a finite period of time, inputs = outputs + change in storage. If all components of input, output, and storage on a volume of space can be independently measured, then the degree to which the left hand side equals the right hand side is a measure of error. This approach is called "closing the water balance" (Sokolov and Chapman 1974) and is rarely achieved. The most problematic variable is usually evapotranspiration. Use of sap-flow equipment in plots may allow "closing of the water balance" under many conditions. This gives valuable information on the relative errors of techniques. This is a major advantage of plot-based measurements over catchment-based measurements in which evapotranspiration is inferred by differencing rainfall and streamflow.

5.5 The Scaling Issue

This refers to the issue of applying the findings from plots or paired catchments to larger catchments. The difficulty is that larger catchments are not just "scaled up" versions of smaller catchments but, rather, assemblages of smaller catchments. In any larger catchment there will be usually a number of small catchments at different points in their forest age-water yield cycle (if such a cycle exists at all). There are also many catchments in which there is no active form of forest management practised. Thus the impacts of forest management may, in proportional terms, be but a small component of the water yield.

5.5.1 Spreadsheet Approach of Weighted Assessment

Suppose, for instance, that a paired catchment measurement showed that formation of a plantation on a pasture side led to a reduction in flow of 1.5 ML ha^{-1} over the life of a plantation. To estimate the yield reduction on a larger catchment one would estimate the area of pasture sites to be converted to radiata pine and multiply this by 1.5 ML ha^{-1} to get the absolute reduction in yield. Then, by use of gauged data or average yield figures for the catchment one could compute the percentage reduction in yield.

Although as simple as one could want conceptually, usually data such as the average yield of agricultural catchments or the area to be planted to pine are not available. As catchment size becomes larger, a particular land use such as radiata pine becomes a smaller and smaller percentage. Hence the hydrologic impact expressed as a percentage change becomes smaller and smaller.

5.5.2 Modelling Approach to Scaling

A more rigorous approach appears to be based on modelling each small catchment individually, with the outflows added (and perhaps "routed" to allow for time affects).

This has been used with limited success in forest hydrology. Typically a "paired catchment" approach is used to provide water use signals (e.g. "Kuczera Curves" – see Chap. 6) and data sets may be used with optimization of complex models to provide "best estimates" of otherwise un-measurable parameters. Then, by modeling a suite of sub-catchments with appropriate hydraulic connections, a reasonably likely hydrologic outcome can be derived. If time intervals are long (e.g. annual data) then the subtleties of the hydraulic connections can usually be ignored, thereby simplifying the modeling. In this sense, the behavior of any larger catchment can, in principle, be reproduced using any information gleaned from the smaller catchments.

There are a number of issues:

1. The forest hydrologist must have a suitable model that somehow reproduces the specific hydraulic geometry of the larger catchments. This is, indeed, a challenging task. An "off-the-shelf" hydrologic model may be able to provide some simulation but the 1:1 correspondence between the large and small catchment and the model is broken. In practical terms this probably means that the forest hydrologist may end up writing their own model (see Box 5.2 on "Macaque" for an example of this)
2. Any such model will demand a formidable number of parameter, and most of these will be impossible to measure directly. A common technique is to use "reasonable values" for many and, if there is some suitable data available, optimize on one or two parameters. Whilst there is often little choice, the physical "purity" of the model breaks down under such an assault.
3. Larger catchments will involve a wider and wider range of species on which there is little or no information, and
4. The combinations and permutations of possible catchment treatments will increase bewilderingly.

Notwithstanding this, some progress has been made, as witnessed by Box 5.2.

Box 5.2: The *Macaque* Model

The *Macaque* model was developed by Watson et al. (1998, 1999) at the Cooperative Research Centre for Catchment Hydrology. The model is physically based, meaning that it aims to represent the dominant, real, physical approach occurring within a catchment using physical equations. This approach is intended to offer predictive capability in situations where measurement of water yield have not been taken. In principle most parameters can be measured in the field or derived from values in literature. The initial work was used to examine "what-if" scenarios associated with timber harvesting in Melbourne's water catchments. The approach can be viewed as allowing scaling up on results from plots or paired catchments.

Although *Macaque* showed considerable promise in the hands of authors, its use appears to have stalled because of staff changes, use of computational platforms that become obsolete, and the learning and parameter overheads in its use.

5.5.3 Scaling Up Controversies

In the north-western US, a long-lived issues has been the scaling up the results of paired catchment projects to examine the effects of land use change and logging on floods. This was a rationale for much early work in catchment hydrology. Thus, suppose logging on a small catchment causes a 10 % increase in peak flows magnitude. Does this translate to a 10 % increase in peak flows on larger streams? Alila et al. (2009) noted that "the science of forests and floods is embroiled in conflict and is in urgent need of re-evaluation in light of changing climates, insect epidemics, logging, and deforestation worldwide". This paper argued that the methodology applied in scaling up was incorrect, and that we need a more rigorous approach in the analysis of paired catchment data involving pairing of floods of similar frequency in the "treated" and "untreated" catchments. This, in turn, sparked its share of replies. The fact that the presence of paired catchment data allows such debates to proceed shows that they are an effective method of research in helping to generate ideas. Their small size will, however, always limit their applicability.

The issue of whether paired catchment projects can provide much information on such large-scale hydrologic issues is arguable. Firstly floods are usually associated with extreme rainfall events of a rainfall intensity rarely encountered in the paired catchment projects. Secondly the causal storms usually have an extremely large geographic spread. Thirdly, the issues usually relate to human property damage rather than the more technical issues to do with flood frequency or magnitude.

In Conclusion

In determining the water use of Australian vegetation, the combination of paired catchment projects and plots appears to be the most powerful approaches. The paired catchment approach is slow but suits long term measurements in stable organizations. Use of plots is faster but more intensive of resources and possibly harder to sustain in the longer term. Both meet many (but not all) criteria of scientific experiments.

Although results can be derived for small catchments, the question of how this information is to be used or even whether it could be applied to large catchments is less clear. A related issue is the absence of comparable information on agricultural hydrology in Australia. Thus it is difficult to use much of the forest hydrology information generated in planning or economic comparisons of land use because there is little comparable data on agricultural crops.

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Chapter 6
Impacts of Native Forest Management on Catchment Hydrology

Abstract Native forest management consists of either cutting to obtain regeneration or thinning of the forests. The chapter examines available Australian information that quantifies these effects. The most reliable information appears to come from paired catchment projects. For most eucalypts, runoff curves give a reasonable description of changes in hydrology associated with cutting. However the southern Australian mountain ash (*Eucalyptus regnans*) has a water yield which also depends on forest age. If the forest is logged then water yield increases, then declines, and then probably slowly increases to the pre-logging level. If the forest is burnt then water yield declines. Thinning may give modest increases in water yield for a few years.

6.1 Introduction

Usually, forested catchments are buffered systems in which rain passes through the forest soil surface into subsoil layers. Most water is ultimately pulled back upwards by the forest for transpiration. Some continues passing downwards either to a stream or to deeper groundwater layers. The forest on the catchment surface has a measureable effect on the water balance. Firstly, the forest density affects the water interception loss. Secondly, different forest types have differing abilities to pass water back to the atmosphere. In one important Australian case ("mountain ash"), this depends on both water availability and the age of the forest; more usually it appears to be independent of forest age. This chapter looks at Australian information on the impacts of native forest management on catchment hydrology. The information is revisited in Chap. 11 in considerations of catchment management issues.

6.1.1 *Sources of Information and the Role of Science*

The relation between streamflow and forests has been a popular source of discussion world-wide for over two centuries. DeWalle (2011) notes that although the work of Zon (1927) and Bates and Henry (1928) at Wagon Wheel Gap in USA

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marked the initiation of forest hydrology as a science, the basic tenets of the discipline were well-known for many years before that. In Victoria, evidence given at the Royal Commission into the major fires of 1939 noted the intentions of the then forests managing authority and the water managing authority to engage in "scientific trials" regarding the water use of different forest types. Unfortunately there is no record of the expected form of these, but presumably they would have been modelled on paired catchment projects such as Wagon Wheel Gap. It was another decade before the first tentative steps in forest hydrology were made (Brookes 1950), and another two decades before active work really commenced. In surveying the history of this in Australia, one is struck by a large volume of debate but the relative paucity of collected data.

Sources of information on the relationship between streams and forests in Australia may be classed as (a) non-quantitative observation by skilled observers, (b) observations of long term change on single-catchments, (c) paired catchment studies, (d) physiological (plot) studies on aspects of the hydrologic processes and (e) production of runoff curves which capture some element of the hydrology. All of these have made a contribution to the debate in Australia and world-wide. However the paired catchment information has most closely met the strictures of scientific hydrology over long periods, with contributions by associated plot studies. Notwithstanding their many problems, the paired catchment approach has probably been the single most effective method of providing information.

Melbourne's Water Catchment Debate; Meeting Community Information Needs

The issue of water use of mountain ash (*Eucalyptus regnans*) on Melbourne's water catchments has been the stimulus of the most impressive hydrology work in Australia, and provides an example of such a hierarchy of information. Thus from about 1920 onwards the managers of Melbourne's water supply formed the opinion that results of major forest fires in their catchments had led to long-term reductions in yields. This opinion was expressed in various venues but was not backed by any systematic measurements or analysis of hydrographic data. Subsequently the catchment managers employed a group of scientists to test hypotheses about the yield decline (Langford 1974, 1976). This led to a number of single catchment studies culminating in the work of Kuczera (1985, 1987) examining data from nine catchments to quantify the above reduction in water yield. Simultaneously an active group of researchers developed paired catchment projects examining the impact of harvesting and thinning on water yield of forests in the catchment; an excellent summary of the work is found in Vertessy et al. (1998). Ultimately the work was scaled down in a reorganisation of the water supply agency but measurement of flows from a number of the paired catchment projects are continuing. The work is discussed in detail in Sect. 6.4.

6.2 Fog Drip and Interception by Native Forests

The presence of a substantial aerial component of trees has been recognized as modifying their environment. The trees may intercept water from fog as “fog drip”, giving a net water gain to the catchment. Alternatively the crowns store water when it rains. This water may then evaporate from the foliage and is viewed as a “loss” to the catchment.

6.2.1 Fog Drip

Fog drip is a process in mountain forests in which water from passing clouds condenses on the foliage of high altitude forests. This then drops to the ground. The first forest hydrology study in Victoria – Brookes (1950) – viewed this as an important process in the Wallaby Creek catchment of Melbourne’s water supply. His estimate was that fog drip could account for up to 190 mm of the observed precipitation. To ascertain if this was, indeed, the case, O’Connell and O’Shaughnessy (1975) established a major study of this process. For study purposes, fog drip was defined as precipitation measured under a forest canopy when no precipitation is occurring in the open.

Two plots, each of 40 m^2 were set up under different aged stands of mountain ash, and equipped with recording rain gauges. These were relocated on a random basis each week. Another recording rain-gauge was placed at a fixed location in a clearing. Fog drip was determined by comparing the precipitation records under the forest with that in the open. The experiment was conducted over a 4-year period. The conclusions were that fog drip under the forest was less than 1 % of gross precipitation in the open, and that there was no significant effect of forest age on fog drip.

Although fog drip was usually of the order of 0.2 mm h^{-1}, it would occasionally approach 1–2 mm h^{-1} during the heaviest fogs. Merriam (1973) carried out laboratory experiments on fog drip and considered 0.1 mm h^{-1} to be light fog and 0.3 mm h^{-1} to be heavy fog. It was concluded that the majority of fogs in this area were “light”.

A few other studies (e.g. Hutley et al. 1997) have shown that fog drip may have a localised importance in specific cases. In this case the process appears to have added an additional 40 % precipitation in an area of highly variable rainfall. However there is no evidence of the process being a widespread contributor to the hydrology of Australian forests.

6.2.2 Canopy Interception

From the time that a person first sheltered from rain under a tree, the role of canopy interception in storing rainfall has been appreciated. Early settlers soon discovered that eucalypts were less effective at providing shelter than European trees because of their relatively thin crowns and the vertical hang of leaves. Over the years a number of studies have characterised this.

As part of their broad approach to water balance studies in Melbourne's water catchments, Langford and O'Shaughnessy (1977) measured the role of interception in native forests and conifer plantations. Gross rainfall, through-flow (water passing through the canopy), and stem-flow (water running down the stem) were measured weekly for up to 7 years at two experimental areas northeast of Melbourne. Linear regressions of through-fall and stem-flow on gross rainfall were calculated for each forest stand and used to derive equations for interception in terms of gross rainfall. The eight forest stands were compared and significant differences were tabulated. No significant differences were found between the magnitude of the processes for mature mountain ash, dry sclerophyll mixed species eucalypt forest, and a plantation of radiata pine. The interception of 1939 regrowth mountain ash was lower than mature mountain ash but the significance level was border-line. Table 6.1 summarises the regression equations obtained; these are also shown in Fig. 6.1. In the equations, T_f is the depth of throughfall (mm), S_f is the depth of stem-flow (mm), and I_n is the depth of interception (mm). These are all expressed as a function of periodic rainfall, P. Typically, each equation is based on a few hundred observations. Generalising, through-fall is about 80 % of rainfall, stem-flow between 1 and 6 % of rainfall, and interception around 15–17 % of annual rainfall.

Dunin et al. (1988) used a weighing lysimeter in a NSW dry sclerophyll forest to follow canopy evaporation during and after rainfall events. Interception losses deduced from the lysimeter response varied between 10 and 15 % of the gross rainfall. Storage capacity of the evergreen forest canopy was inferred to be

Table 6.1 Summary of results from Langford and O'Shaughnessy (1977)

Stand type	Equation
Throughfall	
Mixed species	$T_f = 0.809P - 1.31$
Mature ash	$T_f = 0.775P - 1.36$
Regrowth ash	$T_f = 0.790P - 0.88$
Stem-flow	
Mixed species	$S_f = 0.015P - 0.05$
Mature ash	$S_f = 0.049P - 0.15$
Regrowth ash	$S_f = 0.060P - 0.21$
Interception	
Mixed species	$I_n = 0.176P - 1.36$
Mature ash	$I_n = 0.176P - 1.51$
Regrowth ash	$I_n = 0.150P - 1.09$

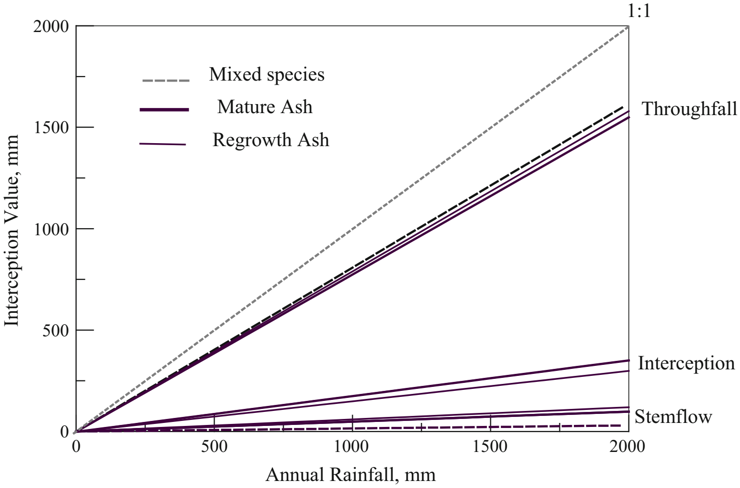

Fig. 6.1 Summary of regression equations derived for canopy interception processes (Langford and O'Shaughnessy 1977)

0.35 mm. Hourly loss rates ranged up to 0.8 mm h^{-1} but more commonly was about 0.1 mm h^{-1}.

Pook et al. (1991) made a detailed study of a single *Eucalyptus viminalis* tree. This had a canopy capacity of 0.25 mm (11.2 L). Total interception was 8.3 % of rainfall; however they found that this was influenced by many factors and that precision of their modelling for eucalypts was poor. Typically the interception loss for the eucalypt was around 1 mm.

Sharma (1984) examined evapotranspiration for a jarrah-marri (*Eucalyptus marginata*, *E. calophylla*) forest in Western Australia, and found that the evapotranspiration far exceeded estimates based on the available radiant energy. It was argued that such losses are due to large interception and evaporation of intercepted water at a rate considerably higher than the potential rate from a dry canopy Crockford and Richardson (2000) found that the maximum possible value for canopy storage capacity of a dry sclerophyll eucalypt forest was found to be a small proportion of interception for events of all sizes. This suggests that evaporation of rainfall from the wetted canopy is responsible for most of the interception loss. They found that average interception was 4–11 % of rainfall. Of interest was their derived model of eucalypt crown storage as a function of accumulated rainfall (Fig. 6.2). This suggests that the small crown storage is rapidly filled (which accounts for the observation of earlier settlers attempting to shelter under eucalypts).

More recently, two plot studies quantifying the water balance have yield estimates of interception loss in dense eucalypt forest. Mitchell et al. (2012) examined the fate of rainfall in an undulating mature eucalypt forest near Myrtleford

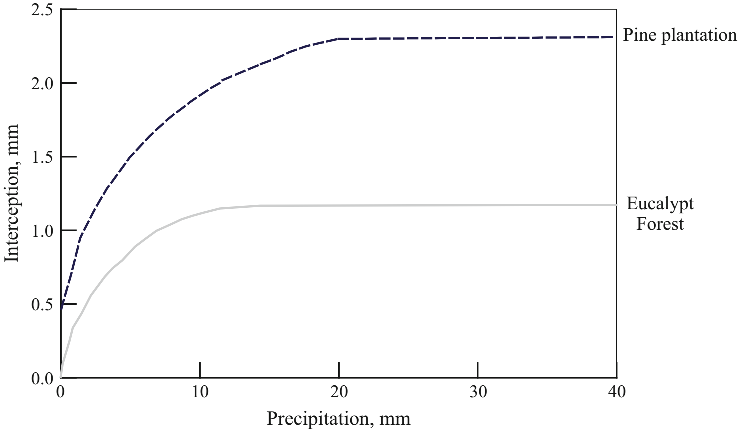

Fig. 6.2 Interception as a function of storm size for a pine and eucalypt forest, as presented by Crockford and Richardson (2000)

(Victoria). They measured values of 9–19 % rainfall loss, with interception comprising up to 29 % of the total evapotranspiration. Similarly Nolan et al. (2014) in her studies on the impact of fires in mixed species recorded interception losses of 9–17 %, with this comprising up to 22 % of the evapotranspiration.

Overall there is a general consistency in the data. Feller (1981) cited an interception range of between 10 and 20 % of the rainfall, and general results are of this magnitude. The interception loss tends to be low when compared with those for coniferous communities from overseas. Thus Puncochar et al. (2012) note that in European alpine forests interception may be 45–65 % of the rainfall, but that stemflow was negligible. Australian workers commonly note the difficulties of carrying out interception studies and the relatively high error levels in equations derived. In general, forest hydrologists have not considered the interception losses associated with native eucalypt forest to be an easily managed component of the forest water balance.

6.3 Basic Runoff Curves for Native Eucalypt Forest

For most native forest in Australia, the experience has been that anything that reduces the density of the forest increases the streamflow yield. Two “runoff curve pairs” have been promulgated to predict streamflow as a function of dense forest – the curves of Holmes and Sinclair, and the “forest” and “pasture” curves of Zhang et al. (2001) (see Sect. 2.5).

Holmes and Sinclair (1986) produced estimates of mean annual evapotranspiration as a function of mean annual rainfall (Fig. 6.3). Their presentation did not include equations, thereby limiting the utility for routine work. Zhang et al. (2001)

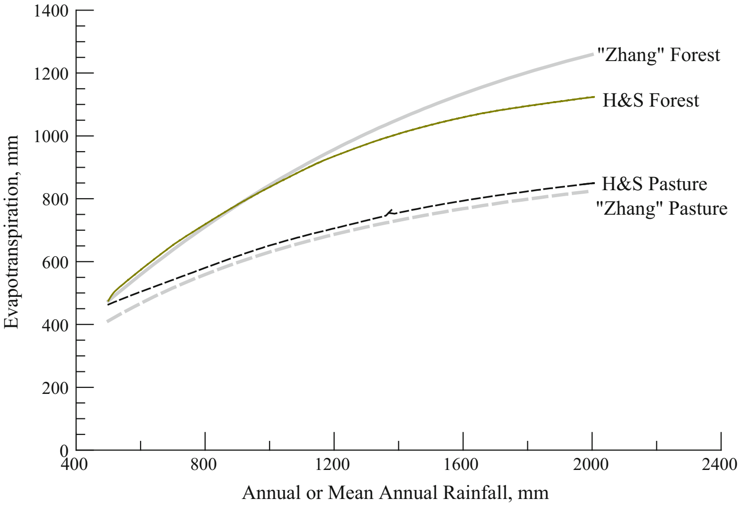

Fig. 6.3 Estimates of annual evapotranspiration as a function of annual or mean annual rainfall published by Holmes and Sinclair (1986) and Zhang et al. (2001)

produced their previously-discussed curves (Fig. 6.3) which gives an estimate of evapotranspiration for mature forest on a catchment. Within noted errors of about 95 mm, the curves are similar. In the form of the curve as presented, streamflow is estimated by subtracting the estimated evapotranspiration from the rainfall.

Greenwood et al. (2011) favours the use of "Tanh curves" (see Ladson 2008) for estimating runoff. Figure 6.4 shows a Tanh curve fitted to annual data from five small catchments gauged in three paired catchment projects in "mixed species" forest. The equation derived was:

$$Q_f = -107.31 + P - 1352.35 \ \mathrm{Tanh} \ [0.000739(-132.39 + P)] \qquad (6.1)$$

Coefficient of Determination = 0.903

in which

Q_f = Annual runoff from mature native forest, mm, and
P = Annual rainfall, mm.

The "forest" curve of Zhang et al. (2001) is also shown for comparison (with the streamflow estimated as rainfall – evaporation). It can be seen that over the range of native forest rainfalls in Australia, the two forest curves are similar. Given the error involved in both functional relationships, it appears reasonable to view them as the same curve over the range of data involved.

Within the limits of error and over the rainfall range of most commercial forest (600–2,000 mm) there is not much difference in these three "forest" curves. As

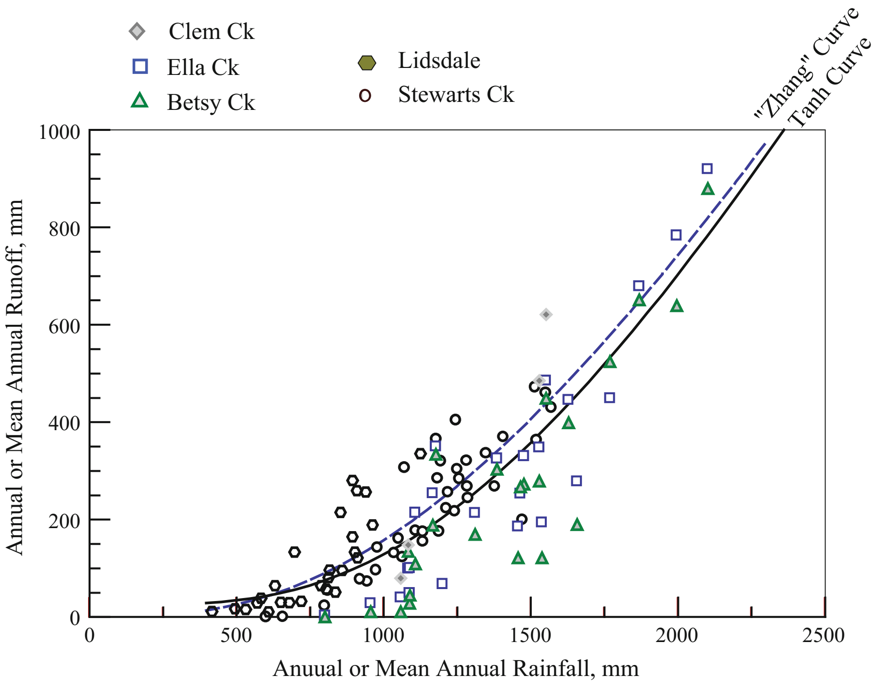

Fig. 6.4 A collation of native forest runoff as a function of rainfall, and a fitted "tanh" curve. The curve of Zhang et al. (2001) for native forest is also shown

discussed in Sects. 6.4 and 6.5, there may be some variation from such relationships for regenerating forest, but this appears small.

6.4 Mountain Ash Water Use and Runoff Curves

Mountain ash (*Eucalyptus regnans*) is a major forest tree occurring mainly east of Melbourne (Victoria), in the Otway Ranges west of Melbourne, and in Tasmania. The tree is the highest flowering plant in the world, with heights of 80 m being commonly attained. The tree occurs in rainfalls from about 1,300 to 2,500 mm in mountain country. Figures 6.5 and 6.6 show views of mountain ash forests before and after burning. Because the tree occurs in high rainfall areas, many of the forests have become water supply catchments for major cities and towns in Victoria, including Melbourne, Colac, Geelong, and Warrnambool. Mountain ash forests are mostly even-aged, although occasionally other forest structures are found. Natural regeneration appears to be associated with fires, in which the parent forest dies and seedlings germinate in the ash of the burnt forest. These give extensive, even-aged stands. Fagg (2006) gives an account of the silviculture of the stand.

Fig. 6.5 Mature mountain ash forest. This old-growth mountain ash forest was near the control catchment in the Coranderrk Paired Catchment Project

Traditionally silviculture has mimicked this; however in recent times there have been calls for management for maximising biodiversity outcomes rather than commercially-valuable products (e.g. Lindenmayer and Wood 2010).

This species appears unique in the world as having a documented forest water use which is a function of annual rainfall and forest-age; this was pointed out by Bosch and Hewlett (1982) and still appears true today. Figure 6.7 is a collage of information showing well-documented measurements of water yield as a function of forest age. The data are shown relative to "old growth"; thus zero indicates the same yield as all old growth, a positive value indicates an increased yield, and a negative value a decreased yield. Sources of data are:

1. Langford (1974) who provided the first published quantitative record of this. He used routine stream-gauging records taken from before and after the 1939 fires in Victoria. His data from Graceburn Creek (2,500 ha, 70 % ash species) and Watts River catchments (10,500 ha, 55 % ash) are shown. The cause of forest regeneration is the 1939 fires. To compute the effects, Langford (1974) used an additional catchment which was unaffected by fire and formed a "de facto" paired catchment experiment with a relatively large error. The magnitude of the response computed by Langford (1974) is substantially greater than that established by later work.

Fig. 6.6 Mountain ash forest burnt in the 2009 Marysville Fire. The fire-killed mature trees and the dense regeneration of understorey is evident 2 years after the fire

2. Data from the Coranderrk paired catchment project established to quantify the effects of logging on water yield (see Bren et al. 2010). This project is continuing. Although the area was substantially mountain ash, many view it as at the lower end of rainfall for this species. Data from Blue Jacket Creek (65 ha, 50 % "thinned") and Picaninny Creek (53 ha, 90 % logged) are shown.
3. Data from the Myrtle paired catchment project (Myrtle 2 Creek, 32 ha, 74 % logged) which was, effectively, a repeat of the Coranderrk (Picaninny) project in a higher rainfall area. Data are taken from Watson et al. (1998)

The larger catchments are mixtures of many forest (and non-forest) vegetation including ash and "mixed species" (in which about five different eucalypt species occur in intimate and varied mixtures). In contrast to mountain ash, mixed species forests are rarely killed by fires. The trees recover by developing "epicormic leaves" on stems and by crown recovery (see Chap. 8).

The following is of note:

1. The scientific data base on which a large literature concerning itself with processes, methods of extrapolation, and politics of forest management is surprisingly small.
2. The results show that after fires there is a relatively rapid diminution of streamflow. In general there is little evidence of streamflow increases in the

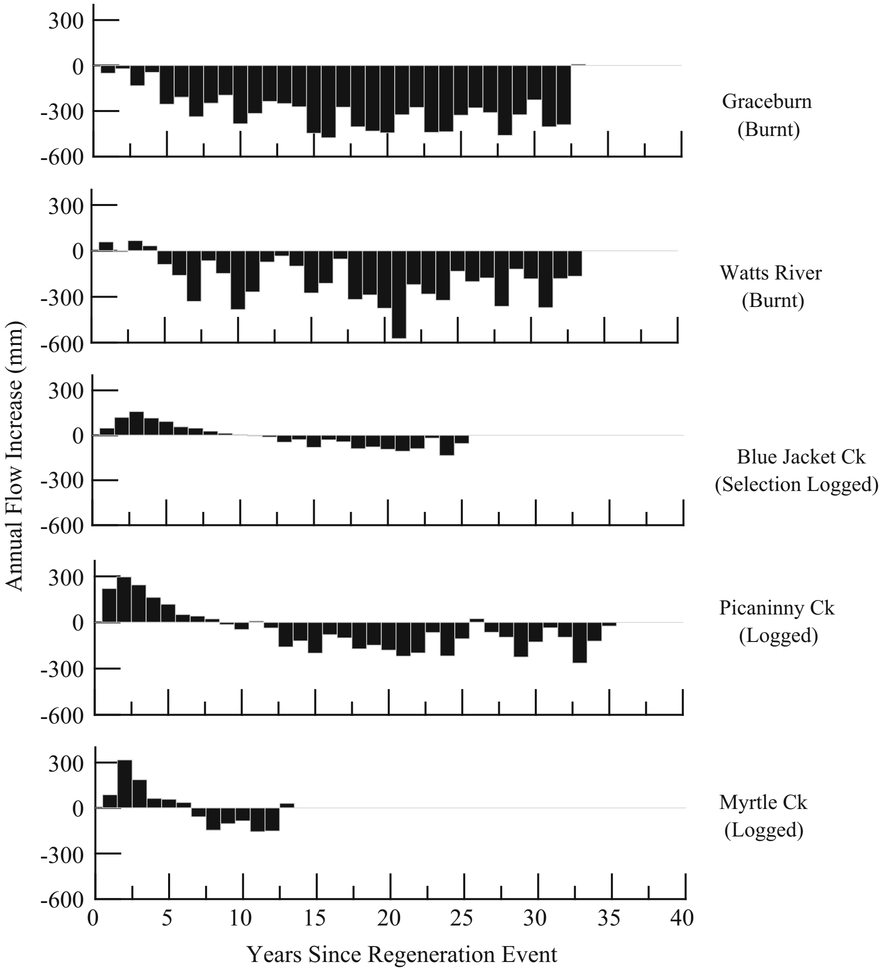

Fig. 6.7 Collage of studies showing water use of mountain ash relative to old growth as a function of forest age

year after fires although transpiration capacity may be diminished. This probably reflects that the largest fires usually occur in times of drought. Hence, there are relatively small amounts of water stored in the catchment slopes able to be released.

3. After harvesting there is an increase in streamflow for some years, followed by a decrease in streamflow as the regrowth grows. This is in contrast to the fire-induced flow change.

4. There is substantial inter-year variability. This reflects annual variability in rainfall, errors of measurement and data recording, and many other unknown factors.
5. The impacts of forest management are buffered in the sense that after logging, streamflow may increase for some years and then slowly decrease. This is interpreted as showing a recharge to slope storage (with a corresponding increase in streamflow) and then a drawdown of slope storage.

Vertessy et al. (2001) examine aspects of the "mechanistic hydro-ecologic" variation in evapotranspiration as a function of age. This was based on many measurements of leaf area, sapwood area, and other water balance components in several mountain ash stands ranging in age between 5 and 240 years. Sap flow measurements showed that sap velocity did not vary appreciably between stands, but a decline in sap flow area (relative to stand basal area) with age produced a decrease in stand transpiration. This was also associated with a peaking followed by a decline in the relative leaf area of the over-story as the forest aged. There were many other factors involve which made a full explanation difficult. The work highlighted the difficulty of using measureable variables such as leaf-area index as a surrogate for evapotranspiration in this (and probably most other) eucalypt species.

6.4.1 Quantifying the Yield Decline: "Kuczera Curves"

The "classic" (and sometime misapplied) work in this was that of Kuczera (1985, 1987). A young scientist, George Kuczera, was given the task of predicting water yield reductions following a bushfire in an ash-mixed species eucalypt forest. This work followed from Langford's (1974) demonstration of yield reductions from regenerating mountain ash forests. Kuczera (1985) defined the following needs:

1. A moderately long record (>15 years) prior to the 1939 fire to ensure that parameters can be accurately estimated.
2. Pre 1939 data must be representative of a catchment whose yield is unaffected by fire.
3. The post-1939 yield trends must be mainly due to ash regeneration following the 1939 fire.

He took the view of identifying a "bushfire response function", noting that the choice of this was "somewhat arbitrary with the final justification dependent on how well the model 'explains' the data." His rationale was influenced by an analogy between reservoir theory and fire-affected catchments. Kuczera (1985, 1987) subsequently argued that the change in yield as a function of time from the burnt catchments could be described by a curve of the form.

$$\begin{aligned} g(t) &= L_{max}K(t-2)e^{(1-K(t-2))} \\ g(t) &= 0 \ \ for \ \ t < 2 \end{aligned} \tag{6.2}$$

where g(t) (in mm) is the change in water yield relative to old growth, L_{max} is the maximum reduction in annual streamflow, and 1/K is the period from the start of the decrease to the point of maximum decrease; commonly (1/K) is taken as 26. The symbol e is Euler's Number (2.718). L_{max} should be taken as negative for the usual form of the curve. The fit of the curve was designed so that the forest was close to its "long term value" (i.e. zero) at about age 150 years.

Kuczera (1985) examined the statistical relationship between the modelled yield decline (L_{max}) and the percentage of ash, mixed species, and the area of the catchment. The model derived was:

$$\mathrm{L}_{\max} = 6.15 \ \ \mathrm{a} \tag{6.3}$$

where a is the percentage of ash in the catchment. If we substitute Eq. 6.3 into Eq. 6.2, then we arrive at the relationship:

$$\begin{aligned} g(t) &= 6.15 \ \ a \ \ K(t-2)e^{(1-K(t-2))} \\ g(t) &= 0 \ \ for \ \ t < 2 \ \ years \end{aligned} \tag{6.4}$$

Figure 6.8 is derived from this work and shows the yield reduction as a function of the age of ash regrowth forest within the catchment for a catchment with full mountain ash stocking. As the amount of mountain ash in the catchment decreases the absolute value of L_{max} correspondingly decreases. Such a curve is often referred to as a "Kuczera curve." The relevant features are:

1. A period of 2 years after the fire in which there is no change in water yield.
2. A continued reduction in annual streamflow with the maximum reduction occurring 1/K years after the fire. The magnitude of the maximum reduction is given by L_{max} (mm). L_{max} is commonly written as a negative value to indicate a yield decline. The maximum yield reduction computed is 615 mm; such a yield reduction could only occur in very high rainfall forest.
3. A recovery of the yield as the forest ages, with return to "old growth" water yields (i.e. change in yield = zero) as the forest returns to "old growth" at about age 200 years.

Assuming the minimum water yield is achieved at 26 years of age, and that the catchment is both located in high rainfall and fully stocked with mountain ash, the equation becomes:

$$\begin{aligned} g(t) &= -23.65(t-2)e^{(1-0.0384(t-2))} \\ g(t) &= 0 \ \ for \ \ t < 2 \end{aligned} \tag{6.5}$$

This is the equation most commonly cited.

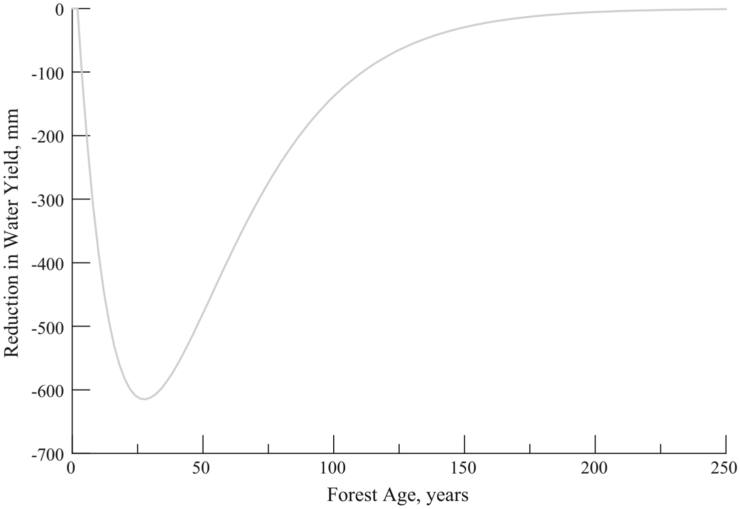

Fig. 6.8 The usual "relative" form of the "Kuczera Curve" quoted for high rainfall, fully-stocked mountain ash sites. The plot shows the reduction in water yield of a regrowth forest compared to an old-growth (>250 years of age) forest as a function of forest age

Figure 6.9 shows a number of "Kuczera curves" which Kuczera (1987) fitted to various data sets. It is to be noted that Kuczera (1987) did not specify "preferred values" of the two parameters in Eq. 6.2**.** The Kuczera relationship shown in Fig. 6.8 above is often cited as applying to water yield reductions from areas which have been logged. Unfortunately many subsequent authors have ignored the stricture of Eq. 6.2 defining the amplitude of this as a function of the percentage of mountain ash in the catchment. Commonly the increase in water yield associated with logging is also often ignored.

An interesting postscript to this work is the analysis of Brookhouse et al. (2013) which repeated many aspects of the analysis of Kuczera (1985, 1987). This used three of the same catchments but included data not available to the earlier analysis. This data was assembled by "flow reconstruction" from 1908 to 2011; in contrast Kuczera's data covered the period from about 1926 to 1981. They found similar trends but that the point of "minimum water yield" appeared to be around 9 years earlier than that quoted by Kuczera (1985, 1987), that the recovery from fire appeared to be faster than predicted by the Kuczera curve, and that the amplitude of the "ash drawdown" was substantially smaller. The work noted that their findings were "quantitatively consistent with Kuczera's (1987)". They were able to demonstrate that an impact of water yield from ash catchments burnt in the 2003 Victorian fires is detectable as a flow reduction from those streams, and concluded that post-fire reductions from such streams would continue for some decades.

The work of both Kuczera (1985, 1987) and Brookhouse et al. (2013) illustrates the difficulties of hydrologic data analysis using "routine gaugings" – particularly the large error implicit in the use of these – to draw hydrologic inferences on the

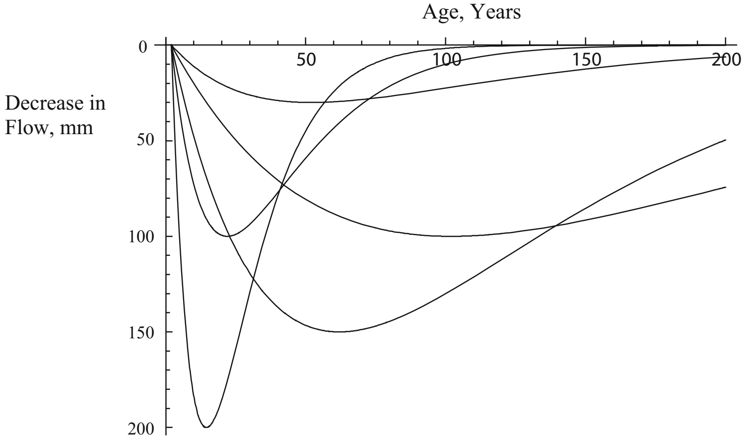

Fig. 6.9 Various examples of Kuczera curves from Kuczera (1985). Kuczera's work defined the form of the curve for burnt forest, but he was inspecific as to whether there was a "correct" set of parameters

water use of vegetation in large catchments. A reasonable inference is also that a simple runoff curve based on forest age is an over-simplification of the hydrology. Clearly much more work needs to be done on this subject.

6.4.2 Response to Logging

Although the efforts of Langford and Kuczera helped shed light on hydrologic changes associated with burning, the hydrologic issues associated with logging were still largely unresolved. This work ultimately stimulated the "Coranderrk Study", some results of which were presented in Chap. 5 and Fig. 6.7. The groundwork had been laid for a paired catchment study examining this yield reduction in 1956; however no active work was commenced until about 1967, with catchment treatments occurring in 1971. Figure 6.7 present results for Picaninny catchment and Blue Jacket catchment. Figure 6.10 repeats the results for Picaninny up to 2011 at a larger scale. For comparison in Fig. 6.10 is a Kuczera curve computed following the formulation of Kuczera (1987) for the amount of mountain ash in the catchment. It can be seen that:

1. The response of the Coranderrk catchment to logging gives an increase in streamflow lasting about 4 years after logging. This then dies away.
2. The flow in the logged catchment then decreases below the expected flow from the "old-growth" control catchment. There is some variation in the magnitude of this response from year to year but, overall, there is a pattern of consistency. Some 40 years after logging, the flow still appears to be below the flow experienced from the "old growth" control.

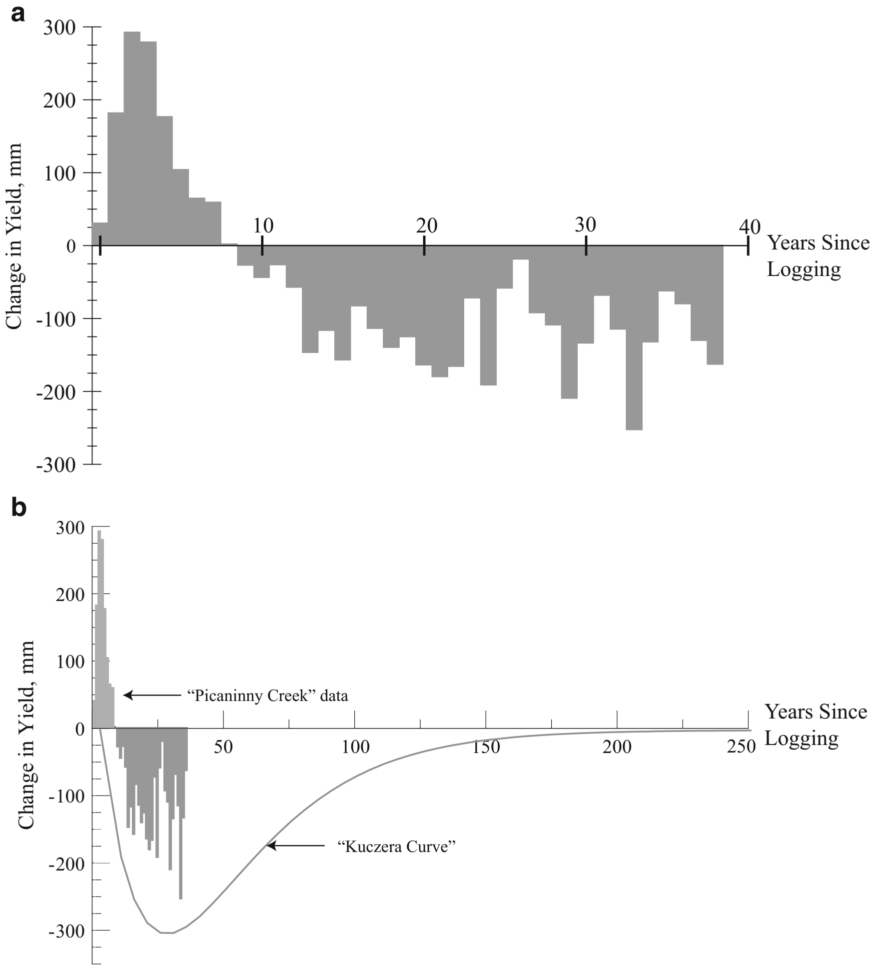

Fig. 6.10 Response of Picaninny catchment to logging. Plot **a** shows the observed response. Plot **b** shows this with a "Kuczera Curve" appropriate to the percentage of mixed species in the forest over a 250 year growth span of the mountain ash

Although the logging response has some elements of the "Kuczera-curve" bushfire response, there are as many differences as similarities. The Kuczera curves do not show an increase in streamflow after harvesting. Although the Coranderrk data show a reduction in flow, the reduction is substantially less than predicted by this form of curve. Thus, the author suggests that Kuczera curves should be restricted to describing the response of forested catchments to fire.

6.4.3 Other Melbourne Water Paired Catchment Logging Experiments

The success of the Coranderrk project led to a number of additional studies within the Melbourne water catchments. Part of the stimulus for this was the realisation that the Coranderrk project area was viewed by many as at the lower end of the rainfall spectrum for mountain ash. The most comprehensive account of the results to date is in the paper of Watson et al. (2001). This gives a number of results up to 1997; further results have not been published. A brief description of projects is given below.

Myrtle 2 This was an old growth (>200 years old) forest and was 74 % clearfelled during the 1984–1985 summer. The nearby Myrtle 1 catchment was used as the control. The pre-treatment period was 151 months. Watson et al. (2001) describe the results as "in the post-treatment period, significant positive disturbances are consistently observed for 2–3 years after treatment. These then decline until, at about 6 years after treatment, a 4 year period with a tendency for significant negative disturbances occurs." Watson et al. (1998) commented that "the results also show that un-modelled variability in streamflow due to factors such as climate is large relative to the magnitude of treatment-induced change in streamflow."

The response is shown in Fig. 6.7; this is taken from Watson et al. (2001) in which his monthly estimates are discretised into years. The upturn at about 14 years after treatment is noted as possibly reflecting an insect attack.

The Monda Group Watson et al. (2001) note that the Monda catchments 1, 2, and 3 were 1939 regrowth and were clearfelled and either seeded (Monda 2) or planted (Monda 1 and 3) at nominal densities of 2,000, 5,000, and 500 seedlings ha^{-1} respectively in the summer of 1977–1978. Regeneration at Monda 2 was achieved by scattering seed at 3.2 kg ha^{-1}, which was expected to give a seedling density of 5,000–10,000 per hectares." The "control" catchment contained 1939 mountain ash.

Figure 6.11 illustrates the changes, as computed by Watson et al. (2001). The result shown is the average of the three catchments, discretised over water years. Watson et al. (2001) argue that the high peak and the sustained increase reflects the relatively low runoff "base" associated with assessing runoff change from logging a 1939 regrowth catchment. Thus, if the 1939 regrowth had a reduced yield of 100–200 mm per year relative to old-growth, then clear-falling would change the absolute level of runoff to that effectively associated with bare ground (and thus might be expected to be 100–200 mm higher increase than Coranderrk results). This is the observed pattern.

A practical consequence of the age-related yield dip behaviour is that if a forest at or near the point of minimum yield is logged (or allowed to grow on) the yield will, by definition, increase. Thus, given the nature of the control catchment, the

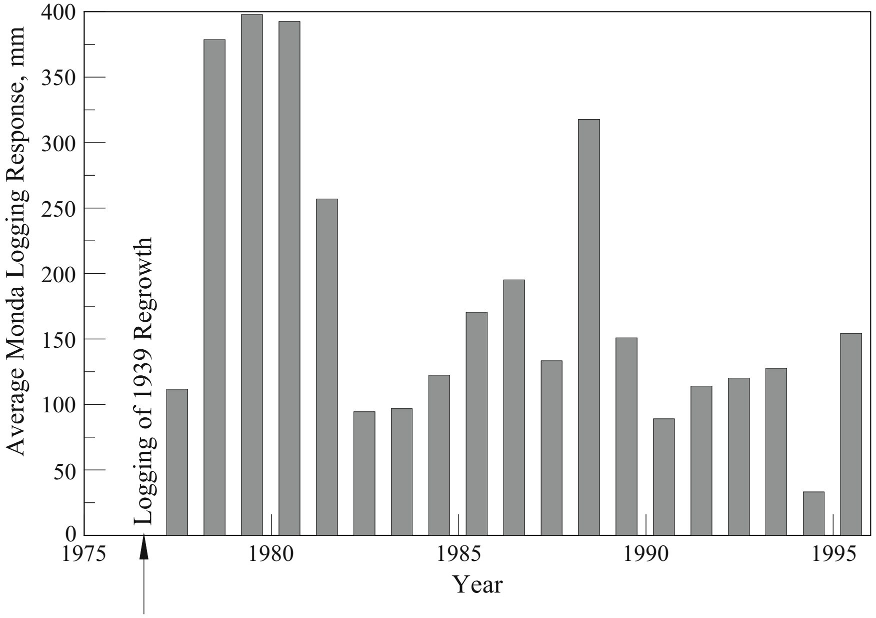

Fig. 6.11 Response of Monda catchments to logging and regeneration. The control catchment was 1939 mountain ash. Data were digitized from the illustrations within Watson et al. 2001

change in flow will not drop much below zero because the control yield itself was low.

6.4.4 Later Work on Mountain Ash Age-Yield Relationships

Watson et al. (1998) realised the deficiencies of Kuczera Curves and defined a set of water yield as a function of age relationships in the form of a complex curve. This is given by:

$$\mathrm{aetash} = \left(-1 + e^{-\frac{t}{p7a}}\right)\mathrm{p3a} + \left(-1 + \frac{2}{1 + e^{-\frac{t}{p6a}}}\right)(\mathrm{p2a} + \mathrm{p3a} - \mathrm{p4a}) + \mathrm{p4a} + \frac{t\,e^{1-\frac{t}{p5a}}(\mathrm{p1a} - \mathrm{p2a} - \mathrm{p3a})}{\mathrm{p5a}} \tag{6.6}$$

in which:

Aetash = Estimated annual evapotranspiration of ash,
t = Age of the forest, years,
e = Exponential constant (approx. 2.718)
p1a−p7a = Constants.

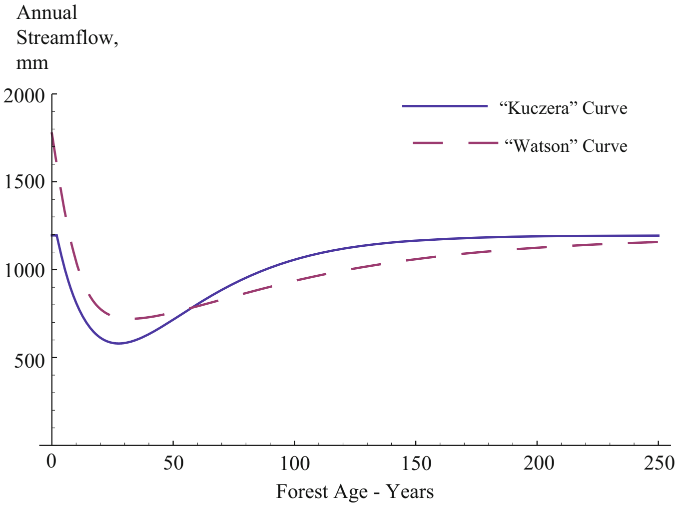

Fig. 6.12 The Watson et al. (1998) water yield-age relationship (relative to old growth) using the parameters shown in Table 6.2. An annual precipitation of 1,995 m is assumed. For comparison a Kuczera curve (absolute form) with an annual runoff of 1,195 mm from old-growth forest is also shown. The Watson curve makes some provision for increased forest flows after harvesting

Table 6.2 Watson parameters used in Fig. 6.13

Parameter	Value
p1a	1,390
p2a	800
p3a	370
p4a	220
p5a	40
p6a	6
p7a	100

The curve can be viewed as a super-positioning of various wave forms representing distinct physical processes in evapotranspiration. Varying the values of parameters gives a wide variety of "curve forms." Being a seven-parameter model allows many permutations and variations to represent complex functions. Some of the constants are interpreted as components of evaporation and can be ascribed units of mm to assist visualisation.

Figure 6.12 gives an example quoted by Watson et al. (1998) using the parameters shown in Table 6.2. The results have been presented as "absolute yield" rather than yield relative to old growth forest. An annual precipitation of 1,995 mm was assumed. For comparison the "Kuczera Curve" for a full ash site (absolute form) is shown; this has an annual runoff of 1,195 mm from mature ("old-growth") forest. The Watson model allows for an increase in flow associated with logging for the first few years.

These curves were embedded in a complex, spatially-based model ("*Macaque*"- see Box 5.2) developed by Watson et al. (1999). Attempts to use them in other situations have encountered difficulties – at least partly because of the lack of good field data to allow derivation of the appropriate parameters. In particular it was argued that the leaf area index of regrowth forests should be an indicator of their relative transpiration (e.g. Vertessy et al. 1998). However this appears to be, at best, an unproven hypothesis.

At the time of writing the major continuing source of information on the water use of the forest as a function of age (and annual rainfall) appears to be the Coranderrk Paired Catchment Project, together with past work.

The concerns of decreased water yield from regrowth mountain ash has led to calls for the cessation of harvesting in ash forests; the water production strategy would be to grow all forests to old-growth mountain ash. An examination of this policy was made by Bren et al. (2013) based on work examining inflows of forest into Australia's River Murray. The examination showed that, in general, there could only be measureable gains from three high-rainfall areas in the eastern Highlands of Victoria. The strategy would have to be to maintain all forests as "old-growth". This would be difficult to do given the propensity of these forests to periodically burn. As well, this catchment management would not meet the criteria of forest resilience expressed in Chap. 11.

6.5 An "Age-Yield" Response for Non-ash Eucalypts?

The original work of Langford (1974) and Kuczera (1985, 1987) was unable to detect any age-related water yield effect of mixed species regeneration. They concluded that the effect was only present in mountain ash. The question of whether logging leads to an age-related water yield decline in eucalypt species other than mountain ash has caused considerable debate in Australia. The small amount of data on this is mixed; one paired catchment project says "no" but plot measurement on the same species says "yes", a second was viewed as saying "yes" but later interpretation says "no", and a third paired catchment project gave "maybe" but then closed before a longer collection of data could resolve this issue. Paired catchment experiments on the western Australian eucalypt, jarrah (*E. marginata*) have yielded a resounding "no." And French hydrologist Vazken Andreassian (2012) has argued that the effect is present in many species world-wide but may be small, difficult to detect, and that scientists in other parts of the world have not gone looking for it. This author's view is that a small affect may exist but it is certainly not been demonstrated by field research.

Figure 6.13 presents examples of selected results from three paired catchment studies in which a catchment carrying a mature eucalypt forest (other than mountain ash) has been logged and regenerated. These have been selected as being representative of a larger body of results from the same projects. The time axes is relative to logging, and the vertical axes is periodic change in flow relative to that expected on the basis of mature forest in the "control catchment". Comments and qualifications are given below.

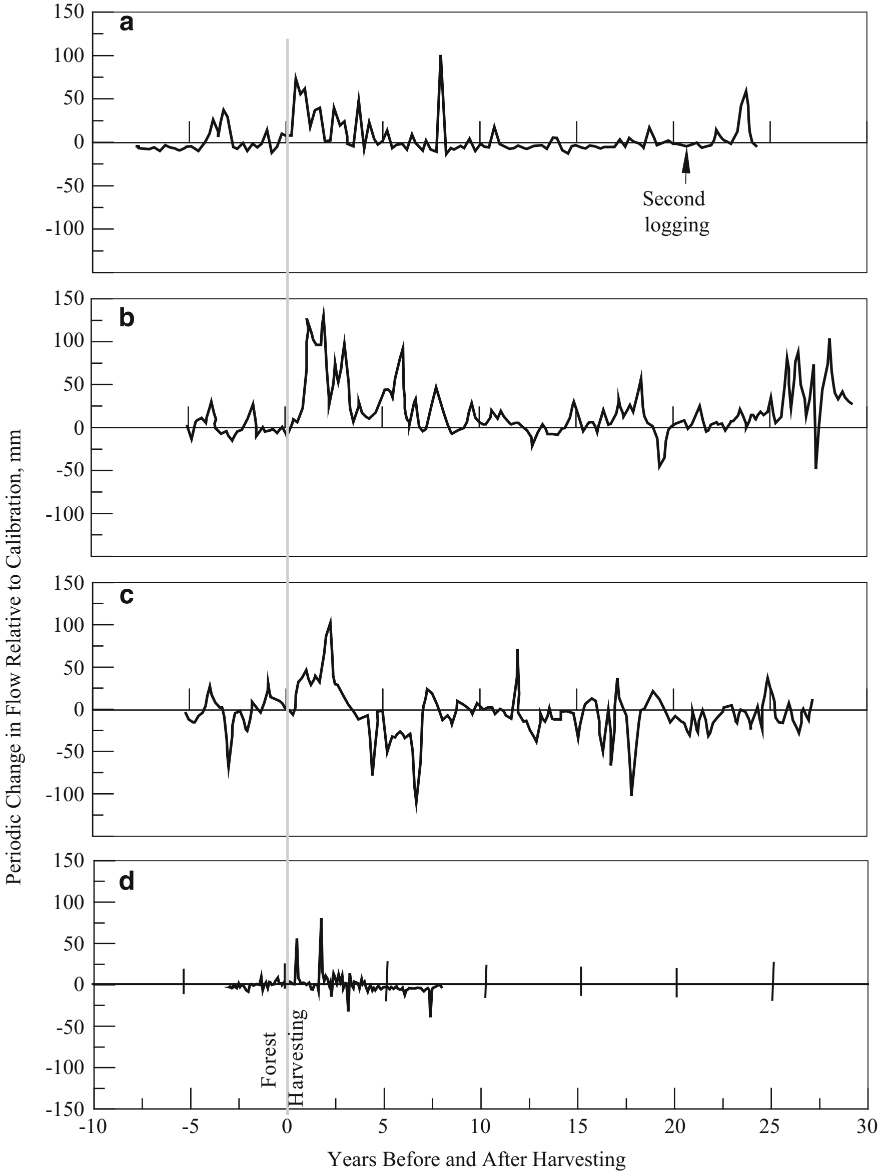

Fig. 6.13 Collage of age-related responses from other eucalypt paired catchment projects. (a) Yambulla (quarterly). (b) Jackwood at Karuah (quarterly). (c) Corkwood at Karuah (quarterly). (d) Wicksend at Tantawangalo (monthly)

6.5.1 *Yambulla Paired Catchment and Plot Studies*

The Yambulla Project had its origins in a conflict associated with rehabilitation of degraded silvertop ash (*E. sieberi*) forest near Eden (NSW) by logging and regeneration. The project involves six small catchments but was compromised by the passage of a fire across the area in the first 2 years of the project; the reader is referred to Webb and Jarrett (2013). They concluded that the response to logging was increased flow for some years, followed by a return to the pre-logging flow regime. Figure 6.13a shows the published result from logging of catchment 2 by alternate coupe and regeneration burning. A second alternate coupe logging occurred about 20 years after the first and is marked. The catchment was one of five treated catchments which showed generally similar results.

Roberts et al. (2001) studied the same species in the same area using plots to measure transpiration, sapwood area, and leaf area for individual trees in three stands of differing age. The results showed that transpiration was 2.2, 1.4, and 0.8 mm day^{-1} in forest of age 14, 45, and 160 years of age. The results suggested an age-water yield relationship but with a small amplitude compared to that of mountain ash.

6.5.2 *Karuah Paired Catchment Project*

This a paired catchment project with treatment occurring on six small catchments carrying high rainfall *Eucalyptus laevopinea*. The project is located near Dungog, NSW. Early results (Cornish and Vertessy (2001) suggested a diminished flow from regrowth, but a subsequent analysis by Webb et al. (2012) was unable to find such a change in the longer sequence they used. The project was unusual in that it had repeated treatments at the same time, and these showed some variation in results between catchments. Webb et al. (2012) interpreted these as reflecting factors such as variation in stockings. Figure 6.13b, c shows the results from Jackwood and Corkwood catchments as presented by this reference. There was considerable variation in the responses of the different catchments, but none showed a long-term decline in yield. Variation was explainable by changes in forest species composition, basal area, and stocking rates.

6.5.3 *Tantawangalo Paired Catchment Project*

This was a paired catchment project in foothill mountain forest (mainly cut-tail – *Eucalyptus fastigata*), and was reported on by Lane and Mackay (2001). The project was instigated after a logging controversy on the issue of impacts of water and involved three catchments. Wicksend was patch-cut to remove 22 % of basal area. The data sequence shown in Fig. 6.13d shows a small but consistent decline in monthly water yields a few years out from the harvesting. A second catchment was thinned to remove 12 % of basal area and this showed a long-term flow increase (see Sect. 6.6.2). The project was closed 8 years after logging. Observers are divided as to whether the results can be interpreted as showing an age-related decline in water yield.

6.5.4 Western Australian Work on Jarrah

Eucalyptus marginata ("jarrah") occupies the gently sloping Darling Range south of Perth (Western Australia). Typically rainfall is around 1,100 mm per annum, and runoff averages 71 mm (7 % of rainfall). The forests have had a long history of utilisation with most being regrowth. The area is important for water supply to the West Australian capital of Perth. Over the years a comprehensive body of paired catchment work, plot, and single-tree work looking at the water use of jarrah trees and forests has accumulated with good reviews covering earlier work by Stoneman and Schofield (1989) and Ruprecht and Stoneman (1993).

In general clear-fall logging has increased water supply by up to 28 % of annual rainfall. Subsequent regeneration of the forests had led to water yields returning to pre-disturbance levels after an estimated 12–15 years. There is no evidence of an age-related decrease in water yield.

Kinal and Stoneman (2011) provide an account of the hydrological impact of two intensities of timber harvesting and associated silviculture in the jarrah forests in south-western Australia. The study was undertaken during a period when average annual rainfall was below the long term average and deep groundwater levels were declining. Following logging groundwater recharge increased and slowed the decline in deep groundwater levels in proportion to the magnitude of the initial reduction in vegetation density. During the time of the study, groundwater levels were well below the stream bed; hence there was no impact of the harvesting on streamflow. This type of work indicates some of the difficulties of long-term hydrologic research in dense forests and where annual rainfall can be highly variable.

6.5.5 Political Aspects of Native Forest Water Use

Logging in Australia is often controversial, and opponents of logging have claimed that regrowth from non-ash species reduces water yields and "dries out the catchment". The inference in the political debate was that any such reduction in water yield was "bad". The corollary of this – whether increases in flow associated with logging are "good" seems not to have been considered in the debate. The data collected does not support the claims of major water yield reductions in non-ash species but there may be minor effects. Terms such as “dries out the catchment” are pejorative (presumably implying reduced slope water storage?) and are better avoided. Clearly the topic needs considerably more research and, perhaps, improved methodology to reduce “noise” which obscures such small trends if they are, indeed, present. For both ash and non-ash species, the noted effects are from a surprisingly small body of studies. There is a clear need for building up the body of knowledge for the future.

Irrespective of whether there is an age-related effect, the reality is that native forests consume water and, in their production of both tangible and intangible benefits, water is a joint factor in the inputs for both wood and conservation products. In a world which is increasingly concerned with water for human consumption, this will be a big modifier of forest management or even the existence of forests.

6.6 Thinning of Native Forests for Water Production

An obvious strategy in management of forests is to thin out the trees; this provides a wood product which can be sold, and by reducing the forest density enhances the water yield. Traditional thinning (Fig. 6.14 effectively leaves trees approximately equi-spaced. As the trees age, they become larger. Falling and moving such large trees leads to forest damage which negates the silvicultural benefits of thinning and hence the technique becomes less and less applicable to growing forests. In such a case, strategies such as patch-cutting or strip thinning in which cut trees do not have to be moved through retrained trees may be used. Figure 6.15 shows examples of thinning forests using conventional and patch thinning. Although there may be water yield benefits, such highly-obvious forest cutting is unlikely to ever be embraced by the public.

Although forest thinning has the potential to increase yield, this would only be applicable in the case of large areas of uniform, even-aged forest of suitable age and species clothing the slopes of a catchment. For native forests, this would be a

Fig. 6.14 Thinned alpine ash (*E. delegatensis*) forest at Matlock in 2006 (Photograph courtesy of Michael F. Ryan)

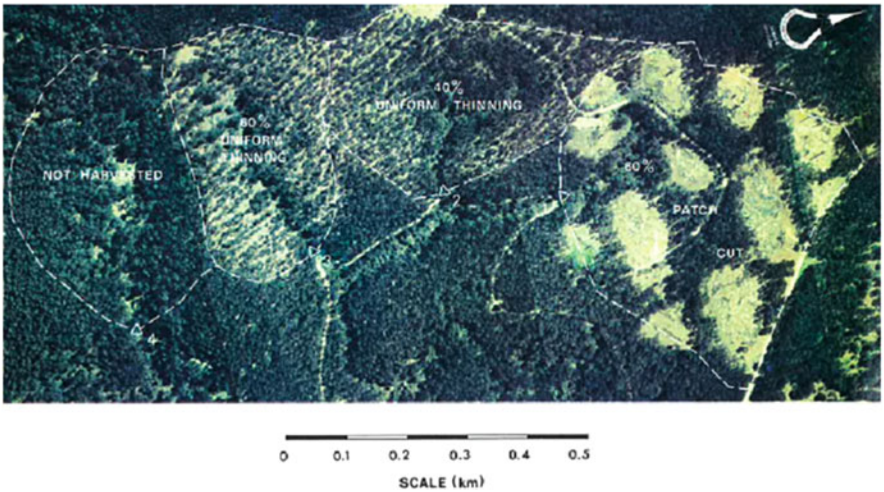

Fig. 6.15 Showing unharvested forest, two levels of conventional thinning (60 and 40 %) and "patch cutting" on regrowth mountain ash in the Melbourne Water North Maroondah Project (Image supplied by courtesy of Melbourne Water)

relatively uncommon occurrence. Thinning may be feasible in small areas but the effect on water supplies from a large catchment would be negligible.

6.6.1 Thinning of Mountain Ash Forests

Uniform commercial thinning of mountain ash is feasible up to about age 40. The bark is thin and sensitive and retained trees are easily damaged. There is an upper limit of basal area removal – typically around 50 % – after which epicormic leaves develop on the stems, thereby leading to degrade of the wood value of retained trees. For larger trees, thinning options become patch-cuts or cutting strips in which the trees are essentially clear-felled. In all cases it is hoped that the retained trees will occupy the growing space and that new growth will be captured on larger trees, thereby enhancing commercial and non-commercial values.

The effectiveness of thinning in enhancing water yields was investigated by paired catchment trials on young regrowth in the North Maroondah area of Melbourne's water catchments (O'Shaughnessy and Jayasuriya 1994). The work was carried out between 1976 and 1985, with monitoring continuing until about 1996. Hawthorne et al. (2013) revisited this work to look at the long term impacts. In some cases, monitoring of the stream flow weirs was reinstituted around 2008, although this was compromised by a major fire on some areas in 2009 (showing, once again, the difficulties of forest hydrology field work!). Methods included

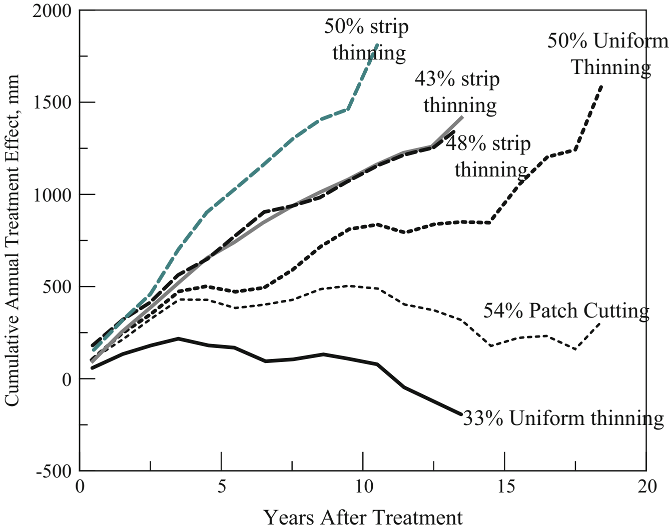

Fig. 6.16 A summary of the long-term cumulative effects of thinning on water yield, as presented by Hawthorne et al. (2013)

uniform thinning (33 % and 54 %), patch-cutting (80 m diameter patches, 54 % basal area removal), and strip thinning (35 m strips, 50 % basal area removal).

Figure 6.16 shows the cumulative effect of the various treatments up to 1996 (Hawthorne et al. 2013). All methods led to an initial increase in flow, and this increase was sustained for long periods in the heavier cutting. The water yield gains of light uniform cutting and patch cutting appear to have been dissipated by vegetation regrowth. The most effective thinning method over the first 10–20 years appears to have been strip-thinning. The peak increases in water yield usually occurred in the high runoff periods of spring.

Hawthorne et al.'s (2013) resumption of measurement in 2008 provided new insight into the long-term effects. In particular, yield from the strip-thinned catchments was well below the expected yield based on the control catchment. It was found that patch-cutting and strip thinning permanently changed the vegetation structure and composition, with growth of non-eucalypt species in the open spaces created by the cutting. In the strip-thinning, the width of the strips has greatly reduced as the crowns of the edge trees have expanded into the cut strips (Fig. 6.17). A comparison of pre-thinning and recent basal area has shown that the removed basal area has not been replaced, but that there is a large non-eucalyptus basal area. In general, the period of water yield increase ended when gaps created were filled with regrowth or non-eucalypt vegetation.

The results of Hawthorne et al. (2013) suggest that "one-off" thinning (as we know it) is not a feasible long-term strategy for increasing the water yield of mountain ash catchments. The heavier patch cuttings and strip thinning were most effective, but ultimately the gains were dissipated by resurgent regrowth of

Fig. 6.17 The strip-thinned Crotty Creek catchment about 30 years after cutting. At cutting the retained and cut strips were of equal width. The expansion of the retained trees into the strips is clearly evident (Photograph courtesy of M.F. Ryan)

eucalypt and non-eucalypt species. These treatments were probably effective initially because of their severe modification of the forest structure and this would not be acceptable in forests managed jointly for water and conservation. Uniform thinning may just meet community acceptability criteria in some (but not all) regrowth forests. This, however, presents only a limited opportunity.

The work of Hawthorne et al. (2013) has showed that thinning can create substantial and measureable increases in water yield for short periods. The hypothesis is advanced that, to sustain these requires a solid regime of regrowth control. Thus, for instance, strip thinning probably needs a 5-year follow-up in which tree regrowth is cut, further thinning occurs in the retained strips, and the strips are maintained in a low vegetation form (such as bracken). Community attitudes to this would, classically, depend on how desperately the community needs additional water. Such harvesting would certainly be controversial since the water harvesting needs would not be in accordance with conservation needs. The question has some relevance for cities such as Melbourne where, from time to time, fire has and will create large areas of mountain ash regrowth.

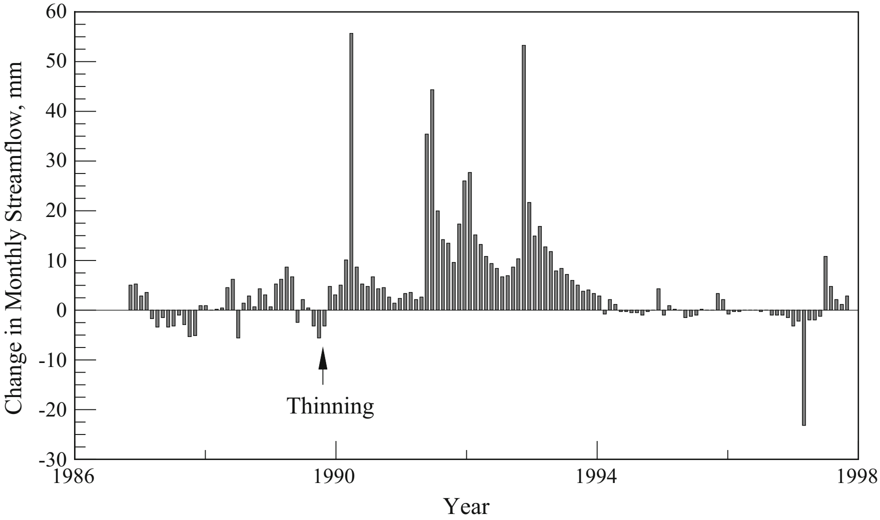

Fig. 6.18 Response of the Willbob catchment to selective thinning in November/December of 1989. In this 12 % of the basal area was removed (Data from Lane and Mackay 2001)

6.6.2 Thinning of Mountain Forest at Tantawangalo

The forest of the Tantawangalo paired catchment project was tall mixed species forest, dominated by *Eucalyptus fastigata* ("cut-tail"). In this the Willbob catchment was thinned to remove 12 % of basal area. The regrowth was thought to be in the order of 40–50 years old. The catchment was logged in December 1989 following a 4-year calibration period. The thinning led to a statistically significant increase in water yield. This increase in flows was followed by a diminution towards or below pre-thinning values. The thinning at Willbob catchment was fairly light (12 % of basal area removed) and hence there was little regeneration of eucalypts but improved non-eucalypt regeneration post-thinning. The increase in flow was of the order of 40 mm year^{-1} from thinning.

The response is shown in Fig. 6.18. It can be seen that the response was evident over about 3–4 years; after this the tree crowns expand to fill the liberated "growing space" and the response disappears. The thinning gave a 31 % increase in streamflow after the first 4 years. Streamflow then returned to the pre-treatment levels. Lane and Mackay (2001) note that the magnitude of the streamflow response for only 12 % basal area removal is "unusual".

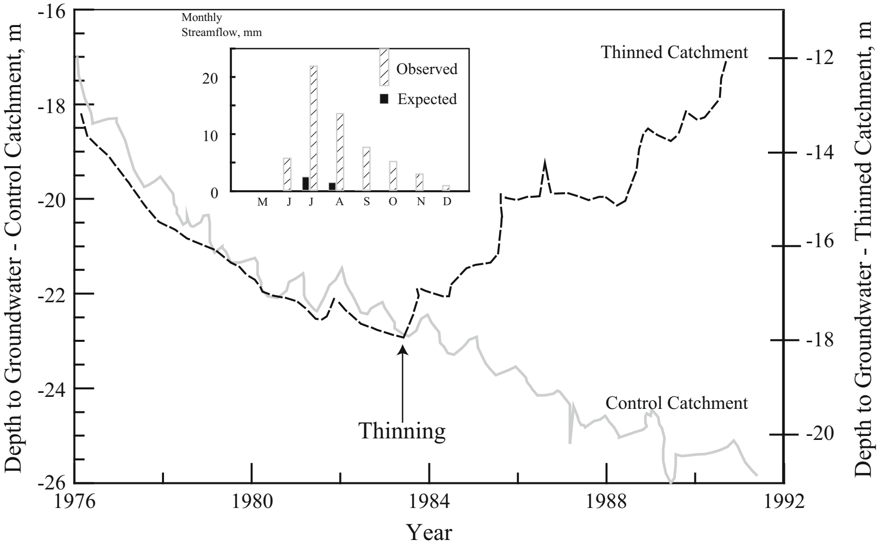

Fig. 6.19 Groundwater response to thinning at Yarragil (W.A.) catchment. The inset plot shows the observed versus the expected (from the control catchment) streamflow after thinning in 1990 (Data is from Stoneman 1993)

6.6.3 Thinning of Jarrah

Stoneman (1993) provides a detailed account of a heavy thinning of a jarrah forest on a 126 ha, forested catchment ("Yarragil 4L"). This used a paired catchment ("Yarragill 4X") as a control. The thinning reduced canopy cover, basal area, and stocking by about two-thirds. Figure 6.19 shows results from this project, indicating increased streamflow and increased slope water storage, with the observed groundwater recharge persisting over about 8 years. Streamflow increased from 0.5 % of rainfall (4.3 mm) to 7.6 % of rainfall (90 mm) 9 years after thinning. Streamflow duration increased, with the largest increases in streamflow in the wet winter months of June–October.

Stoneman and Schofield (1989) showed that thinning of the forests surrounding major water supply catchments that supply Perth could be a useful and economically attractive strategy. However there has been a marked lack of enthusiasm by the people of Perth for this approach.

Conclusions

For most of Australia's native forests, a simple runoff curve such as that of Zhang et al. (2001) appears to give a reasonable estimate of either evapotranspiration or streamflow. Eucalypt forests have relatively little storage

(continued)

capacity in the crowns and neither interception nor fog-drip appear to be processes of hydrologic importance. Mountain ash (and perhaps its near relatives) appears to have a water use which also depends on tree age. Thus, the yield from native catchments reaches a minimum about 40 years after regeneration, and then increases. There appears to be a difference in the response of forests regenerated by fire compared to those regenerated by logging. Other eucalypts that can grow in even-aged stands either do not appear to share this characteristic or show a reduced form of it. For dense forests, some gain in water yield may be achieved by heavy thinning but this appears to last only for a few years. Strategies such as strip thinning or patch cutting show only a short-term increase because of regrowth of non-eucalypt vegetation. Possibly longer term gains could be achieved by removal of such regrowth but this would probably not be socially acceptable.

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Chapter 7
Hydrology of Man-Made Forests (Plantations)

Abstract In Australia, plantations of both pine and eucalypt are major sources of wood. The Chapter examines various approaches to defining plantation water use including use of "Zhang" curves, the Holmes-Sinclair relationship, and "Nanni" curves. All of these lack an Australian experimental plantation base. The results from four paired catchment studies in Australia examining water use of radiata pine are combined to present a simple model of plantation water use relative to both pasture and native forests. The results show that plantation annual water use is dependent on both annual rainfall and age, and is variable on a year to year basis. When averaged over rotations, the water use appears similar to that of native forest at lower rainfalls and is intermediate between pasture and native forest at higher rainfalls. Plot measurements of eucalypt plantations on well-drained slopes give a similar picture. However when eucalypt plantations overlie groundwater close to the surface, plantation water use may be higher.

7.1 Introduction

Wood and other forest products are valuable commercial raw materials. The concept of using plantations rather than native forest for wood production in which the individuality of the wood piece is not a factor has a number of advantages. Firstly, there are large gains in efficiency of production. This has become particularly pronounced as the plantations tend towards a single product. Thus the entire sequence of wood production can be optimised to this end, with benefits in genetics, silviculture, and harvesting. Secondly, because the areas are dedicated to the plantation, there are fewer issues of interaction with other forest users. Thirdly, plantations can be developed in very large units, to support large processing investments.

The proliferation of plantations around the world has had its own share of issues. For the hydrologists these relate to the impacts of plantations on streamflows and competition for water resources with other land uses. Related to this is the question of how such plantations might be "regulated" or managed in accordance with established water management practices. The most common scenario is a complaint of downstream users about changed streamflow on small streams (usually

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diminishment of flow, occasionally other parameters). The issue hardly exists on larger streams because plantations are usually only a small component of the land use.

The usual question asked about the hydrology of plantations is “Will their presence decrease the volume of water available to downstream users?” Less commonly, questions such as “will the properties of streams emanating from plantations be altered?” are asked. These questions pre-suppose some sort of pre-existing standard on which to judge the hydrology. In Australia this has, *de facto*, become the hydrology of pasture-land.

In many cases the expectations that the presence of plantations will not alter the hydrology of a region is unrealistic. The trees bring benefits of high productivity. The use of water to produce this product reflects a resource input as part of the cost of having such a productive species. Thus, water should be included as a cost of production in the evaluation of economic benefits and dis-benefits. The difficulty with this is that the same is true for most other economic uses involving crops or pasture and water. In Australia there is a deficiency in similar information concerning the agricultural water use of crops. This makes it difficult to make valid comparisons or use economic models for evaluating costs and benefits in comparison with agricultural crops or other land uses.

7.1.1 What Is Different About Plantations?

It is a reasonable supposition that, in hydrologic terms, mature forest and mature (or at least older) plantations are probably similar in water use. However, in Australia the rationale for most plantations is a commercial return on investment. Hence for eucalypt plantations grown for pulpwood it would be rare for plantations to be kept for longer than perhaps 15 years of age. For radiata pine plantations, 30 years of age would be at the upper end of their “rotation.” At this time the plantations are felled and replanted. This has a large impact on their hydrology because much of the time the sites are not fully occupied by the tree species. Similarly, the trees usually have not reached physiological maturity at the time of their felling. It may be that if plantation trees were grown to older ages, their water use would be higher but this is irrelevant to Australian plantation hydrology.

7.1.2 Are All Plantations the Same?

The short answer is “no” but we usually do not have enough data to quantify the difference between Australian plantation species. In Australian economic terms, the only concern is for plantations of radiata pine and short-rotation eucalypts – other species tend to be of little areal extent or economic importance, or are found in such high rainfall areas that water use is not an issue.

Within the grouping of "plantations" we have a wide variation in thinning practices, weed control, stocking density, and availability of soil-moisture. It is likely that the differences within such plantations are likely to be as great as between species. Hence, for most purposes, generalisations about plantations are used. If the detailed hydrologic role of a particular type of plantation needs to be known, then plot measurement and/or modelling would need to be undertaken on stands of the correct composition.

7.1.3 Defining the "Water Use" of a Plantation

The absolute water use of a plantation is the water transpired by that plantation over a suitable time period – usually a year. This can be measured – albeit in directly – with sapflow instrumentation. More usually – and viewed as more important – it would be measured by the impact on streamflows to downstream users. Depending on the age of the plantation, the type of vegetation the plantation replaced, and rainfall characteristics this might lead to increased flow or decreased flow downstream.

Although the volumetric streamflow may be important, other properties of the stream emanating from a plantation may be affected. These include measures of stormflow (peak flow for a given rainfall being the most noticeable), low-flow behaviour, groundwater recharge, and water quality (particularly turbidity) of the affected streams.

7.2 Runoff Curve Approaches to Plantation Water Use

A runoff curve is about the simplest hydrologic model one can have. In these the annual water yield is predicted as a function of one variable – usually annual rainfall. A number of these have been cited in plantation water use debates in Australia and South Africa.

7.2.1 "Zhang Curves"

"Zhang Curves" were introduced in Sect. 2.5. These are a set of relations derived by Zhang et al. (2001) to categorise the difference between forested catchments and grassland catchments. Although they were not derived specifically for plantations, they have been widely used by Australian Government agencies as a "de facto"

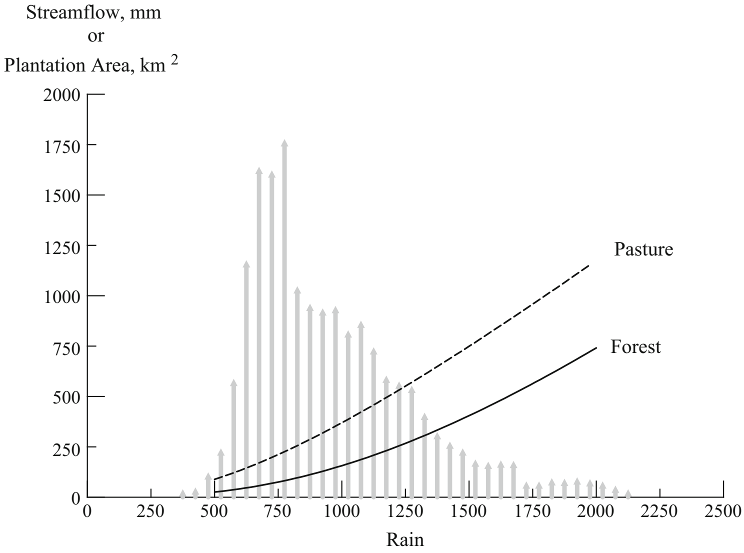


Fig. 7.1 Rainfall distribution of Australian plantations and the runoff curves (streamflow form) of Zhang et al. (2001) (The data are taken from Bren and McGuire (2011))

characteriser of the water use of a plantation compared to a pasture site. This is misleading because their use would only be valid if all the plantations were mature.

Figure 7.1 shows these relationships plotted against the distribution of Australian commercial plantations as a function of annual rainfall; it can be seen that the bulk of plantations are in the 650–1,500 mm annual rainfall zone where the difference between the grassland and forest curves is steadily increasing with rainfall. The curves do produce a reasonable estimate of the long-term impacts of having large areas within a catchment as mature forest, but this is not the same as plantations. Zhang curves have been criticised by several authors (e.g. Greenwood et al. 2008, 2011) as being too imprecise for water resource allocation and management purposes.

7.2.2 "Holmes and Sinclair" Relationships

These are shown in Fig. 6.3 and are detailed in Holmes and Sinclair (1986). The curves were an attempt to define a difference in water use between forest (often taken as plantations) and grassland and were widely discussed when presented. There is no numerical form of the relationships given. Occasionally these have been

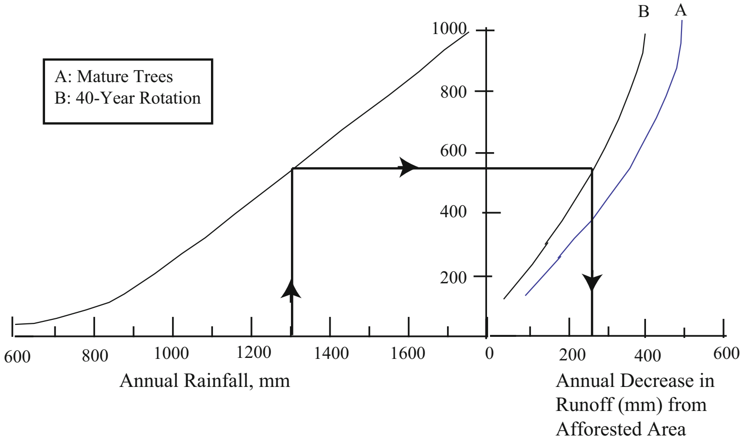


Fig. 7.2 Nanni Curves (Nanni 1970) as presented by Schulze and George (1987). This was an attempt to characterise plantation water use in South Africa

used to estimate apparent water use of tree plantations. The generic term "forest" makes little distinction between plantations and native forest. For practical purposes they have been replaced by the "Zhang curves" of Zhang et al. (2001).

7.2.3 Nanni Curves

For over a century the water use of exotic plantations has raised passions in South Africa (see Kruger and Bennett (2013) for an account of this). Following the extensive and pioneering work of Wicht (e.g. Wicht 1967), there was a need for a synthesis of the data. Nanni (1970) codified the results for pine plantations in a series of runoff curves which became known as Nanni curves in South Africa. Figure 7.2 shows the curves as presented (taken from Schulze and George 1987). Figure 7.3 shows these redrawn to meet modern graph conventions, together with the curves of Zhang et al. (2001) to facilitate comparison with Australia. Nanni curves are "generalised curves" combining many sources of information, and presented graphically rather than numerically. Their use is particularly for *Pinus patula* in South Africa. Their interest to us is a general similarity in the hydrology of regions in Australia and South Africa. We are unaware of any use of these in Australia. Within the limits of accuracy and a tendency for longer plantation rotations in South Africa, the results are not very different from Australian results presented in this Chapter. Schulze and George (1987) note that the approach is "robust" but "too simplistic" for complex decision-making.

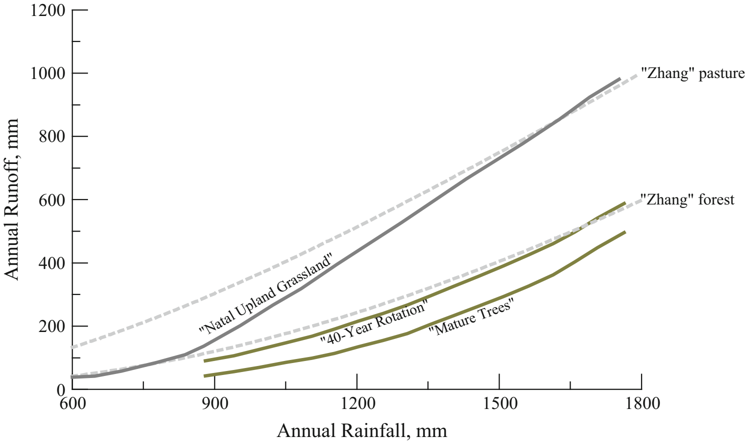


Fig. 7.3 Nanni curves, plotted on the more usual axes used in Australia (annual streamflow as a function of annual rainfall). The runoff curves of Zhang et al. (2001) are shown for comparison

7.3 Water Use of Radiata Pine on Well-Drained Sites

7.3.1 Absolute Water Use

Chapter 5 gave a case study of the Croppers Creek paired catchment study examining the formation of a plantation on a eucalypt forest site. Such a study gives specific information at a location. However this specificity may preclude them from providing a more general answer. More recently, data from four paired catchment studies examining hydrologic change associated with radiata pine formation has become available. Table 7.1 gives brief information on each of these. Three of these were on sites in which mature native forest was converted to plantation. The fourth – Red Hill – was on a site in which pasture was planted to radiata pine. The material presented is from an update of the analysis of Bren et al. (2006) which combines the data from all four projects. Three of the sites had a control native forest catchments and periods of time in which the treated catchments were under native forest.

Using data from all four catchments, the catchment water yield was defined as a function of age and annual rainfall. The relation obtained was:

$$Q = 0.0697 + 0.01545P + 0.000294P^2 - 9.196t \tag{7.1}$$

in which Q (mm) is the annual yield of a plantation of age t years and P (mm) is the annual rainfall. The age, t, ranges between 1 and 29 years. This is shown in Fig. 7.4; the effect of increasing transpiration with increasing age is evident. In combining data from four separate projects there is a lot of variation inherent in the processes. However the two factors of annual rainfall and age appear strong enough to overcome issues such as thinning or site variations.

Table 7.1 Information on four Australian paired catchment projects examining the water use of *Pinus radiata*

Attribute/ catchment	Red hill	Croppers Ck	Stewarts Ck	Lidsdale
Landcover change	Pasture to *Pinus radiata*	Mature Euc.forest to *Pinus radiata*	Mature Euc. forest to *Pinus radiata*	Mature Euc.forest to *Pinus radiata*
Catchment size, ha	195	46	18	9
Annual rainfall, mm	837	1,380	1,181	737
Period of data	1989-Continuing	1975-Continuing	1969–1993	1960–1995
Date of conversion	1989	1980	1969	1978
Reference	Webb and Kathuria (2012)	Bren and Hopmans (2007)	Nandakumar and Mein (1993)	Putuhena and Cordery (2000)

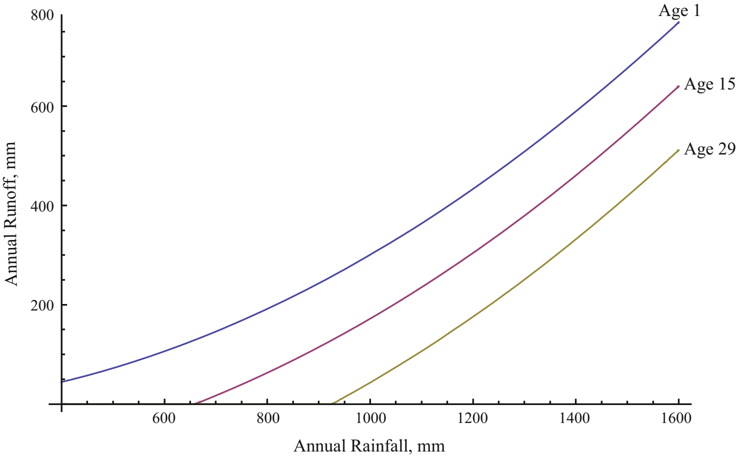


Fig. 7.4 Computed catchment water yield of radiata pine as a function of age and annual rainfall. This is an updated version of the work of Bren et al. (2006)

The “Zhang curves” of Zhang et al. (2001) are based on means. To allow comparisons with means a “Monte Carlo” simulation was made in which five rotations, each of 29 years, were made for the given mean annual rainfall. The rainfall was assumed to be normally distributed with the nominal mean and a standard deviation based on a regression of standard deviation as a function of annual rainfall. The results are shown in Fig. 7.5; the slightly irregular point

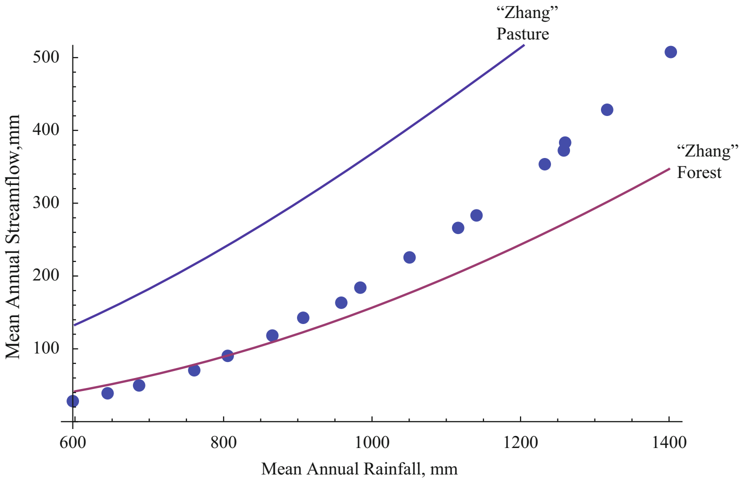


Fig. 7.5 Computed mean annual plantation runoff as a function of mean annual rainfall. The corresponding streamflow lines of Zhang et al. (2001) for pasture and forest are also shown. Irregularity of spacing of the mean points reflects the vagaries of Monte Carlo simulation

distribution is inherent in such Monte Carlo simulations. The line of points in Fig. 7.6 can be approximated by the equation:

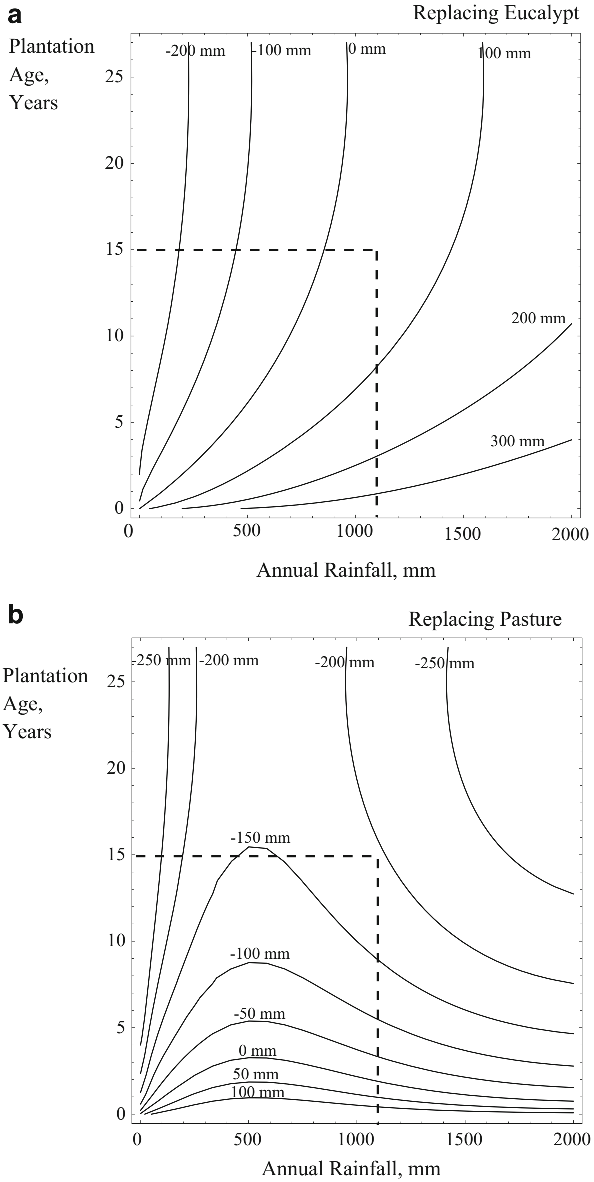
$$\hat{Q} = 33.4618 - 0.27457\hat{P} + 0.00433358\hat{P}^2 \tag{7.2}$$

The "hats" on the variables indicate that mean values are being used. Table 7.2 provides a table of values as a function of mean annual rainfall These include mean annual yield of pasture, mature forest,, and commercial radiata pine plantation, and the mean difference in water yield between pasture and commercial radiata pine.

Such information is worthy of comment. Firstly:

1. The paired catchment measurements are more or less totally empirical, and data are the result of four separate experiments.
2. To get such results is a long chain of planning, experimentation, data processing and computation involving several hundred person-years of work.
3. The use of means as a comparator (as in Zhang Curves) suppresses variation but requires much data and/or use of techniques such as Monte Carlo simulations.
4. Hidden in such means is a cyclic variation in water use as the plantation ages. In actual measurement there would also be the errors associated with measurement to further add "noise" to the data.
5. Although there has been much discussion in Australian media on plantation water use, and demands by planners for "detailed information for use in

Fig. 7.6 Relative change in water yield of plantations as a function of annual rainfall and age of the plantation. (**a**) For plantations formed on native forest. (**b**) For plantations formed on pasture sites. Box 7.1 gives examples of how these are to be read



planning", the information actually used by water planners has usually been very general in nature. It is also hard to find comparable Australian data for agricultural hydrology to allow comparisons of how the best economic return is to be obtained for the use of water.

Table 7.2 Mean runoff from native forest, plantations, pasture and the decrease in streamflow between pasture and plantation forest runoff as a function of annual rainfall

Mean rainfall, mm	Mean mature forest runoff, mm	Mean plantation runoff, mm	Mean pasture runoff, mm	Yield decrease on pasture sites, mm
600	42.9	24.7	132.9	108.2
700	56.2	53.6	183.9	130.3
800	74.5	91.2	240.9	149.8
900	98.1	137.4	303.1	165.8
1,000	127.3	192.2	369.7	177.4
1,100	162.2	255.8	440.0	184.2
1,200	202.7	328.0	513.5	185.5
1,300	248.7	408.9	589.8	180.9
1,400	300.1	498.4	668.5	170.0

7.3.2 Relative Change in Water Use

Usually in Australia the most interest has been in the relative change of water yield. Bren et al. (2006) used data from Croppers Creek, Lidsdale, and Stewarts Creek paired catchments to examine the relative change in flow when a plantation was formed on a native forest as a function of age and annual rainfall. The results are shown in Fig. 7.6a, b. Box 7.1 gives an example of the interpretation of these. The equation from which the figures were derived is:

$$\Delta Q_{euctopine} = 12.269P^{0.5} + 13.436t - 144.745t^{0.5} \tag{7.3}$$

where $\Delta Q_{euctopine}$ (mm) is the increase in water yield (mm) when an area is converted from mature native eucalypt forest to pine, P is the annual rainfall, and t is the age of the trees in years. This is an empirical relation derived from the change in flow on three paired catchment projects in which eucalypt forest was replaced by radiata pine. By using Zhang curves, we can convert this to an estimate of the change if grass had been converted to pine. Since Eq. 7.3 is an empirical estimate of the difference between pine and eucalypt, if we add back our theoretical estimate of eucalypt runoff and then subtract our theoretical estimate of runoff from grass, we get Eq. 7.4:

$$\Delta Q_{grasstopine} = \left[\frac{(1+\frac{2820}{\mathrm{P}})P}{\frac{\mathrm{P}}{1410}+1+\frac{2820}{\mathrm{P}}}\right] - \left[\frac{(1+\frac{550}{P})P}{\frac{\mathrm{P}}{1100}+1+\frac{550}{P}}\right]$$
$$+12.269P^{0.5} + 13.436t - 144.745t^{0.5} \tag{7.4}$$

where $\Delta Q_{grasstopine}$ is the estimated change in yield if a grassland catchment is converted to radiata pine. A negative sign is a decrease in water yield. The results show that planting eucalypt sites to pine increases streamflow except for low annual rainfalls and as the trees get towards the end of their rotation. Planting pasture sites to pine may give an initial increase in streamflow but soon leads to a decrease in streamflow.

Box 7.1: Using the Contour Plots

Consider the contour plots of Fig. 7.6a, b. Suppose we want an estimate of the change in yield on grass and eucalypt catchments for an annual rainfall of 1,100 mm and a plantation of age 15 years. Let's start with the "Replacing eucalypt" case (Plot A). Following the dotted lines at 1,100 mm on the horizontal axes and age 15 on the vertical axes, and interpolating between the contours, it comes out at about 50 mm (exact value 47.8 mm). This means that the plantation would yield about 50 mm more than native eucalypt forest. Following the same procedure for the grassland case (Plot B), we get about −195 mm (exact value −194.6 mm). The negative sign means a yield decrease. Since the error associated with these curves is in excess of 50 mm, one need not be too concerned with accuracy of interpolation.

7.4 Water Use of Eucalyptus Plantations

Unfortunately we do not have the luxury of paired catchment projects for studying the impact of eucalypt plantations in Australia. Hence most information has been gained from plot studies using a variety of instrumentation to measure evapotranspiration. Translation of this information to results in terms of streamflow tends to rely on intuition and comparisons with other standard methods such as the curves of Zhang et al. (2001). Table 7.3 provides estimates of the water use of eucalypt plantations selected from the work of Benyon et al. (2006). This work showed that the water use on well-drained hill-slopes is a function of age and annual rainfall and appeared to be in the 500–1,100 mm year^{-1} range.

Table 7.3 Water use of blue gum on drained slopes in which trees do not have obvious access to groundwater. Results have been selected from those of Benyon et al. (2006)

Plot No.	Annual rainfall, mm	Evapotranspiration, mm	Soil type
EG6	692	747	Sand
EG8	489	488	Sandy clay
EG9	640	680	Heavy clay
EG10	571	529	Medium clay
EG11	614	609	Medium clay

7.5 Water Use When Plantations Can Tap Groundwater

This became an issue in the 1960s when three separate studies showed groundwater recharge under mature pine plantations to be lower than recharge under grassland in plantations on a flat limestone plain landscape in south-eastern South Australia. Benyon (2002) reviewed tree water use in this environment and concluded that transpiration of rainfall falling on such plantations was inadequate to explain their survival and growth. He concluded that "where tree roots have access to highly transmissive, shallow, fresh aquifers. . .plantations appear to be net users of groundwater once full site occupancy is reached." The critical groundwater depth appeared to be around 10 m – below this the vertical lift plus the depth of roots exceeded the capacity of the trees to lift groundwater. In general, highly productive sites in this environment appeared to have good access to groundwater. Table 7.4 provides data from Benyon et al. (2006) quantifying water use of the trees.

Findings such as these tend to stimulate debate on who "owns" such groundwater, and whether tree growers should be taxed or otherwise restricted in the areas they use. However such debates tend to be uncomfortable for all parties because many restrictions proposed may equally impact on farmers. This also reflects that the tree water use tends to be high compared to grassland. Although the knowledge of agricultural hydrology is not good, it is generally known that pasture is a relatively low water user compared to other agricultural crops. Thus regimes taxing plant transpiration may well end up having large implications for farmers. It also raises the question of whether native forest owners should be similarly taxed for the water use of their forests.

Table 7.4 Water use of radiata pine (PR) and blue gum (EG) in which the trees have access to groundwater. Results have been selected from those of Benyon et al. (2006)

Plot No.	Annual rainfall, mm	Evapotranspiration, mm	Soil type
PR1	362	1,074	Sandy clay
PR2	747	1,414	Sandy clay
EG1	737	1,100	Sandy clay
EG2	656	790	Medium clay
EG3	667	1,169	Light clay
EG4	668	1,203	Coarse sand
EG5	717	923	Sandy clay
EG7	771	1,151	Sandy clay
EG12	604	848	Sandy clay
EG13	505	899	Sandy clay

7.6 Other Australian Plantation Species

From time to time other plantation species in Australia have caused concern regarding hydrologic issues. Farrington and Bartle (1991) looked at groundwater recharge beneath a *Pinus pinaster* (maritime pine) plantation on the Swan Coastal Plain of Western Australia. This was on the recharge area of a large aquifer (the "Gnangara Mound") which supplies the city of Perth (Western Australia). They used water balance computations, chloride balance computations and measurements of groundwater table rise. They found that substantially less rainwater infiltrated into the shallow groundwater compared to the native *Banksia* woodland which the plantations displaced. The relative difference in recharge between the two vegetation types increased during years of below-average rainfall. When averaged over the three methods, recharge during the 3 years was 114 mm (15 % of annual rainfall) and beneath *Banksia* woodland was 173 mm (22 % of annual rainfall).

The presence of the pines is only one factor in the hydrology of this groundwater area, with the industrial value of the pines also being important. The area is close to the suburbs of Perth and the viability of pine plantations close to urban areas is usually doubtful because of other issues.

Bubb and Croton (2000) used a paired catchment approach near Gympie in south-east Queensland to quantify the impacts on catchment water balances of major industrial plantations of *Pinus elliottii x Pinus caribaea var. hondurensis* on the coastal lowlands of south-east Queensland. A significant proportion of these plantations are regularly affected by extended periods of water logging. The study measured both outflows and impacts on groundwater. They found that major runoff was associated with years of above-average rainfalls and extensive water-logging. The results showed that rainfall and evapotranspiration were the major hydrologic processes. Few off-site impacts were identifiable.

7.7 Plantation Water Issues Around the World

7.7.1 Eucalyptus Plantations

The genus *Eucalyptus* has 800 or more recognised species, so that generalisations about their hydrologic properties are dangerous. However the tree is a robust grower and valued in many parts of the world for its hard, heavy wood and robustness in the face of climatic extremes. Controversy has arisen in parts of the world over the environmental and social effects of large-scale plantings – but these plantings in turn reflect the inherent productivity of these plantations. Bennett (2010, 2011) gives a good account of the history of the species around the world.

Calder (1986) reviewed the water use of eucalypts with special reference to South India and concluded that "indiscriminate speculation concerning the water use of eucalypts may be misleading; wide variation is to be expected." He noted that where plantations were formed on land hitherto used for agriculture, reductions in streamflow and drawdown of groundwater were to be expected. It was noted that some eucalypts – particularly *Eucalyptus tereticornis* – appear to be particularly adept at using groundwater and that this may lead to issues if the water is not viewed as a joint cost of production of the biomass. A common finding in such situations is that the water use of the plantations is about the same as the water use of the indigenous forest, but in most areas the indigenous forest was cleared long ago (and hence the need for wood).

A particular characteristic of some species of eucalypts appears to be the ability to extract soil moisture from deep within the soil strata. Thus eucalypts planted on agricultural land may transpire substantially more than the local rainfall initially. Calder et al. (1997) examined such a case and estimated a transpiration rate of 3,400 mm and an annual rainfall rate of 2,100 mm. The difference was accounted for by the reduction in soil moisture storage, with the trees transpiring water stored in deep layers of the soil. This has since been observed on a number of sites. It is probable that many other species also do this but it has been noted with eucalypts because of their wide-spread plantings.

A similar effect has been noted in South Africa (Scott and Lesch 1997) in which paired catchment techniques were used to examine the impact of planting on grassland *Eucalyptus grandis* and *Pinus patula*. Afforestation with eucalypts caused a statistically significant decrease in streamflow in the third year after planting, and the stream dried up completely in the ninth year after planting. In comparison, planting with pines produced a significant decrease in streamflow in the fourth year after planting and caused the stream to dry up in the twelfth year after planting. The drying up of the streams was expected from previous experience. As with the Australian experience, the reduction in streamflow appeared to be a function of both annual rainfall and age of the trees.

Of more surprise was the response after the eucalypt plantation was clear-felled at age 16 years. Although the logging was in 1985, flow did not resume until 1988 and then only as an ephemeral response to the largest storms. Some of this can be attributed to profuse growth of coppice shoots. By 1990/1991 streamflow had again returned to something approaching the grassland pattern of behaviour. An interpretation of this is that the eucalypts had "mined" soil moisture to the extent that it required effectively 3 years of soil moisture recharge to bring the logged site back to a similar amount of moisture to that stored under long-term pasture. There is no direct comparison in the paper as to whether the same effect was noted under pines, but observation on falling of pines at another research catchment showed that there was an immediate flow increase. Thus it is reasonable to assume that eucalypts were particularly adept at extracting soil moisture from the stored water in the catchment slopes. In this case the unsaturated zone extended for up to 45 m below the soil surface. Dye and Poulter (1991) postulated that eucalypt roots were able to penetrate to 30 m or more below the soil surface.

The Australian experience of eucalypt plantations formed on pasture sites has many commonalities in that when growth is sometimes higher than expected based on rainfall, there appears to be a decline in the moisture status of deep sediments. Growth may significantly decrease once the trees have exploited the available moisture. In some cases, the presence of stored soil moisture is critical to the economic success of the plantation.

7.8 Balancing the Hydrologic Benefits of Plantations

In many communities around the world, a shortage of forest products has been identified as an obstacle to be overcome. The result has often been forestry programs promoted for their environmental, biodiversity, carbon sequestration, bio-fuel, timber-production, and social benefits. However, the water resource costs are not always taken into account. Calder (2007) suggested some broad rules for examination of forestry projects to ensure that benefits outweigh costs. These include:

1. Application of the “best” science available in the evaluation of the projects.
2. Development of knowledge by field studies and modelling.
3. Communicating benefits and dis-benefits of plantations to policy-makers to avoid “unpleasant surprises” for the community.
4. Development of a “realistic” framework to allow examination of costs and benefits.

For man-made forests there is adequate data to make reasonable estimates of both the absolute water use and the change in water use compared to the existing hydrology. Ideally such estimates should include examination of the costs and value of the water, with this water being valued as a joint factor of production in the forestry program. The same criteria should be applied to competing agricultural crops.

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Chapter 8
Impacts of Burning on Catchment Hydrology and Management

Abstract The role of fire in Australian forest hydrology is becoming appreciated. Fire affects forest hydrology in many ways. Firstly it modifies the existing forests. For some species including mountain ash it may completely kill off mature forests, leading to massive regeneration. This has a characteristic forest water use as a function of age. Other species may suffer crown degrade, which in turn leads to the development of epicormic crowns in which transpiration is less regulated. Fire leads to increased water repellency and sediment supply on catchment slopes. This appears to be associated with short-lived but unusually high flows of massive erosion capacity. As such, fire is likely to be an important force in the formation of stream networks.

8.1 Introduction

It is something of a paradox that in a book on Australian forest hydrology, the section on the role of forest fires is small; it is likely that future historians will be surprised how long it took Australians to realise the pivotal role fires have played in the hydrology and geomorphology of the country. And the interesting thing is that, in many Australian forests, until it is burnt, you don't see the impacts of past fires because they are hidden under the dense understorey. When a fire strips this away you can suddenly see landslips, gully erosion, and the role of past fires in forming the landscape. Similarly, one realises that past fires have been a determinant of the current forest cover. Possibly some of the largest flows the catchment has generated may have been due to the dual processes of black charcoal generating large thunderstorms combined with the water repellancy of the burnt catchment. These processes lead to extremely high peak flows which, in turn, entrain the freely-available sediment.

Our examination of the role of forest fire in Australian forest hydrology will use the burning of the Croppers Creek hydrologic project in 2006 as a case study of what happens when a small catchment is burnt. We will then extend this, via a second case study to examine what happened when many small catchments were burnt simultaneously. In our study of Croppers Creek, the most spectacular changes, the highest peak flows, and the largest volumes of soil movement were all associated with a forest fire. Subsequently the heavily burnt Clem Creek

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catchment displayed elements of the debris flow phenomenon described in Sect. 8.3. And yet, 3 years after the fire, the bare earth deposition zones on the small flood plains were once again densely vegetated, the riparian zone had recovered, and the only obvious sign of the past fire was the ragged crown of the burnt, veteran eucalypts. It was back to business as usual for Australian catchment hydrology!

8.2 Burning of the Croppers Creek Hydrologic Project in 2006

In 2003 and 2006 Victoria had "megafires" in which each fire burnt over 1 million ha (Fagg et al. 2013). The 2003 fire burnt within a few kilometres of the Cropper Creek project area. Tragically and not far away, a fire-fighter was killed by a "freak flood" in the fire area (Box 8.1); this gave a clue to a new and developing area of forest hydrology. The 2006 fire, started by lightning in the Black Range a few kilometres from the project, burnt the entire project area on Day 6 of the fire. The fire intensity in the eucalypt catchments was later assessed as moderate but the intensity in the pine plantation in Clem Creek catchment was thought to have been high (as judged by a later Landsat Imagery analysis and the observed change from white to black smoke at the time of burning), reflecting the high fuel load associated with plantations. Ironically there had been an on-site meeting a month beforehand to initiate planning for the harvesting of the pines, but the fire got to the pines first. The area had been under drought conditions for some years.

The fire may have been of moderate intensity but it was indeed thorough; all equipment was consumed and weirs were put out of action; Fig. 8.1 illustrates some facets of the burning. Unfortunately all surrounding areas also burnt and so there was nothing left to act as an unburnt "control" catchment. It was known at the time that the project area was likely to burn and it was hoped that most equipment would survive the fire and continue recording during the passage of the fire. This was, in hindsight, supremely optimistic.

Subsequently the weirs were rebuilt although this took about 6 months. At the time only Clem Creek had flow, and a temporary recorder was located on the wall to ascertain if the flow from the burnt catchment had a diurnal variation (the response from the burnt catchment was erratic flow, but there was no evidence of a diurnal variation). At the same time various studies, reported below, were initiated. These included nutrient exports, monitoring of the fire and fire recovery using satellite imagery, monitoring of channel effects and, far as possible, measuring stream flow.

Bren (2012) gives a quantitative account of the fire recovery. To generalise:

1. Before the fire, surface runoff hardly figured in hydrographs. For 1–2 years after the fire it became an occasional but major feature – particularly in the severely burnt pine catchment.

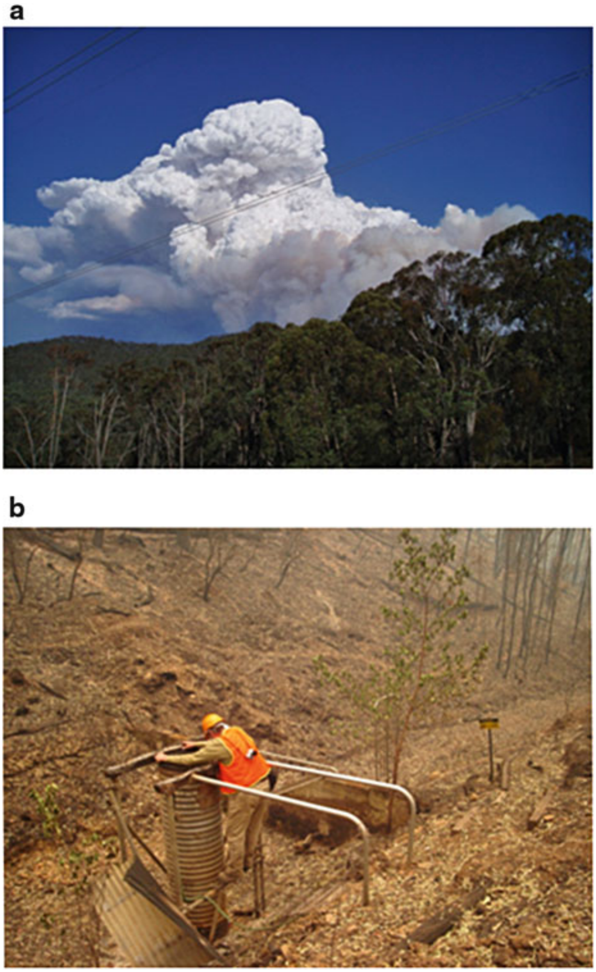

Fig. 8.1 (**a**, **b**) Burning of the Croppers Creek paired catchment project in December, 2006. (**a**) This is what your paired catchment project looks like as it is burning. The smoke changed from *white* to *black*, indicating a higher intensity when the pine plantation on Clem Creek burnt (Photograph courtesy of John Costenaro). (**b**) What happened to our weir? Inspection of the burnt Ella Creek Weir after the fire in December 2006. The rocky nature of the slope soil is evident with the vegetation removed

2. The fires introduced a new hydrograph form to the Croppers Creek records – the "spike hydrograph". These are discussed in detail below.
3. Death of vegetation led to a cessation of the summertime diurnal variation which then returned over the next few years.
4. Other than the influence of spike hydrographs, the rate of recession of the catchments after rainfall was unaffected, suggesting that the fire had did not change the sub-surface hydrology.
5. The effects of the fire lasted about 3 years. After that the catchment hydrology appeared the same as before.

8.2.1 The Dreaded "Spike Hydrograph" and Other Burning Effects

Figure 8.2 shows examples of these hydrographs in which flow rapidly increased, reached a far higher flow level for a given rainfall than hitherto experienced, and then rapidly receded. The analysis of Bren (2012) indicated that these were effectively an addition to the normal hydrographs; perusals of past hydrographs collected at Croppers Creek could find no evidence of them occurring before the 2006 burn. Brown (1972) noted their presence in his study of the impacts of bushfires in the Snowy Mountains. Figure 8.3 shows soil erosion associated with such spike flows. These occurred throughout the year and appeared to be associated with bursts of high-intensity rainfall; in most cases the spike flows were an "add on" to the otherwise expected storm hydrograph.

A previous study detailed in Sect. 4.3 helps provides some interpretation of these. Bren (1979) generated "pulses" of water by suddenly providing more water to a point at a channel in equilibrium; effectively this was a discontinuity in flow at a channel cross-section. It was found that this discontinuity would travel downstream, but the magnitude of the discontinuity was slowly dissipated by channel storage effects. The process is commonly seen when a flood from upstream rainfall propagates in a dry channel as a "wall of water" (actually a wall of water, sediment, and entrained larger material). The hazard is well recognized in sports such as "canyoning" and has led to a number of fatalities. Using this model suggests that the spike hydrographs were generated by a short-lived torrent of water entering the stream from one or a few points of entry well-upstream from the measuring weir.

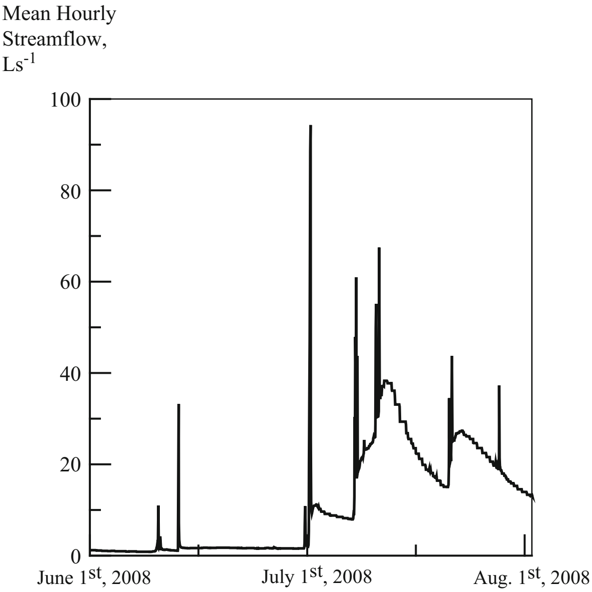

Fig. 8.2 Hydrograph from Clem Creek catchment about 18 months after burning. The vertical "spike hydrographs" are clearly evident. We could find no similar examples of these before burning

Fig. 8.3 Soil erosion at Croppers Creek about 1 year after burning. Such erosion tended to be associated with "spike flows"

The buffering capacity of the stream channel accounts for the relative smoothness of the measured stream hydrograph. As experienced by the weir or the trapped fire-fighting crew, the hydrograph is a discontinuity in flow (a "wall of water mixed with boulders and logs") moving downstream. To an observer downstream, there would be no indications of a "fast rising flow" until the discontinuity in flow was at the point of observation.

Satellite Analysis of Burning Impacts Sever, Leach and Bren (2012) used Landsat 5 TM imagery and the Normalised Difference Vegetation Index (NDVI) to assess the pre-burn state and the post-burn recovery of all the catchments. A flatter area of unburnt native forest north of Croppers Creek was used as a "control." The results show:

1. Both the control area and the eucalypt catchments at Croppers Creek were experiencing stress as a result of the prolonged drought at the time of burning. The plantation catchment did not appear stressed relative to the eucalypt catchments, indicating a physiological difference in the ability of radiata pine to store water in its foliage.
2. Fire appeared to have a much greater effect on the health of the eucalypts on the north facing slopes (which, in the southern hemisphere, face the sun). Betsy Creek appeared less affected by the drought and the fire than neighbouring Ella

Fig. 8.4 Mean values of NDVI on a non-burnt control catchments and the burnt Croppers Creek eucalypt catchments (From Sever et al. 2012)

Creek. This, in turn, predisposes the north-facing slopes to higher fire intensities – a factor of some importance in subsequent erosion.

3. The most dramatic change in NDVI was caused by the destruction of the plantation on Clem Creek. The changes in the NDVI values of the burnt eucalypt forest were modest and the forest recovered.

Figure 8.4 shows the mean values of NDVI taken from Sever et al. (2012). The satellite image analysis also showed the rapid recovery of Clem Creek after planting.

The study is particularly valuable in providing insight in that it suggests that although the fire impacted on the eucalypt catchments, the impact was modest compared to that on the plantation catchment in which the vegetation was totally destroyed, and the surface property of the soils impaired by the heat of the burn. The data also correlates well with other observations suggesting a 3 year recovery period. The relative health of the radiata pine (as instanced by the NDVI values) compared to the eucalypt forest provides some indication of why it is such a successful plantation species.

Overland Flow, Erosion, and Water Quality Smith et al. (2011a) examined runoff generation and sediment exports from the Croppers Creek catchments after burning. This found that the combined effect of fire and salvage harvesting in the pine catchment caused a substantial increase in runoff compared to runoff from this catchment in the pre-burn conditions and runoff from the burnt eucalypt catchments. Post fire maximum suspended sediment concentrations from fixed-interval sampling greatly exceeded pre-fire values for both eucalypt and pine catchments. Soil water repellency was more extensive in the harvested pine catchment than the adjacent eucalypt catchment, reflecting higher burn severity and less shading. Runoff modelling suggested that log drag-lines caused during cable harvesting

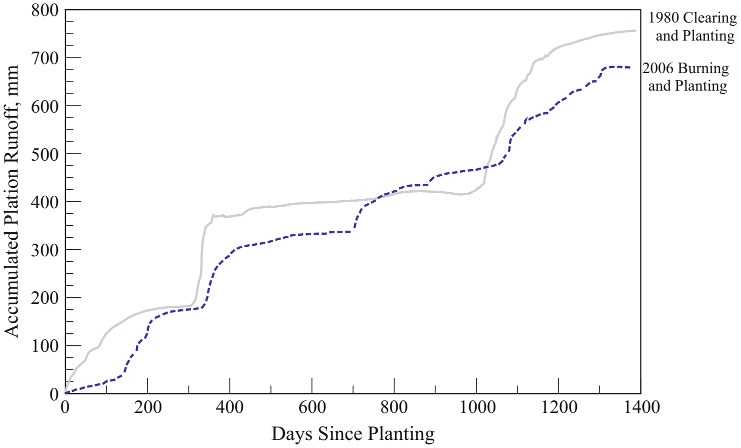

Fig. 8.5 Cumulative change in flows after burning and replanting at Clem Creek the first (1980) and second time (2007) around. It can be seen that, within the limits of error, the results are similar

acted as an extension to the drainage network. The combination of surface smoothness, water repellency, and enhanced drainage opportunities probably explains the generation of spike flows.

The Difference Between the Pine and Eucalypt Catchment After the fire the pine catchment was salvage-logged and replanted. This involved dragging of logs across the catchment surface which, in some cases, created channels that overland flow could pass along to the stream. Figure 8.5 shows the cumulative change in streamflow as a function of days after the date of planting for both the first time around (1980 planting) and the second time (2007 planting). The results suggest a surprising consistency between the two sets of data in the difference in flows between the eucalypt and the pine catchment.

In Summary The impacts of the burning of the Croppers Creek catchments show massively increased erosion associated with episodic events. This was particularly evident on the heavily burnt radiata pine catchment (Clem Creek), but the same effects were evident on all catchments. Burning was more pronounced on the northern slopes. The effects of burning of the catchments appears to be a representative sample of burning effects found across Victoria.

Box 8.1: "Spike" Streamflows Can Be Lethal

It was during the first of the "megafires" in 2003. A group of fire-fighters were returning home after a day on the fire-line about 34 km south-east of Croppers Creek. Their four-wheel-drive vehicle was crossing a bridge over a small stream when a "two metre wall of water and mud" hit the vehicle. Fire-fighter

(continued)

Box 8.1 (continued)

Cheryl Barber-Frankhauser was unable to escape the torrent and was drowned. Her two companions managed to hang on to the back of the vehicle. The runoff/debris flow event was thought to have been created by a stationary thunder-storm cell since nearby gauges registered little or no rainfall. A hydrologist at the inquest is quoted as saying "it is so far above the limit I can't tell if it a one-in-100, one-in-200, or one-in-500 year event; maybe we'll never see this sort of thing again".

Subsequent study of runoff events associated with subsequent fires have shown that generation of massive peak flows that far exceed the traditional runoff analysis of textbooks is a part of the overall fire effects. The causal storm frequency may often be in the 1:2–1:5 year range. Because of the large amounts of sediment available the resultant flow is a turbulent slurry of water and sediment with larger stones entrained.

8.3 What Happens to Hydrology When a Catchment Is Burnt

Figure 8.6 shows the response of streamflow in a small catchment to burning; this is extracted from the work of O'Loughlin et al. (1982). Prior to the fire there was a clear diurnal variation. At the time of burning the diurnal variation ceased because of destruction of the forest canopy. The increase in flow is due to the vadose zone "collapsing". Thus the presence of the trees created an upward capillary force,

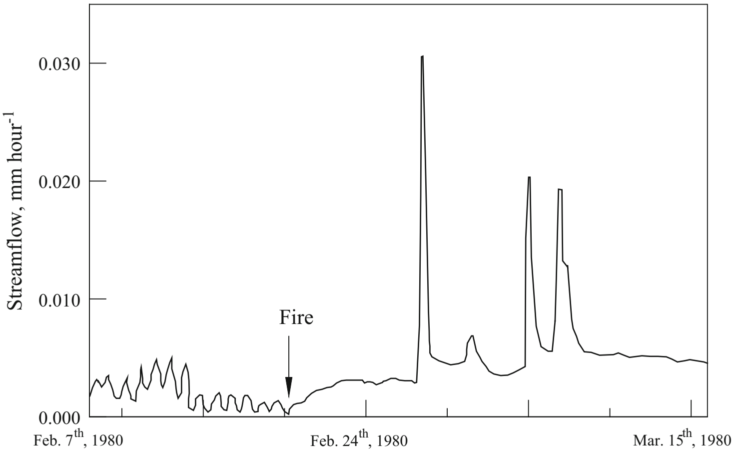

Fig. 8.6 Change in flow when a catchment is burnt from O'Loughlin et al. (1982). In this project – the "Bushrangers experiment," a small gauged catchment was deliberately burnt by a high intensity fire. The loss of the diurnal variation and the increase in streamflow is clearly evident

leading to a higher concentration of water in the unsaturated case than could occur without these living things. When the fire occurred, presumably this upward tension dissipated and this water "fell" back to groundwater. This led to a reduction in soil water tension and, in turn, an increase in streamflow directly after the fire. Such an increase is occasionally noted by fire fighters.

8.3.1 Soil Heating and "Brick" Formation

The first Australian project on this (Beadle 1940) noted that maximum temperatures rapidly decrease with depth into the soil, and that high percentages of water in the soil greatly retarded the conduction of heat. Beadle (1940) noted that there was not a redistribution of water in the soil after fire; the water would vapourise and then was lost to the atmosphere rather than passing downwards and condensing. Subsequently a large number of papers have continued down this pathway noting a plethora of soil-related changes associated with burning, but confirming the results of Beadle (1940).

Certini (2005) provides a review of the effects of fire on the properties of forest soils and notes that the effects are functionally dependent on burn severity. Severe fires remove organic matter, reduce nutrients through volatilisation and ash loss in smoke, and change the physical properties of the upper layers. This sometimes includes formation of small, brick-like aggregates due to extreme soil heating (Humphreys and Craig 1981). The impact on the physical structure of soil appears variable, and appears to range from breaking down of the structure to sometimes stabilising the structure by strong heating; Certini (2005) notes the large variation in effects between different soils. These impacts may affect the long-term productivity of the soil. There appears to be two important hydrologic effect of this – the soil often exhibits enhanced water repellency (i.e. no longer accepting infiltrating water at the soil surface), and the soil provides a large supply of non-cohesive sediment for mobilisation in hydrologic events.

The most recent Australian work (Nyman et al. 2013) characterises the post-fire soil as a two layer system. The upper layer is a shallow, highly non-cohesive layer of ash, charcoal, and heated soil overlying the pre-existing soil matrix. This finite layer is very easily transported and enables significant (and sometimes spectacular) erosion events, including debris flows generated by hillslope runoff. This is depleted and reincorporated into the soil matrix during the recovery period. The generation of this non-cohesive layer is a function of fire severity.

Box 8.2: Measuring Water Repellency of Soil

If a drop of fluid is placed on a block of soil then ultimately wetting will occur and the drop will disappear. By either observing the time taken or changing the characteristics of the fluid, a measure of soil repellency can be obtained. The traditional method is to observe how long it takes for a water drop to penetrate into the soil. However this can take many hours, and is unsuited for field studies. An alternative method is the application of increasing concentrations of ethanol (in drop form) to the soil until infiltration occurs within a standard time (usually about 3–10 s). At this concentration the aqueous ethanol drop has a sufficiently small surface tension to overcome the surface water repellency restriction to infiltration. This is referred to as the "critical surface tension method" (see Doerr 1998). The units are those of surface tension (Nm^{-1}). Most workers use variants of this technique with the aim of getting a consistent and reproducible relative measure. Measuring of water repellency is tedious and difficult to automate, and methods vary depending on the spatial scale of measurement. Water repellency can be measured as a point property or it can be measured in terms of the effects on the infiltration on a larger soil block. Obtaining reproducible measurements requires a lot of practice. See Nyman et al. (2014) for an example of such a study.

8.3.2 *Water Repellency and Soil Infiltration*

The concept of water repellency is apparent on surfaces such as a freshly-polished car, in which the surface tension of a drop of water combined with a non-wettable surface (due to car wax) means that the water sits as a deformed spherical drop on the surface). Measurement is outlined in Box 8.2. The effect in forested catchments was first noted in the US in the 1960s and has since been observed in many countries, both under natural conditions but particularly in association with forest fires. Most soils exhibit some degree of water repellency at some time, but in the hydraulically rough and occluded environment of a forest floor, this is hardly noticeable. Doerr et al. (2000) note that the concept is relative in that there is always some attraction between a liquid and solid. It is commonly accepted that the repellency is due to vapourised organic compounds deposited on the soil as a result of the fire (De Bano 2000). Such hydrophobicity may be developed at depth within the profile as well as the surface, leading to a perched water table formed by infiltrating water. However fire does not inevitably lead to hydrophobicity.

Crockford et al. (1991) examined water repellency in a dry sclerophyll eucalypt forest. They found considerable variation both over time and between sites. In long periods of consistently wet weather, water repellency would disappear. A period of hot, dry weather would cause it to reappear. Repellent soil samples were more repellent to water of throughfall origin, and even more repellent to stem flow than distilled water. The repellency response also varied with the type of vegetative cover present. These observations have been mirrored in other studies around the world.

Water repellency is commonly viewed as a transient condition, although it has been noted as lasting for up to 6 years. Hydrophobic soils can still become wet; it is thought that this partly reflects vapour movement, variability within the soil, and that even a hydrophobic soil will not repel water completely. As soil becomes wetter, the repellancy in general reduces. Many forest soils exhibit water repellency without forest fire, so the presence of fire is better viewed as enhancing water repellent tendencies rather than causing it.

Working on burnt and unburnt forest areas in Colorado, Larsen et al. (2009) attempted to distinguish between the development of soil water repellency, the impact of ash as both a water absorber and sealer, and the removal of the cover of litter and plants by a fire. This involved a range of experiments; these included raking of material off hillslopes and laboratory measurement of created soil surface with a rainfall simulator. Their results showed that (i) post fire sediment yields were primarily due to the loss of surface cover rather than fire-enhanced water repellency; (ii) surface cover is important because it inhibits soil-sealing by raindrop splash, and (iii) presence of ash temporarily prevents soil sealing and reduces post-fire runoff and sediment yields.

Workers on fire effects have traditionally warned scientists against "generalising" from results and extrapolating results from one forest type to another. This appears to be still the case. The role of hydrology science in the future is to derive more generally-applicable models of fire effects.

8.3.3 Runoff from Water Repellent Catchments

If, for instance, an entire third or fourth-order catchment became completely water repellent and was subject to a large storm, then simple arithmetic suggests peak flows of a magnitude (fortunately) rarely or never hitherto experienced. These would be associated with massive erosion and channel formation. That this does not (commonly) happen suggests that catchment water repellency, although an important process, is not always widespread or effective in stopping infiltration, and its impacts are reduced by other factors. These include that the surface of a forested catchment is still hydraulically rough and infiltrating so that there are usually few opportunities for mass overland flow, that soils vary in their susceptibility to increased water repellence, and that there is an element of probability that a storm of the required magnitude will occur at a time when burnt soils are susceptible to runoff/debris flow formation.

Nyman et al. (2010) studied exactly this on a burned catchment in south-east Australia. They found, using plot studies, that 60–70 % of areas were water repellent, but that macropore infiltration dominated the processes. Thus water would effectively be stored in the upper layers of the soil and not contribute to runoff. As discussed in Sect. 4.4, the large-scale properties of the forested slope dominated the small scale properties. Similarly Sheridan et al. (2007) followed water repellence, infiltration capacity, infiltration-excess runoff generation on the slopes of a burnt and unburnt mountain catchment. They found in “wet forests” the infiltration capacity of the slopes remained high, and that although a rainfall simulator could generate infiltration-excess overland flow, this would normally be infiltrated a short distance downslope. They concluded that most infiltration-excess overland flow reaching streams is generated within a few meters of the stream edge; this observation is consistent with those at Croppers Creek above. Measurements in the unburnt areas showed large seasonal oscillations in water repellence and high variability.

More recent work (e.g. Nyman et al. 2011, Smith et al. 2012) has shown that “dry forests” (typically on northern slopes, shallow soils) tend to behave differently. These are strongly affected by water repellence and may produce up to 50 % runoff during heavy rainfall soon after burning. There is an interesting but unproven hypothesis that resultant fire-induced erosion may be an important (and unappreciated) feature in the geomorphic formation of forest stream networks.

Ebel et al. (2012) looked at the hydrologic conditions controlling runoff generation immediately after wildfire in Colorado, USA. They found that runoff generation processes were controlled by and highly sensitive to the ash thickness and its hydraulic properties. This ash layer, with a mean thickness of 1.8 cm, stored most of the rainfall, effectively acting as a porous layer. The hydrologic response to two rainfall events some 10 days apart showed that runoff generation was predominantly by a saturation-excess mechanism for the first storm, in which there was little transmission of water through the ash layer. The second storm process was infiltration-excess runoff. The contributing area was not static for the two storms. They note that the ash, when viewed as a porous layer, has a substantial buffering capacity.

It is concluded that fires, may change the basic behaviour of the infiltrating forested catchment, may add additional storage material in the upper surface, may allow the generation of substantial runoff close to the stream, and may provide large amounts of non-cohesive material that is easily mobilised by water movement. This combination of factors is responsible for occasional, very high (“spike flows” which consist of water mixed with sediment. There is still much to be learnt about the flow generation processes and the role of fire in these.

8.3.4 Erosion from Burnt Catchments

The high flows generated from a burnt catchment are transient and usually unlikely to be viewed by anyone. In contrast, erosion from burnt catchments may lead to gullying on catchment slopes (Fig. 8.7), with large accumulations of debris along

Fig. 8.7 Gullying on catchment slopes a year after burning, Spike flows can exert a heavy hydraulic load on stream beds. The vigorous regrowth of slope vegetation can be seen

streams and in downstream areas (Fig. 8.8). The Croppers Creek experience was that:

1. Because of water repellency, very high streamflows were generated occasionally, and
2. These streamflows would lead to bank and channel erosion because they were far higher than the armouring of the channel could resist.
3. This material (soil and smaller rock particles) would deposit as alluvial fans or as outwash material on small flood plains, and
4. Over the ensuing year the alluvial fans would be "colonised" by riparian vegetation and become invisible.

The high flows and high debris load can be and are detrimental to human structures and values, but in the Australian environment are probably best viewed as "nature at work".

Nyman et al. (2011) amplify this conclusion by providing a systematic documentation of some high-magnitude post-fire erosion events observed in upland catchments in Eastern Victoria. The results showed that 13 out of the 16 high-magnitude erosion events were runoff-generated debris flows in which a high peak flow had enough energy to entrain sediment. These occurred in dry eucalypt forest burnt at high or very high severity in steep headwater catchments. Events were

Fig. 8.8 Sediment accumulation after burning. New sediment has raised the old stream bed by a few hundred millimetres and formed an alluvial fan. This is being recolonised by ferns. Later high flows would remove much of this. Small streams in mountain environments are very dynamic in their behaviour and this is reflected in large "excursions" in water quality

triggered by intense, short duration rainfall events (storm intensity of 35–50 mm hour^{-1} for 30 min). These are common "summer thunderstorms" in this environment (see Fig. 2.12 for an example), and are usually of limited extent spatially. Fire-enhanced water repellency results in high rates of infiltration-excess overland flow, while the burnt soil provides an abundant supply of easily-detached soil and ash to initiate debris-flows on the hillslope. Runoff-generated debris flows were not recorded in wet or damp forest types, suggesting that this process is unlikely to operate in these forest environments. The Cropper Creek experience is probably best viewed as a sample of what nature can provide but at the lower end of the spectrum. The Croppers Creek area is not usually classed as "dry" but because, of the pines, the local fire intensity was higher than might otherwise have been expected. Similarly, although at the time we viewed the sediment movement at Cropper Creek as "impressive", the flow did not have enough energy to move rocks of the size shown by Nyman et al. (2011). Figure 8.9 shows a debris-flow from his findings.

Nyman et al. (2011) conclude that runoff-generated debris flows in dry eucalypt forest are an important process to be considered during post-fire risk assessment. This probably understates their role as an important and unappreciated geomorphological process forming the Australian mountain landscape. Part of the reason

Fig. 8.9 Example of a debris-flow generated after a wildfire in 2009 near Kilmore (Victoria). The debris flow occurred 2 months after burning (Illustration from Nyman et al. (2011))

for the lack of appreciation of this process is the rapidity of vegetation growth on the geomorphic features generated. This makes them difficult to see by the casual observer unless they visit the site soon after the event. It was also of interest to note that although in the past, the possibilities of enhanced erosion have often been cited in the media as objections to forest harvesting or planned developments, the post-fire movement of tens of millions of tonnes of sediment into Victorian waterways was hardly commented on by the Australian media.

8.3.5 Water Quality Impacts from Burnt Catchments

The Croppers Creek post-fire experience was an occasional massive degradation in turbidity or sediment load, and a more general water quality decline for a few years after the fire. There was impairment of a number of water quality measures – particularly oxygen levels and associated stream temperatures due to increased exposure of the stream to the sun. After about 3 years the water quality had returned to close to its long-term values. This experience could be viewed as typifying the water quality response of small catchments.

Smith et al. (2011a, b) made a comprehensive review of the impacts of wildfire on water quality in forested catchments. In general, the major effect was on sediment exports, with (sometimes) massive increases and low oxygen levels in the water. As shown by the Croppers Creek experience, extremely high sediment loads were reported. Their report noted that ash-beds form a large store of particulate carbon and salts (notably calcium, magnesium, chloride, sulphate, and bicarbonate), nutrients (nitrogen and phosphorous), trace metals, and other contaminants. Further, there are many processes which might, hypothetically, occur. In practical terms, the increased amount of suspended sediment is the most commonly reported impact on water quality. Doubtless other effects occur, but dilution effects mitigate these. Where fires burn over mineralised areas such as north-eastern Victoria, it may be possible to detect small increases of metal such as iron, arsenic, chromium, lead, and copper (Smith et al. 2011b).

Fires contribute to higher nutrient loads, and where the fires are widespread then the effects may also be widespread. Thus, the extensive 2006/2007 fires in Gippsland burnt 34 % of the catchment area for the Gippsland Lakes. This was followed by a "blue-green algae" outbreak in these lakes attributed to the high nutrient load (Cook et al. 2008). In particular, the nitrate load was four times the average load and twice that of the second highest recorded load. The outbreak was associated with flood flows (see Sect. 8.5) and a turbidity plume in the lakes visible on satellite imagery.

Export of other nutrients was more variable. In Australia, the worst bushfires occur during long periods of drought at times when streamflows are non-existent or low. Sometimes there is simply not the "carrying water" to export large amounts of nutrients and sediment to downstream rivers and dams. Ash deposits may form a large store of particulate carbon and contain many nutrients and perhaps potential contaminants.

In general, fires probably perturb any measures of water quality emanating from a forested catchment. Usually the water will be rendered unusable for drinking and for most other purposes and the effect may last (intermittently) for some years. If the fire is unusually large then the effect may impact on major dams. A good account of the impact of fires on the water supply of Canberra is given by White et al. (2006). The most common pollutant is sediment, but nutrient levels may occasionally cause issues. More commonly, because of the low streamflows involved, the dilution effects as fire-affected water passes into larger stream networks, and the fact that most forest fires are small, the water quality issues with fires are commonly local and small.

Associated water quality changes may impact on aquatic populations, with the impact greatest in the fire area and diminishing with distance downstream. Thus Lyon and O'Connor (2008) examined the impact of the first Victorian "megafire" in 2003 on fish populations in north-east Victorian streams and rivers. They found that the low oxygen levels of incoming water from burnt areas led to a large decrease in populations in streams emanating from the burnt areas for the first year after the fire but the populations were recovering 2 years after the fire. They concluded that "fish populations that are residing in well-connected streams with diverse habitat types are capable of surviving and recolonising after catastrophic natural events". The maximum "reach" of the fire impact (in terms of fish mortality) was 55 km downstream of the fire.

8.3.6 The "Reseeder" Versus "Resprouter" Dichotomy

Media will commonly refer to the "destruction" of forests by fire. For native eucalypt forests, at least, the forest is certainly heavily modified but whether the word "destruction" is warranted is arguable. These are, broadly, two different forest responses to fire – seeds or vegetative recovery (Nicolle 2006). Most eucalypt species will show elements of both responses in areas burnt with variable intensity.

"Reseeders" are commonly killed by fires and the forests regenerate from seeds liberated from the seed crop. These fall onto the burnt forest floor, germinate, and grow. Mountain ash (*Eucalyptus regnans*) is the most studied of these, but other mountain species such as *Eucalyptus delegatensis* and *Eucalyptus nitens* behave similarly. The older trees die in the fire, and a dense new crop grows through the "stags" (Fig. 8.10a). In such a case there is virtually no transpiration from the fire-killed ash. However a vigorous new crop of seedlings will occupy the vacant "growing space".

In contrast, "resprouters" generate new leaves from hitherto "dormant" buds in the crown and on the stem. These form new leaves (Fig. 8.10b). The leaves which form on the stem and branches are called "epicormics" and give a characteristic "woolly" appearance. The trees regain some photosynthetic capacity quickly but it can take many years to regain the full pre-fire leaf area. In general most "mixed species" forests come into this category. These are usually the common foothill forests of Victoria, with species such as messmate (*E. obliqua*), manna gum (*E. viminalis*), peppermints (*E. dives* and *E. radiata*) and a plethora of other species. For many years after the fire, the crowns of these forests have a "ragged", sparse appearance with many of the branches dead and many of the leaves of epicormic origin.

Nolan et al. (2014) examined the dynamics of evapotranspiration in recently burnt areas. The hypothesis was that post-fire changes in evapotranspiration would be a function of fire severity and topography, and that burning would alter the relativity of the results. Some results from her work have already been given in Sect. 5.4.1 and Table 5.3.

The hypotheses were tested by monitoring evapotranspiration and component fluxes across different topographic positions and fire severities in mixed species eucalypt forest east of Melbourne. Monitoring was undertaken over 1–3 years following the 2009 "Black Saturday" wildfires. Forest severely burnt had a 41 % reduction in evapotranspiration compared to unburnt forest, while evapotranspiration for forest burnt at moderate severity was only 3 % lower over 1–2 years post fire but then 9 % higher over 2–3 years post fire. This suggests that the epicormics leaves associated with fire recovery are poor at regulating transpiration. For

Fig. 8.10 (**a**) Reseeders at work. Fire-killed mountain ash near Marysville, Victoria 2 years after burning. (**b**) “Resprouters” at work; epicormic leaf development on burnt mixed-species forest near Marysville (Victoria) 2 years after burning

severely burnt forest, the lower tree evapotranspiration was partially offset by transpiration from regenerating seedlings. The work found that although topography was a strong determinant of evaporative demand, forest structure, and burning intensity, it did not affect the nature of post-fire recovery.

8.3.7 Twice- Burnt Areas

Usually a forest fire burns fine material but leaves the heavier standing material charred but not entirely burnt. This may subsequently die, with new regeneration coming up (Figs. 8.11 and 8.12). If a second fire should pass across the area, then the new regeneration may be killed by the intense fire which feeds on the dead but unburnt material from the first fire. The area is then left effectively bare with sparse or no tree cover, and little source of seed for regeneration. In either case, and particularly on north-facing slopes, these areas may exhibit extreme water repellancy and loss of infiltrating pathways. This leads to massive runoff and erosion, with the potential for debris flows being generated. The long term hydrologic effects relate both to the site deterioration and the change in vegetative cover. The implications of this are, at the time of writing, just beginning to be realised (see Fagg et al. 2013). Of particular concern is the lack of seed to allow regeneration.

Fig. 8.11 Forest "destruction" from ground level; a severely burnt forest near Myrtleford, Victoria 3 months after burning in 2009. Many trees have been killed but some epicormic growth is beginning on survivors

Fig. 8.12 Forest "destruction" from the air. The catchment of Tourrourong Reservoir in Melbourne's water supply, burnt in 2009. The apparent "lines" of vegetation are due to differing slope angles and the complete destruction of crowns (Photograph courtesy of Michael F. Ryan)

8.3.8 The Burnt Areas Becomes Hotter!

The advent of satellite measurement of the temperature of the earth's "skin" is producing much information on global temperature dynamics. Of particular interest has been the work of Mildrexler et al. (2011). This particularly noted that in a forest the "skin temperature" is similar to air temperature; this is in contrast to other land uses in which surface temperature may be far hotter.

When a forest is burnt, transpiration ceases or is diminished and hence this cooling effect is lost. An immediate affect is that a burnt forest is typically warmer to be in than an unburnt forest on a hot day. It is probable (but unproven) that the loss of the cooling effect on burnt areas leads to higher earth-skin temperatures which, in turn, may lead to thunderstorm activity and more intense rainfall than would otherwise be encountered. The coincidence of a fire and a major thunderstorm (with massive erosion) is sometimes noted (e.g. Leitch et al. 1983; White et al. 2006) and has been the subject of modelling (e.g. Tryhorn et al. 2008).

8.4 Post-fire Hydrologic Rehabilitation

In general, major fires are large and complex and there are simply not resources available for large-scale rehabilitation works. Usually there are considerable earthworks associated with fire control lines and an immediate task is protection of these from erosion by usual methods of diversion of drainage, erosion barriers, etc. Forest fire-fighting is a trade-off between aggressive control measures to contain the fire or the destruction associated with large-scale, unchecked fires. Hence there is always an immediate task of fire-line rehabilitation.

The question of whether post-fire rehabilitation for larger areas is effective (or possible) appears arguable. Wagenbrenner et al. (2006) examined three post-fire rehabilitation treatments in Colorado on burnt and unburnt plots. They found that "mulching" and "contour felling" might have some effectiveness in reducing erosion for smaller storms and localised area but were less enthusiastic about their effectiveness in large storms. Similarly Robichaud et al. (2000) examined various options such as erosion barriers, sediment fences. Their conclusion was that any such approach requires careful evaluation including estimation of the probability of a likely erosion event.

The Australian experience has been that the sheer size of the fires in the last decade and the remoteness of the sites has made such an approach of little real value overall. However, in high-value catchments, where there is a specific asset to be protected, or where the community wants to be "doing something" then such an approach has merit. In some cases projects such as cleaning of road culverts of debris may help accommodate the higher peak flows. Post-fire debris flows which cross roads or impinge on structures certainly impose an immediate maintenance task.

A common suggestion after major fires is that some form of aerial sowing of "fast-growing grasses" be made to stabilise sites. There is no evidence that this approach has any value and it represents introductions of a non-native species into pristine (albeit burnt) environments. The suggestion is to be resisted. The usual finding is that, after burning and rainfall, there is no shortage of regenerating plants in native forests; the problem is that they may not be the desired species.

8.5 Case Study 2: The Macalister River Floods of 2007

This case study is presented as an example of the uncertainty that a large forest fire may introduce into the management and economic life of water resources. In this case the question is whether the burning of the Macalister catchment in December 2006 played a role in the Macalister River floods of 2007?

The Macalister River is a tributary of the Thomson River in Gippsland, Victoria. The catchments of both these were severely burnt in the "second megafire" of 2006/2007. Observers noted the intensity of the burning of much of this rocky, mountainous catchment. On 28th June, 2007, some 6 months after burning, heavy rainfall in the catchments of the Thomson and Macalister and other Gippsland Rivers were responsible for widespread flooding in Gippsland. Of particular interest was the extremely rapid filling of Lake Glenmaggie irrigation storage (Fig. 8.13). The peak inflow into this was estimated by Hawke (2008) at around 260,000 ML day^{-1}, and the dam outflow at 147,000 ML day^{-1} – far higher than flows previously

Fig. 8.13 Glenmaggie weir passing a peak flow of around 260,000 ML day^{-1} on June 28th, 2007, about 6 months after the catchment was burnt. This was in excess of expected flow levels for the given rainfall. The surging in the foreground is water impacting on a power station. The colour of the water shows severe erosion (Photograph courtesy of Joe Matthews and Southern Rural Water)

encountered in the 70 year history of the dam but within the dam's designed capacity. The extremely turbid nature of the discharge gives some idea of the sediment movement involved. The flows were powerful enough to severely damage a 3.8 MW hydroelectric station (constructed in 1993) at the foot of the dam. Sediment deposition is thought to have been close to 7 % of the dam's storage volume, possibly reducing its economic life. Outflow from the dam was then associated with flooding in downstream townships. The magnitude of the flows also raises the question of whether a larger dam might be appropriate at the site.

The causal rainfall was in a mountainous catchment with only a few gauging stations. It would appear that storm was certainly of a large magnitude (typically 150–200 mm daily rainfall over substantial areas, with some areas possibly approaching 300 mm within a few days). One issue was that the storm magnitude was far in excess of forecasting estimates, and thus the water supply authority had little warning. Although the storm was far larger than estimated, the flood generated appears disproportionately large relative to the rainfall. Hore and Matthews (2008) estimated the storm had a return probability of about 1 in 50 years, but that the flows emanating from the catchment had a return probability of about 1 in 200 years (based on past records on unburnt catchments). This difference could be viewed as a fire impact; an alternative explanation is that it could reflect heavy rainfall unmeasured by the rain-gauge network. Computation of the peak rate of flow from the catchment suggests that this was around 200 mm day^{-1} which is extreme for an Australian forested catchment. The magnitude of the flow event caused widespread failure of gauging stations.

In examining the impacts of the fires on this flooding in the light of other material in this Chapter we can discern a number of interlinked “threads”. The event also shows the difficulties of linking “cause and effect” of large catchments. Firstly, it is likely that the death of foliage in the fires led to a loss of “evaporation cooling” of catchments. This, in turn, probably exacerbated normal thermal processes and may well have helped to generate more intense rainfall than might be expected. With our current technology it is difficult to “prove” or “disprove” such a hypothesis on the frequency or intensity of a particular storm event. There is certainly anecdotal experience of large thunderstorms after burning. This is attributable to the blackening of the catchment surface by charcoal, leading to much greater surface heating and updrafts – a process commonly appreciated by glider pilots and large birds. This event, however, was associated with a regional rainfall event in which the role of ground-induced turbulence is less clear. A second area of uncertainty is whether large numbers of “spike flows” in small catchments could or would “join up” to give a large river peak flow and massive sediment transport? However there is little doubt that the presence of large amounts of fire-generated highly erodible material on the catchment surface and a stream channel armouring incapable of dealing with such large flows contributed to the sediment transport.

The event indicates the hydrologic uncertainty introduced when a large forested catchment is burnt; although it may be a reasonable supposition that the high flows (relative to rainfall) and sediment movement were consequences of the fire in the catchment, it is hard to “prove” or “disprove” using existing forest hydrology science. Hawkes (2008) concluded that in this case flood warning systems relying on warnings of high flows at gauging stations were unreliable in the face of such high flows. He also noted that the river velocities were “close to dam break conditions”. Flood warning system for remote catchments needs a good network of automatic rainfall monitoring with some form of automated data processing to provide alerts for very large events. Finally, the dam itself, is now viewed as undersize for the size of its catchment and the flow rates it may encounter.

It is likely that future Australian dam design will have to explicitly consider the probability of fires impacting on peak flows. This will mean a joining of the disciplines of forest hydrology and engineering hydrology.

8.6 Future Fire Hydrology Research in Australia

Since 2002, Australian forest hydrology researchers with an interest in fire effects have been blessed (or cursed) with an abundance of case studies. Fire has burnt the catchments of major cities and towns. Wild fire has burnt out long-running paired catchment studies (it would have been better if it had left a “control”. . .). Fires have burnt close to cities for the convenience of plot locations. In some cases the fires have burnt almost up to the research laboratories. Fires have burnt virtually all types of environments to give a plethora of case studies. The removal of dense undergrowth has given a clarity of view (albeit temporary) of geomorphic effects hitherto rarely (if ever) achieved. And the fires have given a focus for researchers and funding agencies.

In general the research stimulated by the fires has built on many findings from small catchment research in the past. The results have usually been in accordance with the findings of pre-fires studies and shown that the fires have amplified features of the hydrology found in the pre-fire catchments. Results from small catchment studies have been valuable because measurement on these is feasible and there has been a resource of pre-burn studies for comparison with the post-burn catchments.

The wider challenge is to examine the impacts of forest fire on larger catchments such as that of the Macalister River. This includes both the shorter term dynamic effects associated with rainfall and the longer-term impacts. These range from the impact of fires on evapotranspiration due to changed vegetation to the impact of fires on long-term formation of the stream network. The area that seems to be particularly in need is our knowledge of stream entrenchment in the landscape and the role of fires in accelerating such entrenchment in first to third order streams. Related to this is the likely fate of sediment in the streams, the role of fires in the natural environment of Australia, and deciding whether a particular case is "natural" or "human-induced".

With current technology we have some ability to control fires in the Australian forests. As events in the last decade have shown, fires can and will sometimes overwhelm our fire-fighting. Thus the question of how we should view these – as an agent "destroying our forests" or a naturally recurrent phenomenon is a key question. Related to this is the question of whether large, landscape-scale fires are a manifestation of "climate change" or are an intrinsic part of the Australian environment. This is a great subject for debate (but, at the time of writing) has few answers.

Conclusions

Large fires since the turn of the century have shown that they have a major impact on regional hydrology, and have helped shape the Australian mountain landscape. The role of fires in leading to high stream flows, both at the local and regional level, is only just being appreciated. In the longer term, the fires lead to changes in the vegetation which, in turn, changes the small catchment hydrology.

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Chapter 9
Water Quality and Nutrient Issues for Small Catchments

Abstract In assessing water quality of streams from forested areas there are a large number of parameters that can be measured. In practical terms, this is usually simplified to a few, of which turbidity is usually the most useful single indicator of forest pollution. Water quality measurements present many difficulties; all can be overcome by adding more resources but the issues can be formidable. A particular issue is the high quality of water from forested catchments; this often makes measurement difficult unless laboratory techniques are used. Consideration of the design of water sampling schemes is made, and examples of water quality measurement projects are given.

9.1 Why Measure Water Quality?

There is probably no more difficult area in forest hydrology than that of dealing with water quality in small streams because of the number of water quality parameters that can be measured, non-normality of data distributions, the factors that must be taken into account, the practical difficulties of measurement, acid political interpretations that are sometimes made of the data, and the difficulty of extrapolating the results to wider land uses. Water quality work is classically "buying information" with the amount of information gained about proportional to the effort expended in collecting. For anything other than casual observation, water quality work should have both a measurement and quantitative hydrology basis. Ideally, the statistical basis should also be sound but this is a surprisingly difficult ideal to meet. Workers in this field invariably develop a fund of anecdotes to do with erroneous measurement (see Box 9.1). Classically, forest water quality issues commonly relate to how close the water is to meeting relevant water quality standards for drinking, and the impacts of catchment land use on water quality compared to its historic variation.

Forest water quality measurements usually can be categorised as:

1. Monitoring, in which some form of observation is kept on one or more variables of interest. This may range from simple visual observation or a few samples to complex measurement with in-situ equipment or multiple samples taken with some sort of sampling scheme.

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2. Research studies, in which multiple samples are taken over long time periods. These samples may be linked to the stream flow at the time, and be used to compute plots of the water quality with time, mass-balance of nutrients or a statistical distribution of the variable of interest. In general, some hypothesis is being tested.
3. Compliance obligations, in which monitoring ensures that the water quality meets the standards laid down by the Australian Drinking Water Guidelines 6 (2013). These are updated regularly by the National Health and Medical Research Council. This is viewed as the ultimate reference standard for drinking water and contains a comprehensive list of chemical, physical, and biological standards for water supplies.

For Australian natural water, the usual reference for water quality is the "Australian and New Zealand Guidelines for Fresh and Marine Water Quality" (ANZECC 2000). This provides a comprehensive approach to defining water quality issues and maintaining high quality.

Figure 9.1 illustrates a fundamental operation – taking a dip sample from a small stream. Figure 2.4 shows a rainfall water quality sampler. Anyone engaged in this work will testify that the sampling sites are usually difficult to get to, the water is wet and cold when you get it over you, it's easy to fall in the stream, the samples are

Fig. 9.1 Taking a manual water sample in a first order stream. There is not much water depth to play with. This, the most primitive technique in water quality measurement, is still fundamental

heavy to carry, and that successful sampling work involves good organisation and preparation before going "out to the bush."

Box 9.1: Top Quality Scientific Measurement

There was concern that forest harvesting might lead to sediment in the intake of a hydro-electric plant. Should we take our own samples or rely on the staff of the hydro-electric plant? "They're well-trained" the manager said. "They take the sample, look at it, and if it is not right they'll add a bit more dirt to it so that it is."

9.2 Planning a Water Quality "Campaign"

MacDonald et al. (1991) notes that an ideal parameter for monitoring water quality impacts of land management should be sensitive to the land management action, accurate, precise, easy to measure, be related to the uses of the water body, and have a naturally low spatial and temporal variability. Such a magical parameter can be measured, used to assess activities, and give feedback to managers. Unfortunately no such parameter exists and hence most water quality measurement is a compromise attempting to accommodate many factors.

MacDonald and Smart (1993) suggested the following systematic procedure to ensure that sampling programs are cost effective:

1. Establish objectives.
2. Review existing data.
3. Establish statistical utilisation and interpretation of data.
4. Select water quality characteristics.
5. Establish sampling frequency.
6. Locate stations.
7. Determine costs of surveillance.
8. Evaluate the ongoing program.

A review of US experience by MacDonald et al. (1991) found that establishing objectives was the most important – and most difficult – step. This review also noted the need for development of testable hypotheses in developing the measurement program, and the need for peer-review to uncover weaknesses. Nothing appears to have changed in the two decades since.

The Australian Drinking Water Guidelines 6 (ANZECC 2000) suggest that, for source water, the variables in Table 9.1 should be "monitored." For routine measurements, a "monthly" monitoring frequency is suggested unless there are water quality "incidents" occurring. It should be remembered that if water is passing into a dam, the presence of the dam and its associated storage will alter the water quality of the stored water by a variety of processes. For research projects, ideally weekly or more frequent samples would be taken.

Table 9.1 Parameters suggested for "source water" monitoring by the Australian Drinking Water Guidelines 6 2011

Parameter	Comment
pH	Sometimes hard to get consistent readings because of low buffering in streamwater
Turbidity	Most useful overall indicator of sediment pollution
Temperature	Can be influenced by riparian shading. Has a diurnal and annual variation
Dissolved oxygen	Usually high. Low levels can indicate organic debris in streams
Streamflow	Key variable but hard to interpret unless there is systematic gauging
Rainfall	Ditto
Escherichia coli (E. coli)	Indicator of faecal contamination in water. Often high in natural streams because of animals (native and exotic) in the catchment
Other faecal indicators	Ditto
Colour	Usually correlated with turbidity
Conductivity	Easily measured indicator of nutrient load
Alkalinity	Often correlated with conductivity
Organic carbon	Useful indicator of water residence time in flooding forests
Algae, algal toxins and metabolites	Often "come and go" in natural streams

9.2.1 The Pure Water of Mountain Streams Makes Measurement Difficult!

In other areas of hydrology, water quality monitoring is often concerned with measuring polluted effluents. Whilst these undoubtedly have their measurement problems, there is usually little doubt as to the "pollutant." In contrast, small mountain stream often have markedly pure water naturally. This leads to difficulties in measurement because the water is close to the quality of de-ionised water standards; hence our variable of interest may be close to or beneath the detection limits of laboratory instruments. This is sometimes referred to as "censored data" in which one can only say that a parameter is below a lower limit (e.g. Lee and Helsel 2007).

Table 9.2 provides analytical data on the water quality of the rainwater and three contiguous streams at Croppers Creek. For comparison, the usual limits for drinking water taken from WHO (1997) for drinking water are also listed. It can be seen that:

1. The water is of high clarity, as indicated by the turbidity values. Of particular interest is the extremely low (for natural streams) turbidity and colour for Betsy Creek (0.7 nephelometric turbidity units (NTU) and 2 Hazen Colour units). Sometimes the turbidity of this was about 0.2 NTU, which is about as low as one can get naturally. This consistently had best physical water quality in the three streams sampled, although there was no apparent reason why this should be. Figure 9.2b shows outflow from this stream.

Table 9.2 Natural water quality of three contiguous first-order streams in the Croppers Creek Hydrologic Project (Hopmans et al. 1987)

Parameter	Rainwater	Ella Creek	Clem Creek	Betsy Creek	Drinking water
Colour, Pt/Co scale		7	6	2	<15
Turbidity, NTU	1.8	1.2	1.4	0.7	<5
Suspended solids, mg L^{-1}	4.8	3.7	6.4	2.8	No limit
Conductivity, mS m^{-1}	0.75	2.5	3.0	2.3	<5
Na, mg L^{-1}	0.27	1.82	1.94	1.76	<200
K, mg L^{-1}	0.19	0.46	0.45	0.59	No limit
Ca, mg L^{-1}	0.24	0.46	0.80	0.31	<200
Mg, mg L^{-1}	0.09	1.32	1.50	1.10	<50
Cl, mg L^{-1}	1.1	2.4	2.4	2.4	<250

2. In practical terms both the rainwater and the stream water are pure, and levels measured in the water are well within the limits of acceptability for drinking water. In many aspects the water approaches lower-grade laboratory water. Thus high-quality equipment, excellent standards, and well-developed techniques are needed to obtain consistent and reproducible results.
3. The total electrolyte concentration of the rainwater increases substantially as the water passes through the catchment slopes and flows out. Concentrations usually increases in the order Mg>Na>K>Ca>Cl. Hopmans et al. (1987) suggest that is the result of nutrients leaching from the forest canopy and additions from the weathering of soil parent material.

To the author, the clarity of the water in these small streams was a consistent and unappreciated miracle of nature – roads might be muddy, raindrop splash on bare soil surfaces had coated measuring equipment with dirt, the forest could be dense and damp and appeared to have no magical properties, the stream bed was a mixture of dirt, rocks, and organic debris, and yet a sustained outflow of crystal-clear water was passing downstream.

9.2.2 What Parameter Should I Measure?

MacDonald et al. (1991) in a review of his forest water monitoring guidelines pointed out that under US legislation, there were approximately 100 water quality criteria recommended. Of these, commercial forest activities possibly affect turbidity, suspended solids, colour, dissolved oxygen, conductivity, and temperature. Levels of major nutrients are of interest to researchers. Occasionally other criteria may arise in controversies – particularly herbicide and pesticide levels. Table 9.3 suggests where these parameters may be used in forestry investigations. Commonly

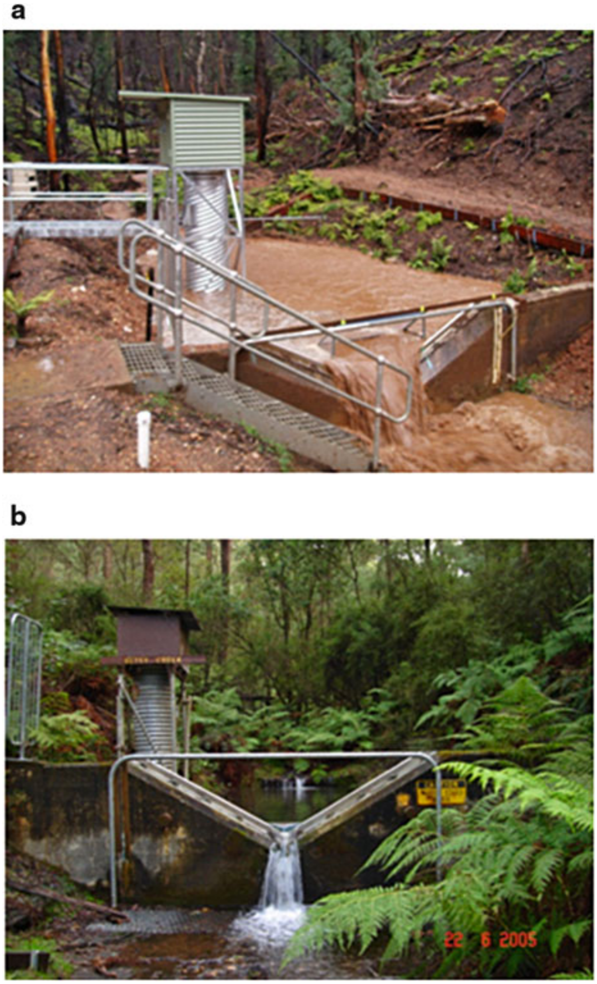

Fig. 9.2 Extremes of water quality at Croppers Creek (**a**) Clem Creek after fire with high flows and an associated very high turbidity and (**b**) Betsy Creek 18 months before the fire with very high water quality. The turbidity of this water is at the lowest end of naturally-occurring waters

there is a positive correlation between turbidity, suspended solids, and colour so that there is little gain in measuring all three.

9.2.3 Water Sampling and Statistical Sampling Issues

Figure 9.3 shows a portion of the hydrograph from Ella Creek, and records of water quality for turbidity, conductivity and total suspended solids (TSS) for a period in 1998/1999. This work (reported in Hopmans and Bren 2006) was examining the water quality issues associated with the conversion of native eucalypt forest to radiata pine plantations. Ella Creek was the control catchment carrying native

Table 9.3 Parameters commonly used in water quality issues pertaining to forestry

Parameter	For investigating
Turbidity	Logging, roading
Suspended solids	Logging, roading
Colour	Logging, roading, general disturbance
Dissolved oxygen	Organic debris in stream
Conductivity	Salt levels in stream
	Other minerals
Temperature	Riparian exposure
	Possible indicator of low oxygen levels

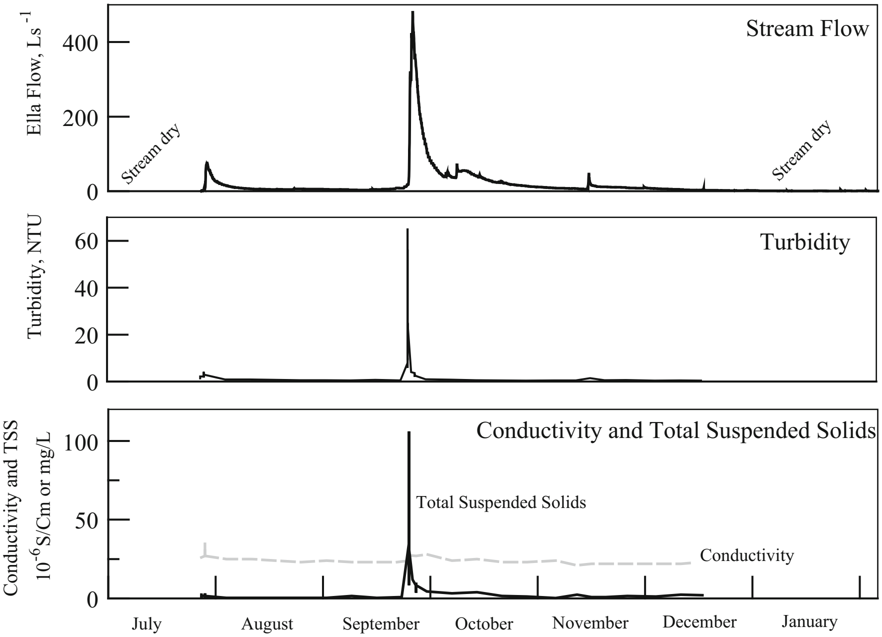

Fig. 9.3 Annual hydrograph at Ella Creek and records of water quality

eucalypt forest. The storm in September, 1998 was the largest flow measured at Ella Creek. Of particular note:

1. The ephemeral Ella Creek commenced flowing in July 1998. At this time there was (as usual) higher levels of total soluble salts (TSS) and turbidity as the sediment which had accumulated in the channel over summer and autumn was swept away.
2. Water quality as measured by turbidity was low for almost all the time except for the initial period of the large storm. At this time the stream scoured sediment it could move, leading to high values of TSS and turbidity. However this impact died away much faster than the storm flows as most of the erodible sediment was removed from the stream channel during the initial period of the storm.

3. Water conductivity was almost unaffected by high flows, reflecting the groundwater origins of the storm runoff. Conductivity is a measure of the dissolved salts in the water. In this case these were not at a high level. The transformation of the neighbouring catchment to pine did give an increase in nutrient export from the catchment because of the increased flow of water rather than changing the concentration of nutrients in the water.

Generalising from the body of experience with such measurement programs, the experience and results showed:

1. Streamflow is highly variable. Any sampling scheme should ideally sample both the high flow periods and the low flow periods with an acceptable frequency. Sampling schemes should use stratified sampling to optimise their efficiency.
2. In this case the data were collected by a mixture of automatic and manual sampling. Intense sampling will generate large amounts of laboratory work; the logistics of any sampling campaign requires coordination with the laboratory. Typically this may result in "bulking" of samples to obtain mean values over defined periods of stable streamflow during a major storm event.
3. The aim of obtaining "temporal longitudinal measurements" (i.e. measures of water quality variables extending over long periods of time) requires different sampling strategies from characterising the parameter over a short time period.
4. The major water quality variations tended to be at the start of a period of higher flows when material deposited on the streambed would be "flushed" from the catchment. After this had been dissipated, water quality would return close to its long-term average. This is particularly illustrated by the hydrograph and associated sediment concentrations shown in Fig. 9.4 from a mountain catchment of 136 ha (Leitch 1982). In general, sediment movement stops fairly early in the runoff process because there is no more available sediment to be moved.
5. Variables such as stream temperature and perhaps conductivity can have a diurnal variation which must be considered.

At Croppers Creek the automated, in-situ monitoring of water quality developed many issues of accuracy and reliability and was ultimately dropped in favour of laboratory analysis.

For some characterisations, a random-sampling strategy would appear to be in order if the mean and standard deviation of the water quality property are of interest. Attempts to apply true random sampling are difficult:

1. There are usually only a few points along the stream where samples can be taken.
2. In general, manual samples can only be taken in daylight hours because of safety issues. Similarly it is difficult to organise manual samples to be taken during non-working periods (Christmas, etc.).
3. Because of the difficulties of getting to streamside sampling points, a random longitudinal sampling scheme (i.e. where people take samples from randomly selected points along the stream at the same time) ranges from inconvenient to impossible.

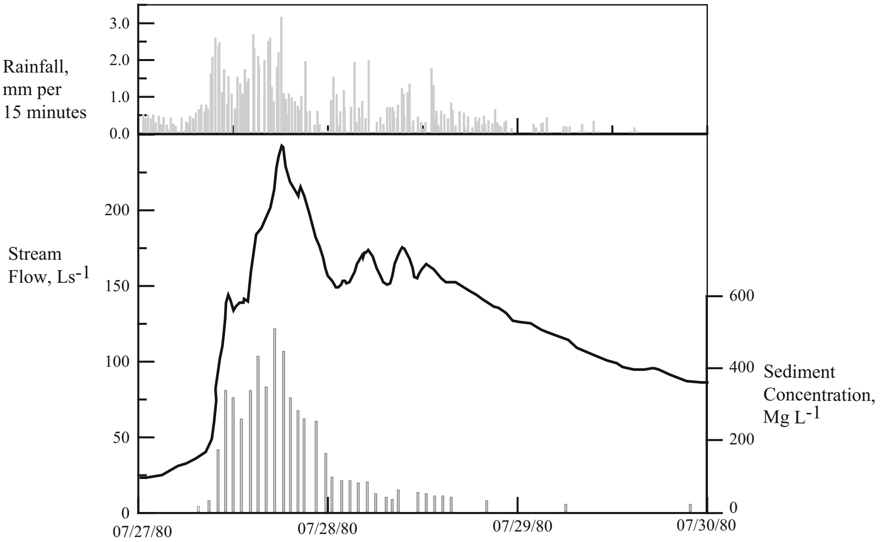

Fig. 9.4 A rainfall hyetograph, hydrograph, and record of sediment concentration in a small stream in the East Kiewa catchment, as reported by Leitch (1982)

4. It is unlikely that any water quality variable sampled, even at a time of constant flow, will have a normal distribution, and hence non-parametric data analysis methods will need to be used. Belle and Hughes (1984) provide an interesting synthesis of such methods that might be used. The reader is referred to Helsel and Hirsch (1992) for a complete elaboration.

The net result is that much water quality work does not have a good statistical basis because the logistic demands of this cannot usually be met. At the same time, usually the issues to be addressed are often difficult to couch in terms of simple statistics.

9.2.4 Technology to the Rescue?

The advent of automated samplers (Fig. 9.5), together with sampling monitoring by computers or data-loggers has eased many sampling issues by allowing samples to be taken any time at a convenient location. These samples may be bulked to provide a composite sample for a defined period or individually stored and handled. Streamflow monitoring algorithms controlling the automatic samplers allows samples to be taken in proportion to the flow to collect a true mean of the variable being sampled. However this generally requires a proper flow monitoring station, necessary equipment to store and process bulk samples, and a good grasp of programming and interfacing technology. This has proven to be entirely feasible for paired-

Fig. 9.5 A sophisticated water sampling setup at Ella Creek weir. To the right is a data-logger-controlled water sampler. Samples pass into a bulk container to give an "average sample" for a given period. Shelves allow storage of containers, hoses, etc. Technical officer John Costenaro is seen doing the never-ending paper work associated with running a water-sampling program. The ability to do the routine work protected from the weather adds greatly to the quality of such programs

catchment projects using skilled technicians, but less so for casual sampling projects.

Similarly, in-situ stream probes may be able to measure variables more or less continuously with only an occasional sample being taken for laboratory checking. To date, experience with such technology has been chequered. In particular the temperature variations of being outside led to anomalous results (particularly apparent diurnal variations in parameters such as conductivity which actually reflects inadequate temperature correction in the probe), the purity of water in many forest streams is so high that the probes cannot give reliable data, and the shallow depth of water and the presence of air bubbles in first and second order streams can make probes which send some form of beam into the water unusable because the beam is not passing into a water continuum. Optical sensors degrade because of algal growth. With experience and patience, these problems can be overcome, but the issues of water quality, getting the "right" probe location, temperature variations, and instrument "drift" (in which the instrument reading of a standard wanders because of environmental conditions or deficiencies in the instrument) are difficult to overcome in remote field environments without considerable project development. Most water quality campaigns will involve a mix of technologies, but the humble sample taken in the field and carted back to the laboratory will still have a place in forest hydrology for the foreseeable future.

9.2.5 Water Quality Computations

A fundamental distinction in water quality data are between those parameters for which a mass balance can be made and those for which this does not apply. Thus sediment load in mg L^{-1}, when multiplied by a volume of water per hour gives an estimate of the mass of sediment passing the point of measurement per hour. In contrast, turbidity multiplied by the volume of water is usually meaningless (although such a stratagem may occasionally be used to “weight” values).

Longitudinal Dilution and Dispersion Although there is a stability in the levels of natural minerals in stream water, this is not the case for pollutants added to a stream. Firstly the rate of inflow into the stream will be a function of time and will usually rapidly increase and then decrease over time. Secondly the concentration of the pollutant will usually decrease as it travels downstream due to diffusion (dispersion) and dilution. Thirdly the pollutant may interact with the stream bed materials, suspended organic matter, and sediment in the water; in particular, many pesticides are sorbed onto clay particles in the water. The process is easy to observe by adding food dye to a small stream. Hence the concentrations of a pollutant may be very different a short distance downstream or upstream from the concentration measured at a point. Although the processes involved have been studied in larger rivers (e.g. Beer and Young 1983), the process has not been much studied intensively in very small streams. It is viewed as “difficult” because of the complexity of factors and the difficulty of measurement. Figure 9.6 illustrates the observed behaviour when a conservative solute (chloride ion) is added to a stream; the data are taken from Jobson (1996). Kazezyılmaz-Alhan and Medina (2006) and Kazezyilmaz-Alhan (2008) present a methodology for computing water quality hydrographs for such pollutants. Usually any pollution generated on an individual first-order steam is so dispersed and diluted over time that it is not detectable on larger streams unless highly accurate measurement supplemented by long periods of sampling are used.

A practical consequence is that while it is possible to characterise water quality changes in a stream, it is difficult to predict what these mean to water quality some distance downstream from the point of measurement. If you are sampling a point-source pollutant, thought should be given to where your measurements should be taken and what they might mean if applied to a larger system since this may markedly influence the results obtained. A corollary is that it is very easy to overstate the impact of some form of pollution if dilution and dispersion are not allowed for. Selection of a sampling point for water quality studies may be a major determinant of the results obtained.

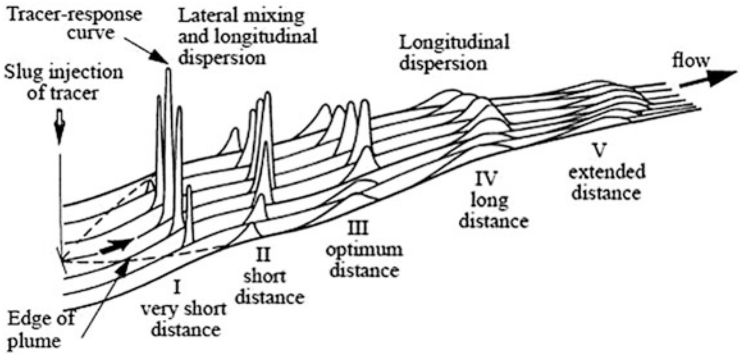

Fig. 9.6 Illustrating longitudinal dilution and dispersion when a "slug" of pollutant is added to a stream, and the course of the pollutant is followed downstream (From Jobson 1996)

Stratification for Sampling and Derivation of a Rating Curve Cursory examination of hydrographs shows that variables such as the mean sediment concentration will be much higher at larger flows than smaller flows. Hence an approach is to attempt to stratify the hydrograph into "low flows" or "high flows" and then derive appropriate statistical parameters for each of the strata. If a forest treatment is involved then the sampling work may end up with a 2×2 table (high flows, low flows x before treatment, after treatment). This would be a satisfactory method of analysis but would be cumbersome to obtain the data.

It is often hoped (but rarely realised) that there will be a linear or curvilinear relationship between the selected measures of water quality and streamflow. Figure 9.7 shows examples of this for turbidity and conductivity for Ella Creek; in the first case there is no clear relationship and in the second, the conductivity appears substantially independent of flow. Any relationship derived should reflect rising stage, constant stage, or falling stage hydrographs. This is sometimes referred to as "hysteresis." Figure 9.8 shows an example of such a relationship for the storm event illustrated in Fig. 9.3. Thus the turbidity increases and then decreases at a faster rate than the flow changes. There is rarely a 1:1 correspondence between measures of flow and measures of water quality.

Systematic Water Quality Variation as a Function of Time Particularly if the parameter can be automatically measured and logged, it may be possible to derive water quality parameter values as a function of time (e.g. turbidity at 30 min intervals). A full suite of time-series data may then be used to derive values. Figure 9.9 shows both the mean daily stream temperature and daily temperature amplitude (about the mean) as a function of time over the course of a year. A clear, systematic, seasonal variation can be seen. A diurnal variation in stream temperature can also usually be found (i.e. temperature reaches a minimum at night and a maximum in the day). Unfortunately this is about the only example of such a systematic variation over time that the author is aware of; most variables have a much more erratic distribution and/or can't be logged automatically.

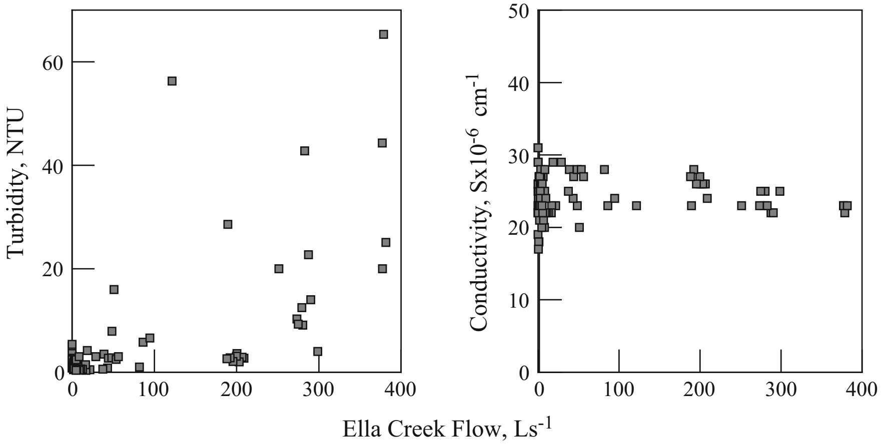

Fig. 9.7 Stream turbidity and conductivity as a function of streamflow for weekly samples over a 2 year period (1997/1998) for Ella Creek (From Bren and Hopmans 2000)

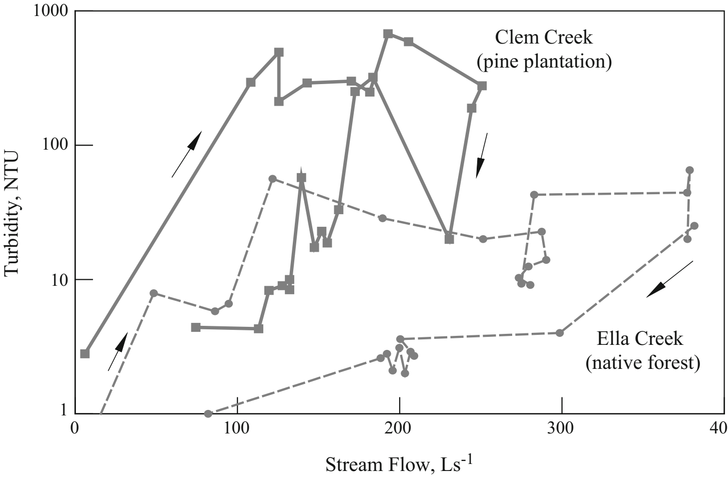

Fig. 9.8 Hysteresis curves showing the variation of turbidity as a function of streamflow during the course of a large storm (21st–28th September 1998) on Ella Creek (pine catchment) and Clem Creek (native forest control catchment). The arrows show the sequence of data collection. In both cases turbidity increased and then decreases. The hydrograph is shown in Fig. 9.3 (From Bren and Hopmans 2000)

9.2.6 Water Quality Snapshots

An approach that goes in-and-out of popularity is that of "water quality snapshots" in which many samples are taken along creeks in the area of interest over a short period of time. Typically a sampling group is assembled to cover many sampling

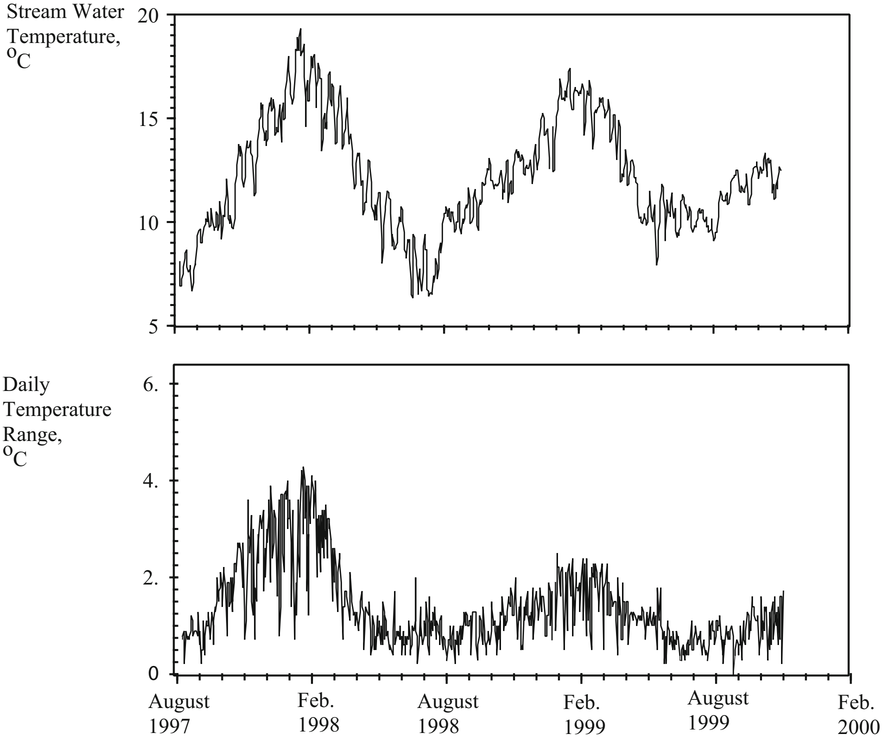

Fig. 9.9 Annual variation in stream temperature and the diurnal temperature range over a 2.5 year period at Clem Creek (From Bren and Hopmans 2000)

points at once. These samples are analysed for a range of parameters, and this data may be supplemented by spot measurements or routine water analysis data. The purposes are usually (a) to determine if the water complies with appropriate water standards and (b) to see if water quality can be linked to a particular land use. An example of the latter is the work of Mossop et al. (2013) to determine the "impacts of intensive agriculture and plantation forestry on water quality in the Latrobe Catchment, Victoria". The work was undertaken by an environmental regulatory agency. The study aims were "to investigate water quality and assess toxicants from two land uses (potato farming and plantation forestry)". The approach used "a multiple lines of evidence" approach including water chemistry analysis for pesticides, metals, nutrients and hydrocarbons, a range of laboratory-based and in situ bioassay toxicity tests using macro-invertebrates and algae and "rapid bioassessment" indices. Adsorbent "Chemcatchers" were also placed in the stream to allow adsorbtion of various herbicides. Bioassessment techniques were substantially derived from the AUSRIVAS ("Australian River Assessment System") methodology for river health assessment. Such an approach presupposes that the mass of data will detect shifts (temporary or permanent) in the distributions of stream-dependent biota as indicators of stream health and the impacts of land use.

The work represented a comprehensive (and costly) "sampling campaign" using a wide range of measurement techniques not usually applied to small streams. Sampling used eighteen sites between the two targeted land uses. Analysis included determination of levels of 115 pesticides. Sites were designated as "control" or "impact" depending on whether the site had potato or plantation forestry upstream. However the report noted that the assortment of land uses contributing to the catchment of any one sites causes difficulties in attributing observed impacts to specific land uses.

The work found a substantial impact of potato farming on turbidity and pesticides level, but concluded that for most of the plantation rotation, water quality issues with plantation forestry were not substantial. There was an expressed concern that young plantations may have a pesticide potential. Mossop et al. (2013) notes the particular difficulty of interpretation of many of the AUSRIVAS scores as the data were "considered to be outside the experience of the models" – this was noted as a "common issue for headwater streams". Their interpretation of results also had difficulties dealing with the cumulative nature of the stream impacts, that sampling sites had mixed land uses, and that there was little experience in the interpretation of many of the "new" water parameters.

Of note in such an approach is the cost in collection and laboratory work. "Snapshot work" is an efficient way of characterising the water quality of a particular creek and may be efficient in deciding whether issues such as pesticide use need further regulation or study. They are not an efficient tool for investigating specific effects of a land-use because:

1. The concept of a "control" is, at best approximated, rendering interpretations contestable or arguable,
2. As in this case, usually there are a multiplicity of land use effects and it is difficult or impossible to disentangle these effects.
3. Because of logistic considerations, sampling is usually confined to one period and hence the seasonal variation is not considered.
4. Because of time and cost limitations, there is little consideration of "catastrophic events" associated with fires, large floods, etc.
5. There is little chance in such sampling schemes to allow development of knowledge of "pollution mechanisms."
6. If many parameters are measured, then by chance alone some of these will appear to be correlated with the presence of a particular land-use.

It is concluded that sampling campaigns along large streams are efficient for characterising water quality at one or more locations but are not an efficient method (compared to paired catchment projects) of determining land use effects on water quality.

9.3 Case Study 1: The Croppers Creek Water Quality Study

This is presented as an example of long term study involving water quality. At various stages many types of water sampling equipment and strategies were employed. Inevitably, in a study running over many decades there will be changes in the technology of measurement and the appropriate detection limits. The process did show that, after the introduction of a new "in-situ" method, there was consistent fall-back on weekly water samples taken to a well-equipped laboratory in Melbourne to help ensure the technique was giving reliable data.

In the 1960s Australia there was a major expansion of radiata pine plantations. At the time this led to many claims that plantations "impoverished sites", that water quality downstream was impaired, that fertilisation associated with plantations was "eutrophying streams" and that herbicides sometimes used in plantations were contaminating downstream waterways.

Forestry authorities felt at the time the claims were overstated or without basis, but recognised that there was no comprehensive information with an Australian basis on such matters. Even the definition of the terms was vague – for instance, what did "impoverishment" mean? As a part of the response the Croppers Creek paired catchment project was installed (see Chap. 5). This aimed at quantifying both streamflows and water quality affects. Over the years these aims have been met with Hopmans and Bren (2006) summarising water quality results up to the end of the first pine rotation, and Smith et al. (2011) summarising the results after the catchment was burnt in 2006.

The work followed the model of Hubbard Brook project in its approach (Likens and Bormann 1995). This involved use of paired catchments and intensive water sampling to study both the hydrology and geochemistry of processes. The development of new methods of chemical analyses (particularly atomic absorption spectroscopy) in the 1950s made studies characterising the chemical signature of the high-quality stream and rain-water feasible; before this technology was developed, the analytical methods were inadequate or very cumbersome.

Examination of the rainfall showed it was of very high quality water, but that the water quality of rainfall had a distinct seasonal pattern. In general, conductivity, turbidity, suspended solids, K, Ca, Mg, and Cl were higher and pH more acidic during the summer months. This was attributed to the greater contribution of dry fall out and dust mixed with the rain collection. Nutrient concentrations in rainfall were found to decrease with increasing rainfall. Table 9.2 (from Hopmans et al. 1987) compares the mean quality of rainfall with quality of streamflow from the native forests; both have low levels but the stream water tends to have higher concentrations of major elements found in the catchment soils and parent material. There was a strong positive correlation between turbidity and total suspended solids, reflecting that they both more or less measure the same quantity. In general, water quality decreased during the early part of storm runoff and increased after the initial flush of accumulated sediment.

9.3.1 *Effects of Clearing and Planting with Radiata Pine*

A detailed account is given in Hopmans et al. (1987). The clearing (see Fig. 5.2) was a major conversion involving pushing over native forest and broadcast burning on the slopes of Clem Creek catchment. Streamwater quality of Clem and Ella catchments were compared. Temperature, colour, suspended solids, and pH were not significantly affected by clearing. Interestingly, turbidity decreased relative to the reference (Ella Creek) catchment. It is thought this reflected the unchanged, infiltrating nature of the catchment slopes, the effectiveness of the 30 m buffer strip, and the increased streamflow leading to a greater dilution of matter that did find its way into the stream. Conductivity in streamflow of Clem Creek increased slightly relative to the reference catchment, probably reflecting a slight increase in concentrations of some nutrients following clearing.

The treatment of the catchment substantially increased the export of nutrients and suspended solids, but this was due to an enhanced streamflow rather than increased concentrations in the streamwater. Thus the results can be viewed as:

1. The water quality of water emanating from the catchment was substantially constant, irrespective of whether the forest was pine or native eucalypt, and
2. The nutrient export was more or less proportional to the water yield from the catchment.

There was no indication of any degrade in the nutrient availability on the catchment.

9.3.2 *Effects of Fertilizers*

The radiata pine plantation was treated with phosphate fertilizer (P-S-Ca, 18-9-14 % at a rate of 570 kg ha^{-1}) in 1998 (see Fig. 9.10). Two years later, in September 2000 approximately 20 ha of the 43.6 ha plantation was treated with urea (46 % N) at a rate of 665 kg ha^{-1}. The effects of these fertilizers on N, P, S, and Ca in stream water of Clem Creek were examined by comparing pre-treatment with post-treatment levels, and by comparison with levels in neighbouring Ella Creek.

Application of phosphate fertilizer increased P in stream water of Clem Creek from 0.002 mg/L to 0.010 mg L^{-1} during the first 6 months after treatment. Thereafter levels remained slightly elevated compared with pre-treatment concentrations for most post-treatment periods. No increase in P levels attributable to the fertilizer application could be detected during stormflow periods.

Application of urea did not significantly affect median concentrations of total N in Clem Creek, but levels of nitrate-N increased during some periods. However results also showed short-term increases in median concentrations of total N and nitrate-N in stream water during two storm events. Thus it was concluded that there was a small increase in stream nitrate levels associated with N fertilisation.

Fig. 9.10 Helicopter application of fertiliser to Clem Creek catchment, 1998. Use of GPS control facilitates avoiding placing fertiliser in the riparian zone

9.3.3 Effects of Herbicides

Then, as now, control of woody weeds was important in forming a plantation. The weedicide "hexazinone" was effective at this, but its use led to allegations of stream pollution. The Croppers Creek project offered an excellent chance to test this; the work is documented by Leitch and Flinn (1983).

Residues of hexazinone in streamwater were monitored over a 9-week period after helicopter application of the herbicide at a rate of 2 kg ha^{-1} to Clem Creek catchment. The aerial application was made in December 1981 following conversion of the steeply sloping catchment from native forest to *Pinus radiata* 2 years previously. Automatic samplers were used to sample streamwater at intervals of 0.25–2.0 h throughout the 9 weeks, with the more intensive sampling occurring during and immediately following spraying and during the only substantial storm event. A total of 69 representative samples were analysed, and levels of 4 μg L^{-1} hexazinone were detected in six of these samples. This was well below the maximum recommended concentration for potable water of 600 μg L^{-1}. Such low residues were attributed to several factors including the way the spraying operation was conducted (with respect to soil moisture, meteorological conditions and droplet size) and the presence of a 30 m wide native forest buffer on each side of the stream.

Similar results were obtained by other trials in the US using small catchments. Thus Neary et al. (1986) found that application of hexazinone to a small catchment in Georgia (USA) led to a small, short-term increase in hexazinone concentrations. When interpreting such results, considerations should be given to the effects of longitudinal dilution and dispersion (Fig. 9.6) in both selecting sample points and considering the impacts of the spraying on downstream users.

Wightwick and Allinson (2007) examined studies of pesticides in Victorian water-ways and noted that studies such as those above peaked in the 1970s and 1980s, and had been rarely done since, and that more recent studies tended to focus on groundwater pollution. They noted that generally concentrations detected in waterways had been low and below the levels indicated by guidelines as “of concern”.

9.3.4 Long Term Effects on Water Quality

Hopmans and Bren (2006) concluded that there was little evidence to indicate that water quality was adversely affected by the change in land use from undisturbed eucalypt forest to a more intensively managed plantation. Overall there has been a small increase in turbidity from the original median value of 2 to 4 NTU, but turbidity and suspended solids in stream water from the radiata pine plantation have remained within the historic range of values of the original eucalypt forest. Solute concentrations in stream water of the radiata pine catchment have remained within the historic range of values of the original eucalypt forest.

The results did show that the plantation formation had some impact on the hydrology of the catchment and water quality of the stream, but that overall the effects were not large.

9.3.5 Use of Biota as a Measure of Water Quality

An increasingly important “integrated” indicator of water quality are measures of the biota of the rivers. Related to this are various biotoxicology measures of the impact of the water (and pollutants) on biological processes (see Mossop et al. (2013) for an example of these). These concepts have been little explored in headwater streams, with the temporal and spatial variability being noted as a problem. However the Croppers Creek project did give the opportunity to examine whether the water quality effects of plantation conversion were detectable in changes in biota.

Kellar et al. (2004) examined the variability of invertebrate communities between and within streams of the Croppers Creek project and a number of neighbouring streams. The study was designed as a "catchment-level impact assessment" to determine whether the effects of the conversion of Clem Creek and the burning history of Betsy Creek (a low intensity wildfire and a fuel-reduction burn) had "over-ridden" the existing variability in stream biota. Such "over-riding" would be an impact of changes in streamwater chemistry, stream-water temperature, and perhaps flow. Core samples of the stream bed were taken, material sieved out, and invertebrates were identified to the lowest practicable taxonomic level.

The results found 9,185 invertebrates belonging to 122 taxa. The relative abundance of invertebrate taxa differed between the "treated" catchment (Clem Creek), the "burnt" catchment (Betsy Creek) and the controls. However these did not differ in species richness. There was a significant interaction between time and site at the streams, reflecting that the stream biota has a temporal variation in concert with the stream water quality.

The report concluded that there was no detectable effect of the plantation conversion on the invertebrate richness of the stream. It was noted that Betsy Creek had a lower density and species richness than the other streams. This may have reflected a past history of burning but more possibly reflected the greater ephemerality of this stream compared to the others. The report noted the high variability of invertebrate measures both spatially and temporally in these streams. This suggests that it is difficult to use these measures as a consistent surrogate of water quality in the short-term, but that they do provide long-term indications of changes in stream biohealth.

9.3.6 Did the Cropper Project Provide the Information Required?

The project indicated the buffering provided by the infiltrating slopes protects the water quality. In this circumstance, plantation formation does have effects on the hydrology but they are minor and short-lived. Changes in the volumetric outflow of water may change the nutrient balance but the effects are not large. The project did indicate some areas for concern about the future nutrition of such plantations (particularly the need for N, P, and Ca) but these issues are long-term.

Hence it is concluded that the project did meet its aims. Furthermore, it allowed international comparisons. Although such studies are all "one-off" case studies, the similarities of findings do help in formulating generalisations. Interestingly, the community appear to have accepted results from this and other projects since issues associated with the water quality of radiata pine plantations generally appear uncontroversial now.

9.4 Case Study 2: Water Quality Effects of Forest Roads

For the reader interested in this topic there is a large range of papers to choose from. Forest roads are substantially a twentieth-century phenomenon and, other than forest fire, probably have the most wide-spread and pervasive influence on forest water quality of all management actions. We have selected two papers as representative of Australian work in the field.

Grayson et al. (1993) examined the effects of water quality of a reach of road built to facilitate logging for the "Myrtle" paired catchment project in Melbourne's water catchment. The Myrtle project showed that the harvesting and regeneration operations did not have a major impact on the stream physical and chemical water quality. In contrast the road study showed that annual sediment production for forest roads was in the range of 50–90 tonnes of sediment per hectare of road surface per year (1 ha of road surface is about 2 km linear length). Of this, two thirds was suspended sediment and one third was coarse material. The use of gravel reduced sediment production provided a sufficient depth of material was used. Good road maintenance reduced sediment contamination. It was noted that roads by their nature, even when well maintained, produce large amounts of sediment so that careful consideration of their placement and management is paramount.

Lane and Sheridan (2002) examined the impact of a newly constructed, unsealed forest road stream crossing on water quality. They found there was a statistically significant difference in water quality downstream of the crossing, but water quality remained good during non-rain periods. Rainfall events comprised about 20 % of the observation period and led to decreases in water quality for about 10 % of the observations. It was estimated that at least 2–3 tonne of material was added to the stream during construction and from erosion. In some cases the water quality degrade was enough to warrant further investigation under the current water quality guidelines.

Although the role of roads in stream degradation has been recognised for many decades, the issue still persists because of the pervasiveness of roads in Australian forests. The role of road management in catchment management is considered further in Chap. 11.

9.5 Protection of Water Quality in Forestry Management

Most Australian forestry authorities have "Codes of Practice" for the protection of water quality. Private operations often define "Best Management Practices" to minimise water quality aspects. These are considered in more detail in Chap. 11. Usual provisions include:

1. Provision of "buffer strips" of 20 m or more from the edge of streams to leave retained strips. These protect the ground from mechanical disturbance and ensure that the thermal environment of the stream is unchanged.

2. Stipulations aiming at minimising the number of roads crossing the stream network, reducing the amount of runoff from roads, and dealing with the runoff by treating it before it reaches streams. This usually involves diverting road drainage into undisturbed forest before it becomes a large, concentrated flow.
3. Regulations concerning applications of pesticides, herbicides and fertilisers near streams to prevent direct contamination by drift passing into flowing waters. Modern spraying equipment often includes GPS devices to monitor proximity to streams.
4. Careful placement of areas of heavy trafficking or compaction away from streams.
5. Seasonal closures of forests or forest operations to avoid wet weather logging and cartage.

Although harvesting and roading impacts may, in total be substantial, the largest single degrader of water quality is almost certainly the consequences of wild-fire. This is detailed in Chap. 8.

9.6 The Future of Forest Water Quality Studies

The material in this Chapter has covered the "classic" approach to forest water quality issues in which a forestry procedure is linked to the water quality of a small stream. It is likely that this will be the approach for the foreseeable future. The disadvantage of this approach is that the difficulties of measurement and interpretation lead to a large overhead in obtaining meaningful results. Additionally, many stream ecologists have noted for many years that stream deterioration or degradation is due to a number of factors acting in concert rather than one single water quality parameter. Finally, although rarely articulated, is the recognition that stream quality is governed by many land-uses, of which usually forestry is just one component.

In recent times a number of trends have become evident:

1. Public interest in traditional measures of forestry impacts such as those dealt with at Croppers Creek has diminished. Possibly this reflects that studies such as Croppers Creek have quantified water quality impacts. At the same time, there appears to be a widening concern by the public and regulatory bodies at the proliferation of herbicides and pesticides and their possible effects in rivers and estuarine systems. Usually forestry inputs are a minor component of these but the issues have the potential to arouse public ire.
2. Advances in measuring technology have greatly expanded the range of water quality variables that can be practically measured, made far lower detection limits than in the past possible, and are making in-situ monitoring far more accessible than in the past. These include heavy metals in water and sediments, a large range of measures to detect pesticides in water and sediment samples, and more recently complex measures of biotoxicology.

3. Using biological assay procedures for larger rivers, a number of tests of phytotoxicity are now available for small streams. The use and misuse of these and the interpretation of the results will be a challenging field for scientists. The author believes that a paired catchment project approach is very workable approach to testing hypotheses involving such data.
4. In many cases agricultural catchments have become so degraded that there is no expectation of their water meeting standards for potability. This places much more stress on the maintenance of water quality from forested lands, with particular emphasis on pollution from herbicides. This, too, may be very challenging for forest managers in the future.
5. The role of forest fires in degradation of the quality of water from mountain catchments is beginning to be appreciated as a relatively common degradation cause, rather than as an "exceptional event."

It is concluded that many of the traditional questions raised concerning links between forest management and water quality have been answered. However because of the value placed by the public on clean water, newer and more complex questions will need to be resolved in the future.

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Chapter 10
Flooding Forests

Abstract Flooding forests are those which rely on long periods of inundation either for supplying adequate water or for meeting other life-cycle needs. The forests have a distinctive "look and feel" and are highly productive biologically. These forests have evolved in an intimate relationship with their source of flooding. A common cause of problems is river regulation of the water source which, in turn, leads to changes in flooding frequency and duration across the forests. Examples of these forests are given, with the issues confronting Australia's river red gum forests viewed as typical of a wider class of flooding forest issues.

10.1 Introduction

In recent years the term "flooding forests" has become added to the vocabulary of the forest hydrologist. Whereas most forest hydrology has been concerned with small catchments, these may jump to the other end of the stream order spectrum since the flooding is often associated with flows from large (up to 7th or 8th order) rivers passing water onto a tree-clad floodplain. In general these rivers have been dammed and flows are regulated to provide domestic and irrigation water, regulate salinity, maintain river navigability, maintain the visual appeal of the river, and meet a myriad of other needs. This changes the flooding behaviour of the forest. Although this Chapter refers to "forests", usually this is a simplification. Typically such areas consist of a mosaic of vegetation which may include natural grasslands, lakes, waterways, reed areas, and forests of varying composition. Associated with such areas is usually a characteristic and often prolific wildlife. Changing the forest flooding characteristics impacts on all of these features.

In Australia, flooding forests are now viewed as "refugia" to be conserved for biological conservation. The forests are now hardly used for commercial purposes. Around the world there is much interest in flood-tolerant species to be used for wood production. Many Australian eucalypts have great potential for this because of their ability to withstand both flood and drought and to produce high-quality wood.

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10.1.1 What Is Meant by "Flooding Forests?"

A flooding forest is one in which periodic flooding is an essential component of the long-term survival of that ecosystem. Wetlands rank amongst the world's most biologically productive areas and a flooded forest is a forested wetland. The result is an extremely diverse area in terms of both plants and animals. Figures 10.1 and 10.2 provide two examples of flooding forests – river red gum (*Eucalyptus camaldulensis*) along the River Murray of southern Australia (see Sect. 10.2) and swamp cypress (*Taxodium distichum*) in the Mississippi Delta of USA (Sect. 10.3). Both forest types can survive for very long periods under flooding but cannot survive indefinitely. The trees have an ability to translocate oxygen through the stem to the roots to assist survival. In each case the forest has a distinctive "look and feel" which reflects the hydrology; this is greatly valued by the community, as witnessed by the use of such forests by artists, photographers, and writers who attempt to "capture" the unusual "ambience." And, in each case, the survival of the forests may be compromised by river management activities. Thus forest management usually involves developing a working knowledge of river hydraulic management to facilitate negotiations with river managers.

Although all such forests may have human residents, the periodic flooding makes living in the forest (except in a boat) untenable. Thus the flooding tends

Fig. 10.1 Examples of flooding forests: river red gum forest (*Eucalyputus camaldulensis*) intermingled with "grass plains" in the Barmah Forest, Victoria

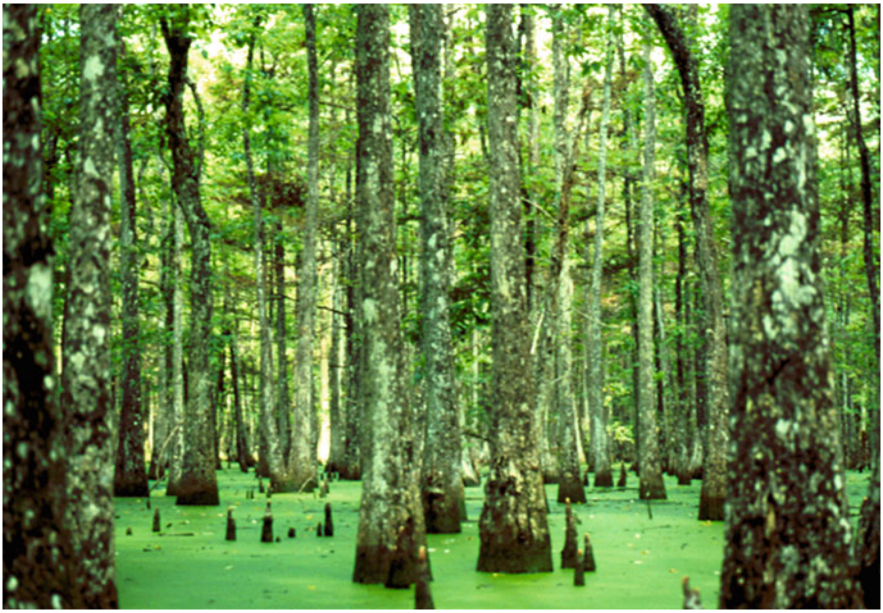

Fig. 10.2 Examples of flooding forests – swamp cypress forest (*Taxodium distichum*) in the Atchafalaya Basin at Amelia Swamp (Photograph William H. Connor, Baruch Institute of Coastal Ecology and Forest Science, Clemson University)

keep the forests as refugia for birds and animals and leads to low human populations. Historically they were once viewed as "damp, unpleasant places" but now they are highly valued for natural, scenic, and biodiversity reasons. This reflects both the biological productivity of these forests and changing views on this by society. The reader is encouraged to find local examples of flooded forests.

10.1.2 The Distinction Between Riparian Forests and Flooding Forests

A "Riparian Zone" is defined as the interface between land and a river or stream. Plant habitats and communities along the river banks are often called riparian zones. In desert areas these may be the only areas of healthy or dense vegetation. In humid areas these may be the most vegetated areas of the catchment and are commonly distinguished by the health and vigour of their forests. This usually reflects abundant soil moisture, high humidity, and some shelter from adverse environments. Commonly the trees in such a zone are taller, larger, and carry more leaf mass than trees on the catchment slopes. Often such trees are subject to occasional flooding which quickly passes. However, other than size and health, the species of trees are similar to those found immediately upslope. Although these trees may benefit from flooding for short periods, their health is not impaired by an absence of flooding. Similarly, such forests usually cannot tolerate extended periods of flooding without the trees showing signs of distress

In contrast, flooding forests generally occur on large floodplains or inundated area and appear to need flooding to meet some physiological need. Thus mangrove forests (*Avicennia* species) occur along coastlines and freshwater flooding appears to mitigate the impact of salinity from flooding induced by ocean tides. Other forests such as swamp cypress (*Taxodium distichum*) appear to benefit from the transport of nutrients and the presence of water. The Australian red gum (*Eucalyptus camaldulensis*) occurs in large, single species forests along the River Murray in south eastern Australia. For these forests, flooding appears to provide water and nutrients in a habitat which is otherwise too dry for the trees to successfully compete.

10.1.3 Ecological Adaptation for Survival During Flooding

Tree species found in flooding forests have specific adaptations to allow survival, although the exact adaptations appear to be specific to different species. These include:

1. Ability to translocate oxygen through woody tissue to cells in the root. This allows the roots to survive in low oxygen environments.
2. Ability to synchronise their reproduction with the flooding cycle, or evolution of strategies such as floating seeds that allow survival.
3. Ability of seedlings to grow fast enough to keep foliage out of water, thereby allowing photosynthesis and transpiration.
4. Ability of seedlings to develop deep roots to allow survival during summer drought in Australian red gum forests.

There are many complex morphological, anatomical, and physiological adaptations by flood-tolerant trees; a good review of these adaptations is found in Kozlowski (1997).

No tree species can withstand indefinite flooding, although inundation for periods of many years can often be tolerated. Similarly seeds of trees cannot germinate and flourish under water, and most tree seedlings have a very limited tolerance to immersion of foliage. Hence virtually all tree species require a “drying out” period for regeneration.

10.1.4 The Forest as a Hydrologic Refugium

In biology a refugium is a location of an isolated or relict population of a once more widespread species. Most flooding forests have an intricate network of waterways that carry water in an out of the forest. Often, by the nature of flooding forests, these areas are inaccessible or difficult of access to humans. Flooding forests generally occur on large floodplains and these may contain cut-off meanders of past channels. These are usually not directly connected to the main stem of the river. Thus such isolated channel and land areas are often viewed as refugia for a variety of land and aquatic organisms (Rayner et al. 2009). Probably the best known example is that of the Bengal tiger in the Sundarbans (literal translation – “beautiful forest”) – a large flooding mangrove forest at the mouth of the Brahmaputra and Ganges River in Bangladesh and India. Most such forests carry large numbers of bird, animal, fish, and plant species that are less common or non-existent outside the forests. Usually monitoring of these species is difficult; hence the status and health of the forest trees is used as a direct indicator of the welfare of the biota associated with the forests.

In many cases human economic systems have evolved in these forests. Thus the economic value of the Sundarban forests have long been recognized, and the area supports a number of forest industries including timber, fuelwood, pulpwood, and thatching material. Usually the flooding or threat of flooding limits human intrusion and precludes invading species.

10.1.5 Australian and International Examples of Flooding Forests

Flooding forests occur in most countries and tend to be overlooked until they disappear as a result of drainage or river modification. Major Australian examples are:

1. The river red gum forests of the Murray-Darling Basin. The best known example of these is the Barmah Forest on the Victorian side and the Millewa Forest on the NSW side, but there are many other areas along both the Murray and Darling Rivers and their tributaries. These include the Gunbower-Perricoota Forests and many smaller areas along the River Murray, and the Macquarie Marshes in the Darling River system.
2. The “swamp gum” forests of Victoria and Tasmania. *Eucalyptus ovata* is a common tree occurring in riparian and flooded habitat and, as is reflected in its name, is known as an excellent tree for flood-prone sites. Reflecting the relative infancy of appreciation of flooding forests, there is surprisingly little literature on its flood tolerance. Many other eucalypts have great potential for afforestation projects in flooding areas.
3. Mangrove forests (*Avicennia* spp.) found in large areas directly adjacent to the coast around Australia. These are usually directly exposed to tides, which leaves large areas of salt evaporate. Freshwater flooding from land appears to ameliorate this. Although, in aggregate, there are large areas, they tend to be located in remote and inaccessible coastal areas. They are usually are managed primarily

for coastal protection in Australia. In Asia similar forests are managed both for wood and food.

Internationally, examples include the swamp cypress forests of the Mississippi Delta (Sect. 10.3). Additional examples include:

1. Willow Forests of the Danube River in Central Europe. Currently these occupy only fragments from the area covered in the past, and belong to one of the most threatened forest ecosystems. The wettest areas are occupied by “alluvial forests” of willows, poplars, and alders. Higher, dryer areas have ashes, elms, and oaks mixed in. The forests are viewed as of great biological diversity and have a myriad of factors modifying them including needs for hydro-electricity, river navigation, and many river frontage developments.
2. Flooding forests of the Rio Negros (near Manaus, Brazil). This is a tributary of the Amazon, with the name reflecting the black, carbon-laden water that often emerges from flooding forests. The forests are famous for their biodiversity (Daly et al. 1989). Klinge et al. (1990) give a classification of forested wetlands in tropical South America, and show how extensive these are. They note that trees of the Amazonian inundation forests produce fruits and seeds that float on water, whereas species growing on nearby “terra-firme” (i.e. dryland) don’t. The areas show extreme forest destruction due to soil erosion by rivers; however this is counteracted by the establishment of new forest vegetation on recently deposited sediments resulting from erosion. The areas have extremely fertile soils which are replenished annually by the flood. Possible threats to the forests have been hypothesised but the area is large and remote and sometimes “difficult” to access.
3. Riparian poplar forests, found in river valleys along “the crown of the continent” in Western Prairie states of US and Canada. Rood and Mahoney (1990) pointed out that these are a major component of lush river valleys in otherwise barren plains. Withdrawal of flooding associated with damming of major rivers has caused decline (“collapse”) of the forests. Rood et al. (2005) notes that this situation is still far from resolved. The damming led to a lack of spring flooding which, in turn, led to decreased seedling establishment (because of moisture stress) and decreased forest health. Poplars are phreatophytes, gaining water directly from the water table, and thus reduced river flows and flooding impacts on forest health. Poplar seedlings are intolerant of drought but tolerant of flooding and hence withdrawal of flooding directly impacts on the regeneration of the forest. The removal of silt (and associated nutrients) by settlement in the dams is also hypothesised as a factor in their decline. Changing flow regulation can help ameliorate some of the issues but compromises other dam values.

10.1.6 Threats to Flooding Forests

By definition, flooding forests exists in an intimate alliance between the forest and the source of fresh water (usually a river). Most forests have evolved in a natural environment with their source of flooding. Thus the forests can be viewed as being in a long-term "equilibrium" with the flooding. The forest flooding can be viewed as supplying the forest with water and nutrients. In the case of red gum (*Eucalyptus camaldulensis*) it is likely that the evapotranspiration need is around 1,000 mm per annum, and the forests grow in areas with about 400–500 mm rainfall. Thus the difference is supplied by flooding. In the long term, if flooding with withdrawn from the forests they are likely to die. Most flooding forests also receive deposits of soil carried by the flood, and this is a net import of nutrients into the forest. Additionally, the flooding serves to exclude competitors since most dry-land trees cannot tolerate the many months of inundation.

Because of this intimate relationship with flooding, these forests are vulnerable to hydrologic change associated with river management. Most rivers have fluctuating water levels such that some of the time water is passing out of the river onto the floodplain. At other times, the water is either draining from the forest to the river, or the river is too low to be having much direct influence on the forest. In particular:

1. The forests may not receive enough flooding – commonly due to river regulation leading to reduced flows, but often this can be associated with blocking of inlet channels into the forest.
2. The forest may receive too much flooding due to abnormally high river levels and/or obstructed forest drainage. This also occurs when the forests become used as the recipient of drainage from large areas. A common cause of too much flooding is the maintenance of rivers at a level suitable for navigation.
3. The seasonality of forest flooding has changed – usually due to river regulation. Thus a forest that once flooded in the spring now floods in summer or autumn.
4. Water quality at times of flooding may be changed. In particular, many floodplain areas are net accumulators of sediments and nutrients. The presence of upstream dams often means that the sediment has settled in these. The water may also have substantially lower oxygen content and this can impair the respiration of the trees and impact on biota.

Such effects can be subtle and difficult to diagnose. Thus, in the Australian river red gum forests, areas further away from the river are deprived of flood waters due to the reduction of high flows, but areas close to the river are subject to semi-permanent inundation associated with irrigation flows. The presence of large dams has had a particular impact on reducing large river floods – these are the only floods that can penetrate to the far corners of adjacent forest.

Although the changes in flooding may have distinct consequences, the combination of forests and water is conducive to the presence of life. Hence there is abundant life in the flooded forest – the concern is that it is not the same "types of life" that would occur in a "natural" floods. In making such a statement, it is acknowledged that the definition of "natural" is also difficult.

10.2 Case Study 1: River Red Gum Forests of the River Murray

In economic terms, the River Murray is Australia's major river. This receives most of its input from high rainfall in the "Snowy Mountains" in the east of the country. The river then flows through sub-humid zones into South Australia, whereupon it passes to the coast. The river serves as the boundary between the States of Victoria and New South Wales (see Appendix 1).

Flood prone areas commonly carry the iconic Australian species river red gum (*Eucalyptus camaldulensis* – see Fig. 10.1). In some areas these form large forests. The largest of these – the Barmah-Millewa Forest, has achieved national and international recognition as a "Ramsar" wetland and bird-breeding area. The dual name reflects different names for the one ecological entity in NSW and Victoria. The term "forest" is not entirely accurate since it is a maze of waterways, native "grass" plains (actually a complex of grass and other species), and lakes. The area was formed by a fault (known as the "Cadell Tilt") causing a lake to form. Sediment deposition then led to an extensive flood plain. The river channel through the forest is a constriction in the River Murray's flow path. This constriction restricts the flow of water from the large dams to the east to irrigation areas to the west. If flows exceed the constriction capacity, then the forest floods. The presence of the forest is sometimes viewed as a limitation on economic development of irrigation areas downstream.

There have been many studies on the hydrology of the area and the impact of river regulation (e.g. Bren 2005). In particular:

1. The forests require water from flooding to provide water for growth. The trees can survive but not thrive on the 400–500 mm per annum annual rainfall.
2. Naturally the forests would flood for 4–6 months of the year – usually from late winter to early summer. Floods were driven by high spring rainfalls and snowmelt in the mountains to the east. The construction of large irrigation storages has diminished this source of flooding, so that the high flood peaks occur less frequently, flooding is shorter, and the frequency of floods is much more variable.
3. The river is now kept at bank capacity in summer to transmit irrigation water downstream. Often irrigators "reject" water at times of rainfall and this leads to unseasonal floods in the lowest-lying parts of the forest.

Cunningham et al. (2007) examined the health of river red gum forests along the length of the River Murray and noted that their health declines towards the western end of the river because of increasing withdrawal of water to meet human economic wants or needs. At the time of writing, provision has been made for “watering” (aka flooding) of about half the forest area. The remaining half cannot be effectively flooded under the current flow regime. The needs of some large forest areas downstream are being met by constructions of channels from irrigation storages or by pumping water into the forests. Smaller forests languish. Issues involved are noted below and are reasonably viewed as “generic” to flooded forests worldwide.

10.3 Case Study 2: Swamp Cypress Forests of the Atchafalaya Basin

This is the largest wetland in the United States and is located in south-central Louisiana. The Atchafalaya River is an alternative course of the Mississippi River and is a growing delta. The “forest” is actually maze of “bottomland” forests, “swamps”, bayous, and lakes. Only a few roads cross it and these generally follow the tops of levees or are on pylons. By law, flow through the Atchafalaya Delta must be maintained, but this has proven to be complex, difficult, and controversial. Issues include the diversion of the Mississippi River into the delta to relieve flooding pressures on downstream communities, maintenance of important navigation channels, derangement of hydrology by access canals for oil exploration, and increased penetration of salt water from the Gulf of Mexico.

As in other wetland forests, the area has a vast bird population and serves as a refuge for the endangered Louisiana black bear. It is now viewed as one of the last great wildernesses remaining in the United States. Because of its biodiversity it has always had a human culture which used the forest as a food source. In the last two centuries this centred around a “Cajun” (French-Indian) culture which has become famous for its cuisine. In recent times, economic activity has been centred on recreational activities (e.g. canoeing and hunting) and use of the areas for oil production. The forests have a distinctive visual appeal that attracts people from all over the world.

The major forests are of bald cypress (*Taxodium distichum* – see Fig. 10.2) and water tupelo (*Nyssa* spp). Faulkner et al. (2009) notes that the long-term sustainability of these swamp forest is unknown due to large-scale changes in hydrologic regimes that prevent natural regeneration. Seeds float and are disseminated by floodwaters. Seeds of swamp cypress will not germinate under water and seem to do best on wet but not saturated sites. Swamp cypress has a structure called “knees” – woody projections from the root system that project above the ground or flood waters. They were once thought to provide a pathway for oxygen to the roots, but are now viewed as providing structural support.

A comparison with Australian red gum forests showed a surprisingly similar collection of issues in hydrologic terms – derangement of the hydrology, changes in water sources and timings, and the need for the forest manager to tackle, head-on, large economic forces. One major difference was that for red gum forests, the basic problem was withdrawal of the flooding. For swamp cypress forests, the major problem was often excessive flooding with no drying out.

10.4 Quantification of the Flooding Regime

In any involvement concerning the adequacy of the water regime, a necessary first step is to quantify this. The biodiversity of flooding forests provides endless fascination for people involved in these areas. However the role of the forest hydrologist is to quantify past, current, and future flooding regimes that has allowed such biota to flourish. We will use work on Australia's river red gum forests to illustrate aspects of this.

No two years of flooding are ever the same, but generally analysis shows that forest flooding is consistent and reproducible given the same inputs and "system settings". More usually, only a few of the inputs are known and the "system parameters" are usually unknown or uncontrollable or both. The result is that large flooding forests behave more like a "chaotic system" in which small changes to inputs lead to large changes in behaviour (see Sect. 10.4.5). There are many variables that can be useful in defining flood characteristics. We have defined some of these and suggested some methods of estimation. It is stressed that there is no perfect way of providing all information, and that in any particular case there will always be difficulties.

10.4.1 Sources of Flood Water

Usually the source of water is one or more major rivers passing through the forest or along the forest edge. Often these are "distributaries" in which a channel has bifurcated or passed into an "anastomosing" (irregularly branching and rejoining) network which ramifies through the forest. In such a case the nearest flow record upstream of the forest is often the best source.

Figure 10.3 shows the derived relation between the percentage of the Barmah river red gum forest flooded and river flows in the River Murray at Tocumwal (NSW) as given by Bren (2005). In this case, flows above about 12,000 ML day^{-1} would begin to flow over low points in the bank of the river into the forest. Once in the forest it was lost to the river in a meandering series of channels, cut-off meanders, and wetlands. As flow levels rose, more and more water passed into the forest. At about 60,000 ML day^{-1} the extent of forest flooding was essentially complete. At higher flow levels the depth of flooding increased, but the areal extent hardly varied.

These data were derived by using annual flood maps, computing the percentage of the forest flooded, and relating this to monthly flow records. As such, the data used represented a collection over about 25 years. Such a relationship is invariably a

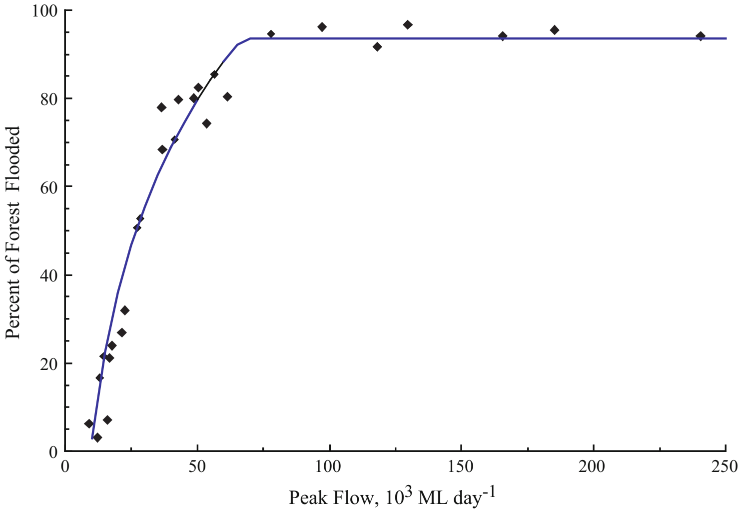

Fig. 10.3 Derived relation of the percentage of Barmah Forest flooded as a function of peak flow in the River Murray, Australia (Bren 2005)

simplification of complex hydraulic processes. There are many other variables (usually unknown) that influence such a relation, including the settings of water diversion gates, and the rate of rise of the river. Derivation of such a relationship (albeit crude) is an essential first task in quantifying hydrology, since it allows flow data to be converted to a first (albeit approximate) estimate of forest inundation.

10.4.2 Annual Flood Frequency and Annual Flood Duration

At any point in the forest an annual flood frequency and an annual flood duration can be defined. Flooding frequency is defined as the percentage of years for which a given point receives inundation. Flooding duration is defined as the average number of months in a year for which that point is inundated. In general there is a correlation between the two. Thus points with a high flooding frequency usually have a long flooding duration. In general, there is an ordering of ecological associations of plants with the different flooding frequency and duration. Thus, in the Barmah Forest we can define:

High flood frequency sites. This includes almost permanent inundated sites in which no ground plants grow, giant rush, reeds, and passing down to the "Grass Plains." The grass plains are complex assemblages of non-tree water plants. Typically, these may be flooded 80 % or more of years, with the areas being under water for 9 months or more in a given year.

Medium flood frequency sites. In general, these carry red gum with a diverse understorey; the understorey and tree growth reflects the frequency and duration of flooding. Typical flood frequencies and durations are about 25–80 % and 2–9 months respectively.

Low flood frequency sites. These tend to be areas near the edge of the forest or sandhills running through the forest and probably surrounded by lakes in a geological past. Flood frequencies and durations range from 0 % to 25 % and 0 to 2 months respectively. Tree cover in these is often smaller and less-developed red gum or black box (*Eucalyptus largiflorens*). These areas are often used by fauna for refuge to escape flood waters during flooding.

Colloff et al. (2013) looked at the change of native grassy wetland (*Pseudoraphis spinescens*) boundaries in the River Murray system including a major area within the Barmah Forest (Fig. 10.4). This ecotype has suffered major contraction associated with invasion from river red gum (Bren 1992) and reeds. They concluded that this species requires marked wet-dry conditions that recur almost annually; flooding needs to be deep enough and long enough for the plant for form a sward, and the dry phase long enough to eliminate competitors. The newer flow regime does not meet these conditions because of irrigation commitments. Colloff et al. (2013) concluded “provision of a flood regime that most closely matches plant-specific water requirements. . .represents the single management action that holds the best prospect for conservation and management of grassy wetlands.” Given the importance of the River Murray to four Australian states and the complexity of water management, this is more easily said than done.

10.4.3 Flood Seasonality

For a natural river system, the sequence of annual flows is usually predictable. Thus in Australia’s River Murray, low flows usually occur in late spring to autumn. At the start of winter higher flows and “freshets” – periods of storm-flow – start to occur. During late winter to mid-spring the period of highest flows occurs. This is illustrated in Figs. 10.5 and 10.6. Typically forest flooding occurred in the mid-winter to late spring period.

River regulation since about 1932 in this system has led to changes in the seasonality of flooding. The net result is that the low flows which occurred in summer and autumn have been replaced by flows at the maximum in-stream capacity of the narrowest point in the river channel through the forest. Miscalculations or unexpected periods of rainfall lead to flows passing into wetlands close to the river. Thus some areas receive unseasonal floods. At the same time the vigour and regularity of the spring floods has been diminished (Fig. 10.6).

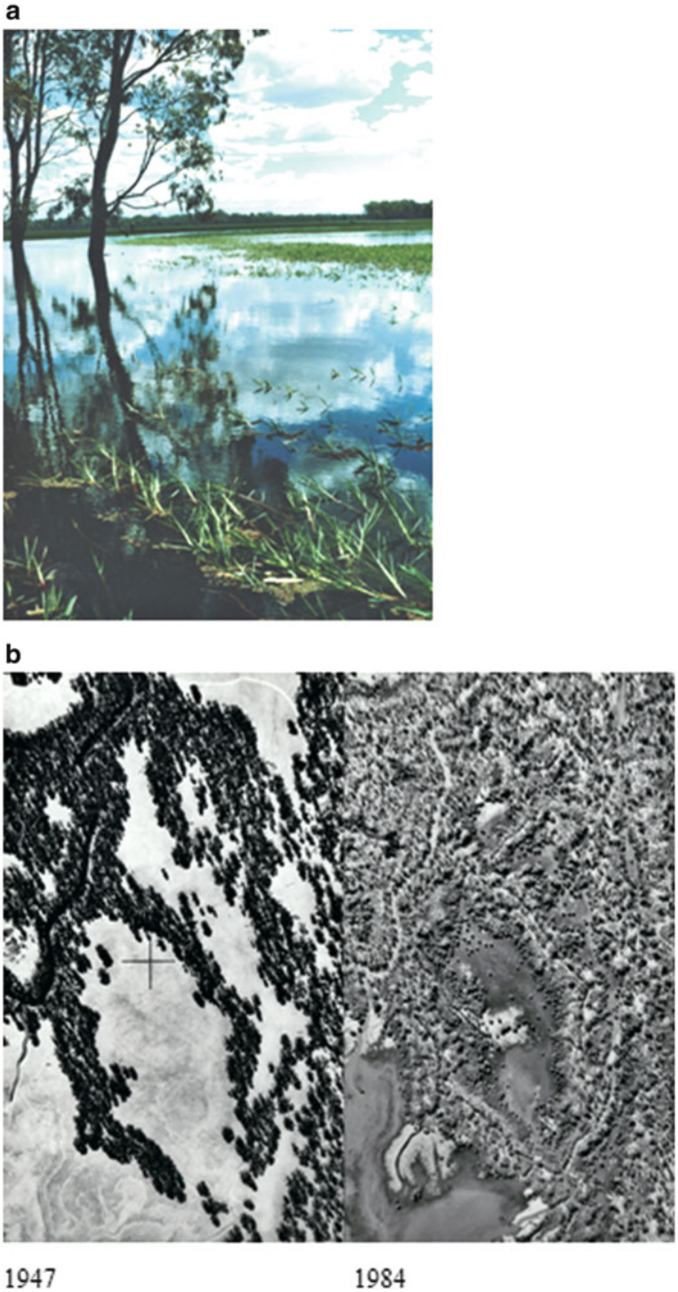

Fig. 10.4 The fate of the Moira Grass plains. (**a**) View across the plains and (**b**) Vertical aerial photographs of the same area taken 37 years apart. The encroachment of red gum onto the plains is clearly evident (Bren 1992)

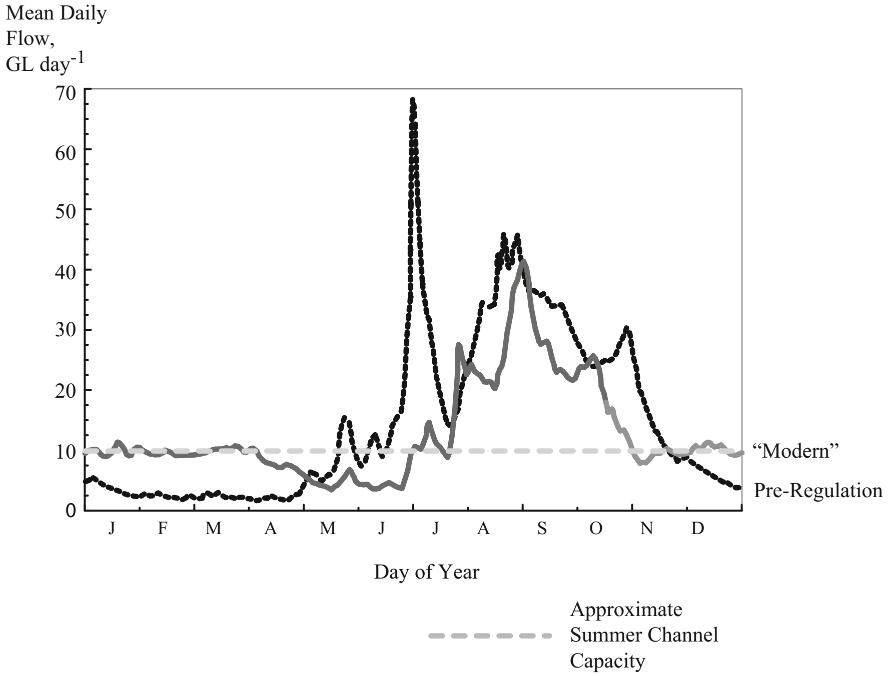

Fig. 10.5 Mean daily flow in the River Murray as a function of the day of year for a "pre-regulation" and a "post-regulation" period and the channel capacity through the forest in the summer and autumn period (From Bren 2005). A gigalitre (GL) is 10^9 L

10.4.4 Methods for Quantification

In general, the forest hydrologist has a wide variety of methods for quantification. In principle, sophisticated remote sensing and use of "LIDAR" to give topographic information can provide large amounts of information. Figure 10.7 shows a "LIDAR" image of a portion of the Barmah Forest.

The most basic steps are:

1. Mapping of flooded areas and relation of these flood maps to periods of flow. If the river is held at constant flow for long periods of time it may be possible to produce a flood map as a function of a particular river flow. More usually the flood map is viewed as representing peak flow or peak monthly flow. The map may be prepared by use of remote sensing, or field inspection. The author's experience was that aerial inspection of a flooded forest is a useful thing to do.
2. Collection of hydrographic data on flow in the river(s) during the period of map preparation.
3. Input-output analysis. If there are records of river flow above and below the forest, by differencing the summed inflows and summed outflows, it may be possible to obtain the volume of water stored in the forest as a function of time.

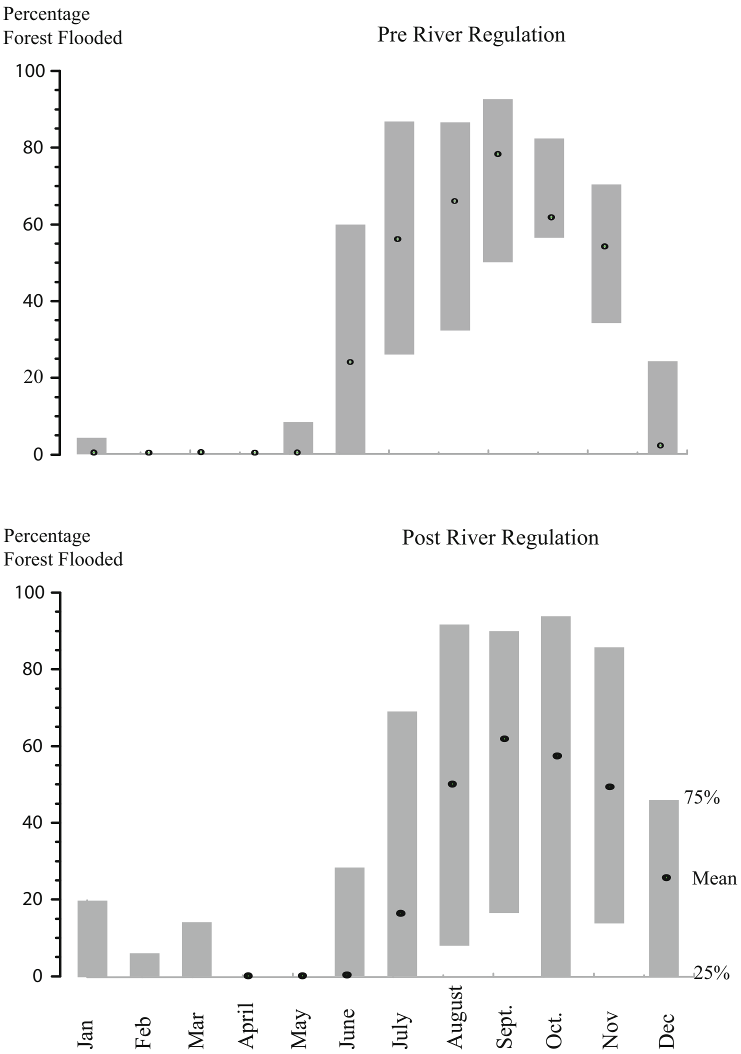

Fig. 10.6 Box plot showing the mean, and 25 %, and 75 % percentiles as a function of months for the pre and post river regulation since the first dam was constructed on the River Murray in 1934. The reduced post-regulation mean and the enhanced variability are clearly evident

The author's experience in doing this has not been good; despite the soundness of the idea, the error level in flow data are commonly so high that little credence can be placed on the computed numbers.

4. Collection of information on the "settings" of factors that control water level in the forest. These may include dam outflows and water gate settings.
5. Examination of past records. Often files of agencies contain maps of the extent of flooding for particular events.

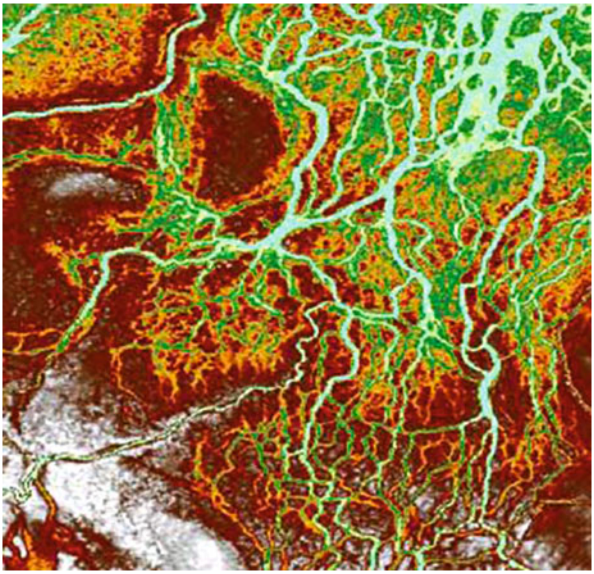

Fig. 10.7 Portion of a digital terrain model formed from a "Lidar" scan of the Barmah Forest. The interlinked channel network providing flow is clearly evident and indicates the complexity of flood modelling using this approach. Illustration by courtesy of Ben Tate of Water Technology Pty Ltd and Department of Environment and Primary Industry (Victoria)

6. Talking to neighbours, old residents, etc. Often these people have spent decades being "forest watchers".
7. Survey of forest health, looking for indicators consistent with withdrawal of water (in red gum, crown dieback), or excessive water (in red gum, invasion by a blue-stain fungus).

More dynamic work may include collection of water levels over time at various points in the forest, measurement of flow velocities and direction, and observation of water at key locations in the forest.

A number of "modern" techniques may help. Use of "LIDAR" permits accurate topographic maps to be made. Use of complex hydraulic models (e.g. the "MIKE" series of hydraulic models) may allow complex scenarios to be evaluated (e.g. Thompson et al. 2009). However the costs and overheads of such techniques are large. Usually such projects would be undertaken as joint exercises between the river managers and the forest managers once a certain level of quantification had occurred. Not the least issue with complex models applied to complex forested wetlands is the question of whether the results being returned represent "reality." Dai et al. (2010) examined the performance of the MIKE SHE model of a forested watershed to estimate groundwater depths on a coastal plain in South Carolina and concluded that the model could give reasonable agreement with observed data, but observed that modelling of the spatial distribution of shallow groundwater remained "challenging". The author's experience is that the use of "advanced techniques" is not for the financially faint-hearted.

10.4.5 Chaotic Hydrologic Systems

Classically, the hydrologic systems of upland streams are "stable" systems in which a small change in some aspects leads to a correspondingly small change in the output. Thus, in a catchment (and, with all other factors equal), a small increment in rainfall will lead to a small increment in stormflow generated.

In contrast, the spatial hydrology of major wetland forests is often "chaotic." In these a small change in some factor leads to a completely different output. The concept was first elucidated in mathematics. In classical simulations one has the governing equations, the "initial conditions" of the system, and the "boundary conditions" controlling what enters or leaves the area of the simulation through the edges. In stable systems, a small change in a parameter or condition will lead to a small change in the output. If that change is halved, then the change in output will fall by approximately half. In contrast, in a chaotic system, the smallest change in a parameter or condition may lead to very different outputs or behaviours. The system is reproducible in that if all conditions and parameters are the same, then the system will behave in the same way. However, very small differences (usually unavoidable) in a chaotic system lead to very different outputs. Since in any system, the parameters and inputs are never exactly the same, a chaotic system will exhibit "wild" behaviour.

Many flooding forests exhibit chaotic behaviour in their hydrology over at least some of the flooding range. Thus in an analysis of behaviour of red gum flooding, we found that very small floods and very large floods were predictable (the forest had almost no water or was completely inundated). However intermediate floods exhibited much variability and no two floods were completely the same. Examination of why this was so suggested some variability was attributed to where the water entered the forest. However much was also due to the fact that water would favour different flow paths at different times. This seemed to reflect forest debris, recent silting, and hydraulic roughness in complex flow channels. An example of this was water flowing into a Y junction, in which accumulation of forest debris would tend to make water favour one branch of the Y over the other. This debris would then wash away, leading to the other branch being favoured. The result is that the junction effectively behaved like a random switch. This, combined with other such junctions and many other factors gives a chaotic element to flood behaviour. Thus, quantification of the flooding of a large, forested area will always have a statistical component to it.

Although chaotic behaviour may be unavoidable, floodplain management should aim at avoiding new sources of variation. In particular, blockage of flow conveyance channels and creation of new flow conveyance channels is a particularly potent source of hydrologic change.

10.5 Negotiations with River Managers on Forest Issues

Around the world, rivers are viewed as valuable assets. Thus, in Australia, the River Murray collects water from the mountains to the east and flows to exit to the sea near the major city of Adelaide. Water from the river sustains the capital cities of Melbourne and Adelaide and many provincial cities, towns, and individuals. Flow in the river provides water for irrigation communities. Much tourism is based on recreational boating and river flows must be maintained at an adequate level to both sustain navigation and to give river-land visitors a "suitable experience". Most major rivers would have a similar list of users and "constraint use".

Almost more than any other hydrologic issue, dealing with flooding forests puts the forest hydrologist on a collision-course with managers of major water resource installations. River structures typically cost vast amounts of money, were once viewed as icons of "community progress", and are integral to the financial viability of regions and cities. Usually the structures were built before forest flooding issues were defined, and hence the management may have well-defined practices which have evolved over many years. Suggesting that these be modified to help overcome forest deterioration issues can be a brave act.

Over the years and around the world, there has been some success in modifying river regulation to assist in forest management. It is usually a compromise situation since river managers have many other demands to meet. Success appears to be associated with:

1. Quantification of the hydrologic impacts in terms of the key variables (usually flow and its annual variation) used by the river managers. This allows proposed flow regimes to be translated to impacts on the forest.
2. Developing concepts of structures which may help alleviate issues in the forests. Structures may include water gates to allow water into or exclude water from the forests, channels to take water to distant parts of the forest, levee banks to avoid flooding of neighbouring properties, and pumping systems to take water to distant parts of the forests. Structural solutions to flooding issues are a double-edged sword since the structures themselves may exert a large "footprint" on the forest (e.g. roads, power-lines, channels, earthen banks) and usually involves a new sequence of problems. Energy costs of any system that involves pumping water can be very high.
3. Definition of the economic and environmental services given to the community by the forests, and quantification of the loss over time. This provides an excellent starting point in initiating negotiations with river managers.

The Australian experience with red gum forests is that there is massive "goodwill" towards the forests, but that each forest has a different collection of issues which are not easy to resolve. Solution of these issues becomes intimately involved in wider issues such as States rights in water ownership (the forests sometimes straddle Victoria and NSW), the division of water between water users (i.e. city consumption, irrigators, and environmental needs) and the issues of what is "natural" in a substantially-managed system. People involved in such areas are often passionate advocates for their particular cause. Any solution reached is always going to be a compromise between the different facets. Pleasantly, flooding forests have evolved in an environment of flow variation. Thus the impacts of flooding change are felt in the long-term rather than the short-term.

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Chapter 11
Catchment Management Issues World-Wide

Abstract Water catchments meet a vital need for water in our society. Good catchment management is a first protection method; others are dam storage, water treatment, and good distribution networks. Catchment management is usually a compromise strategy between many difficult issues. In general, forested catchments yield less water than agricultural catchments, but the water is of higher quality. Simple runoff relations such as "Zhang Curves" can be used in planning the water supply capacity of new, forested catchments. The attitude of the public to active forest management on water supply catchments appears to be dependent on their past exposure to managed catchments. Thus if the catchment has had a long history of forest harvesting and there are few perceived problems, then the harvesting will be uncontroversial. However if there is no such history then harvesting is likely to be controversial. The aim of modern forest management in catchments is to generate "resilience" in the forests. Most catchments of the world have little latitude in how they can be managed because of population pressures.

11.1 Issues, Issues Galore in Catchment Management

Consider the issues of a catchment manager. A major city with big catchments providing water to sustain residents, industry, and tourists! All expect that when they turn a tap on, clean, drinkable water will come out. On the few occasions in the past when this has faltered, the reaction has not been kind to water authorities. The catchments pass water into dams; the dams pass their water into outlet pipelines which are interlinked to pass water into or around treatment plants. From there, the water goes into a maze of interconnected pipes, tanks, service reservoirs, and more pipes until, finally, it passes to the consumer. There is a somewhat analogous maze of waste-water pipelines and facilities, but they are not (usually) a part of this story.

Clearly the catchments are of vital importance to the city's future since these supply raw water to the city. How should they be managed? Should people be allowed to live, farm, and run businesses in them? Or should they be untrammelled wilderness lands? The newspapers are claiming that "terrorists" might get into the catchments and "poison the city" and this has caught the ear of the politicians, but the laboratory people say they couldn't do it. To whom should one listen? And

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should the land management aim at being pro-active towards pollution hazards, abolish any pollution hazards, or just do the best with the water that comes out?

And what of the forests in the catchments? Some of them are getting old. This might be advantageous in that they use less water than younger forests, but some areas are changing into a succession form of vegetation that is less attractive. Indeed, many of the forest areas have a “ragged appearance” and observers comment on how sick many of the older trees look. What are the options here? Traditionally anything that involves “forest management” (involving cutting trees) in the catchment has been very vocally opposed by a citizen action group (“Friends of the Catchment”) who also have the ear of leading newspapers. Will the papers come down against any forest management? And many of the catchments are now national parks to preserve conservation values. What does this mean? Is some sort of catchment management to preserve water values possible in a national park?

To add to the catchment manager’s woes, the question of forest disasters comes up. In the past there have been massive wind-throw, insect attack, and fires. More recently it seems to have been fires, fires, fires. There is a mountain of reports looking at the fire protection options which seem to concur on recommending a big investment in roads and helipads to support active fire suppression, with lots of fuel-reduction burning on northern slopes and some cutting of “fire-breaks”. Where do these sit with national park values and “closed” catchments? In the past our organisation had said that this was all “excessive!” Can we and should we do an about-face on this? All of this burning would mean lots of tankers and people, and exposure of the catchments to chemicals such as wetting agents and fire retardants. There is the risk that about 1 in 10 of the fuel reduction burn goes awry; how will we look when that inevitable day comes when the lit fire burns adjoining farms and houses? And those roads all contribute their share of turbidity to the water too.

So here you are, as the catchment manager. You possess the wisdom of Solomon – that’s why you got the job. What could, should, or would Solomon do?

In forest hydrology, catchment management brings together social, political, technical and economic issues in complex ways. The art of catchment management is to both meet the need of a community for water and to observe other requirements as well in a sustainable and economically feasible manner.

11.2 The Basic Water Supply Catchment

Our concern in this Chapter is with the management of catchments for water supply. Figure 11.1 shows this as a schematic. A stream passes water into a dam, which supplies water to a township. The town is in a lower topographic position than the dam so that water has enough energy to pass to the town, and the both the stream and dam size is are large enough so that the dam always contains water (i.e. there is enough reserve storage in the dam to accommodate long periods of low flow in the stream). If this is not the case then there may need to be supplementation by

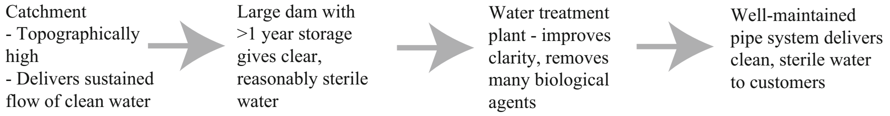

Fig. 11.1 Schematic of a safe water supply with multiple levels of protection for the community

additional dams, use of groundwater, use of desalination, or transporting water in from an external source.

Assuming both the stream and the dam are of adequate size then the town has an assured water supply. There are two traditional protectors of public health. The first line of defence is good catchment management to ensure that water that passes into the dam is at least of adequate quality. The second (beyond the scope of this text) is storage in the dam for a year or so. This dilutes any contaminants, allows sediment to settle out (improving turbidity), and causes organisms to die, thereby making the water sterile. Until relatively recently, a well-managed water catchment and a good dam were considered as all that was necessary for towns large and small.

More recently two additional lines of defence have become common. The first of these is "water treatment" which gives coagulation and removal of fine particulates and corrects for any perceived chemical issues. This process may remove some organisms which have managed to pass through the dam. The second is some form of disinfection (commonly chlorination) which actively kills bacteria in the water. Thus water passed into the distribution pipe should be sterile, very clear, and have chemical properties suited to the end uses. A fifth line of defence is available for larger systems, in which "problem water" can be bypassed or diluted by using alternative dams and pipelines. Introduction of these lines of defence gives far greater flexibility in catchment management because local deficiencies in water quality or water yield can be overcome.

11.3 World's Best Practice in Catchment Management

One definition of "best practice" is a method or technique that has consistently shown results superior to those achieved with other means, and that is used as a benchmark. The Division of Forestry and Wildlife of Hawaii defined this as "effective, practical, structural or non-structural methods which prevent or reduce the movement of sediment, nutrients, pesticides and other pollutants from the land to surface or groundwater or which otherwise protects water quality from potentially adverse effects of silvicultural activities. These practices are developed to achieve a balance between water quality protection and the production of wood crops within natural and economic limitations."

The assumption is that "best practice" will be a compromise but somehow provide an optimal solution to meet a plethora of social, economic, environmental, and economic goals, and that the land manager can, somehow, weave a path between the various obstacles to meeting their aims. This is not always the case; in many places in the western world there is strong public support for "closed catchments" (see below) and in these there are few politically-acceptable options for catchment management other than maintenance of the status quo until some form of disaster, climate change, or ecological change overwhelms the existing policy.

Although the term "best practice" is vague, it does point the way towards development of a series of practices suited to a particular site that cater for various needs. Best management practices for catchments may include provision of:

1. Specifications and prescriptions for roads.
2. Harvesting regulations laying out prescriptions for:
   - When cutting and harvesting are allowed.
   - Type of machinery to be used.
   - Methodology for defining and marking buffer strips around streams and other hydrologically sensitive areas.
3. Types, rates, and restrictions on herbicides and pesticides, and restrictions near streams.
4. Methods for dealing with particular forest types.
5. Prescribed fuel reduction burning.
6. How rules and regulations are to be enforced.
7. Use of documentation aids (GIS packages, etc.) that give analysis and documentation. See Zhang and Barten (2009) for an example of such a package.

11.4 The Public and Attitudes on Catchment Management

Survey of the scant Australian literature on this and observations of reactions over the years suggests the following:

1. In general, the public has a scant knowledge of the streams from which their water comes, but knows that they are "out there somewhere." This is particularly the case for "closed catchments" since the public cannot visit these areas.
2. The public is conservative and is happy to continue with arrangements which have been shown to deliver pure water. Thus if the catchments have always had a tradition of forest management and logging then forest harvesting is not an issue. If there is no history of forest management other than maintenance of the status quo then any change will be resisted.
3. The public is suspicious about any change in management arrangements, particularly if it involves logging. Thinning of the forest is more likely to be tolerated. Scientific evidence showing no impact of the forest management on

water supply does not always appear to impress the public and is often disputed with unusual vigour.

4. Failures of the water supply system leading to impairment in water quality (particularly health) which impacts on either health or the local economy leads to some form of political retribution. Sydney's "*Giardia* crisis" is an example of this.

11.4.1 Sydney's Giardia Crisis

This involved the supposed contamination of Sydney's main water supply, the Warragamba Dam, by the pathogens *Cryptosporidium* and *Giardia* in 1998. At the time Sydney was preparing to host the 2000 Olympic Games. Announcement of possible contamination and the issuing of "boil water" alerts (in which water should be boiled before drinking caused disbelief and disquiet. Sentiments along the lines of "How could this happen to Australia's largest city?" were expressed on talk-back radio. Headline writers enjoyed the crisis (e.g. Large headline "Contamination", sub-heading "A taste of the third-world", and the article starting "Sydney woke yesterday morning and found itself in the third-world").

The contamination was thought to have been caused by low-quality stream-water entering the dam. The catchments are a mixture of forest, agricultural land, and urban areas, and so there are many possible sources. There was no measureable outbreak of any sickness associated with the supposed infection. Suggestions made at a later inquiry included misidentification of microbes, over-estimation of their abundance, and an overly-dramatic response by the various authorities involved. The handling of the "crisis" by Sydney Water (a state-government owned Corporation) was heavily criticised and led to the resignation of both the Chairman and the Managing Director. The question of whether a Government-business ownership of water resource facilities contributed to the incident became a source of major debate. As a result the "Sydney Catchment Authority" was created in 1999. This assumed control of Sydney's catchments and dams, with a charter of improved monitoring of water quality. A comprehensive reference on this is Stein (2000) and an interesting commentary on the politics of the crisis is found in Carson and White (1998).

Giardia and *Cryptosporidium* are found in faecal matter from both domestic and wild animals and cannot be completely removed by most water treatment or chlorination. Most water supplies around the world have some exposure. Carson and White (1998) pointed out deficiencies in the approach of many groups to the "crisis" with many aiming to make both short and long-term political gains. The incident did highlight that no city is entirely safe from water pollution incidents and that a failure in the catchment/dam/water treatment system leads to retribution at a political level. The Sydney Catchment Authority now has a strong "catchment health program" involving catchment science, interaction with communities, developing appropriate legislation, reducing pollution sources, and managing emerging catchment issues.

Ashley Webb (Forests NSW) used a study tour to examine the application of "Payment for Catchment Services" in which the people of a city pay for specific catchment improvements to improve water quality. He noted that such schemes could have direct application to catchments such as those of Warragamba Dam (part of Sydney's water supply), in which 60 % of the land is privately owned.

11.5 "Open" or "Closed" Catchments?

For most catchments of the world, the land-use is well-established, and the catchment manager's task is to cajole or coerce the population towards "best management practice." In some cases cities have large tracts of forest land which are effectively "owned" as water catchments and they can control the land use to some extent. Thus the city of Melbourne, Australia has progressively extended its catchment area to about 154,000 ha of forest. Much of this has been used almost exclusively for water harvesting. Both the forests and the water yield reflect the very high rainfalls over much of the area; at the time of dedication of the catchments to supply water for a distant Melbourne there was bitter resentment by the timber industry that their best resources were withdrawn (see Evans and Calver (2005) for an interesting account of this). A century or so later there has been strong and continued support by the people of Melbourne for the maintenance of the status quo. However other factors including the continuous growth of Melbourne, restrictions caused by the catchments to regional economic development and the impacts of major forest fires will lead to difficulties for the maintenance of such policies in the future. Significantly, more recent expansions of Melbourne's water catchments have not imposed the same restrictions on land-use and entry as in the "older" catchments.

11.5.1 What Is a "Closed Catchment?"

A closed catchment is one in which the only land use allowed is water-harvesting, and in which entry to the catchment is limited to water management personnel. Examples of truly "closed catchments" for major cities are rare but include parts of Melbourne's water supply system and, arguably, the "Bull Run" catchment of Portland, Oregon.

As originally envisaged, a closed catchment would have little or no human visitation. Most have a basic road network to service water diversion equipment. Major fires have made Australian catchment managers sensitive to fire protection needs and now most catchments have a network of roads for fire access. More latterly "fire breaks" – gaps in the forest cover – have been cut; these arguably provide a basis for burning back during major fire operations but also impair natural values.

11.5.2 Advantages and Disadvantages of Closed Catchments

For most communities, the pros and cons of closed catchments are academic since, without substantial (and politically unacceptable) dislocation of local populations, they cannot remove settlement from within their catchment. However closed catchments offer:

1. Generally water of high chemical and physical purity. Roads may lead to some deterioration in water physical quality. Biological quality can be variable (and often poor) because of the presence of large populations of native and feral animals. Because of the “conservation” status of such areas, animal control methods to reduce faecal contamination are likely to be controversial. In Australia, populations of feral horses and deer cause poor water quality. Limited culling of these have been undertaken.
2. Meeting a public perception of “good catchment management.”
3. Substantial freedom of the catchment managers to optimise the water supply aspects (or do what they want) without having to deal with residents and the public.

They have their share of disadvantages:

1. Their presence may cause bitter resentment by local residents who feel that local resources are being “stolen” by a distant city which has no interest in their area other than to harvest “their” water which is then sold commercially to residents in other catchments. In some cases there is little or no provision for environmental flow downstream after water diversions. Evans and Calver (2005) discuss this as a historical factor in Melbourne’s water development.
2. Their presence dislocates road and rail networks which must go around the areas or accept unusual restrictions on road standards, size of cuts and fills, traffic parking, and traffic that can use it. This, in turn, offsets environmental effects of land management on other, neighbouring areas. As societies become more sophisticated, this becomes less and less acceptable.
3. Catchment authorities have traditionally been reluctant to pay land taxes and rates on their land, arguing that the land is held for the good of the city. Critics of this have pointed out the large profits sometimes made by these water supply authorities using monopoly powers. Some water supply authorities make a voluntary payment in lieu of foregone rates.
4. The management authority must bear the full cost of managing the land, including weed control, fire protection, and feral animal control. There is little cash-flow generated by the land use other than the water value, so the land-value is not being optimised in an economic sense. The value of the water to the Water

Supply agency is an interesting matter of "transfer pricing." Sometimes the water may be given a low internal value so that catchment management is effectively a loss-maker. Effectively this subsidises the cost of the water supply into the city, but also makes claims for taxes and rates applied to the catchments harder to sustain.

5. Policing of the "closed" aspects can be onerous and difficult, and has often been actively resisted by community groups such as hunters.
6. Because the "closed catchments" may have high conservation values, this can lead to them being placed in reserves under the control of other government agencies. This may result in "difficult" situations in which water production may compete with conservation management.
7. The "closed" policy precludes visitation to attractive areas with waterfalls, large trees, etc. This restricts local eco-tourism.
8. The non-availability of catchment access to the public generally means that the public has little idea of the catchments or their management problems. Hence it is difficult to build up a "fund" of public goodwill to help tide over occasional management issues.
9. Because of an absence of competition, the catchments can develop large populations of birds and animals which impair water quality. These can be difficult to manage without unacceptable culling.

It is of note that the city of Melbourne was very positive towards "closed catchments" for most of the twentieth century. However, in recent decades, their expansion of water harvesting capacity has meant shared land uses with recreationists, forestry, and agriculture and a shared irrigation and water supply dam which allows water-based recreation. This has been associated with interlinking of reservoirs and introduction of a number of water treatment plants and a large desalination plant, so that raw water quality from reservoirs is of less importance than in previous decades. It is the author's view that the concept of a closed catchment was a useful one for less sophisticated water supplies but is outdated and will, in time, fade away in a modern world (Box 11.1).

Box 11.1: "The Battle of Bull Run"

Historically, Melbourne's "closed catchments" have often been compared with the "Bull Run" catchments of Portland, Oregon. This is U.S. Forest Service Land providing water for this city. In 1952, logging commenced in this 25,000 ha forest. This began a battle (described by Larson (2009) as "Machiavellian", "long-running", and "bitter") between the forces for and against logging. The major argument against logging was the impact on water quality. The US Forest Service cited a need to improve forest resilience. There was an agreement between all parties that any decision to log or not to log must be "science-based" but there the agreement ended. Larson (2009) notes that "scientific data supporting one side's position was summarily

(continued)

Box 11.1 (continued)

rejected by the other as inconclusive or incorrect”. Finally, in 1996 logging and commercial forest management in the catchment was banned by a Federal law. The conflict illustrates the basic conservatism of communities when it comes to their water catchments.

11.6 How Much Catchment Do We Need to Supply a City?

Chapters 2, 6, and 7 presented the runoff curves of Zhang et al. (2001) for evapotranspiration (ET) of forest and grassland as a function of annual rainfall (P). The curves can be expressed as:

Forest

$$Q_f = P - \left(\frac{1 + 2,820/P}{1 + 2,820/P + P/1,410} \right) P \tag{11.1}$$

Grassland

$$Q_p = P - \left(\frac{1 + 550/P}{1 + 550/P + P/1,100} \right) P \tag{11.2}$$

in which Q_f, Q_p is the annual streamflow in mm generated by an annual rainfall of P mm.

Consider a citizen consuming 400 L day^{-1} on average (this figure is the average consumption per head of the author’s home town, Ballarat). Then, over the course of a year the citizen has consumed $\left(\frac{400\ 365}{1,000,000}\right)\mathrm{ML} = 0.146\,\mathrm{ML}$. Suppose this amount of runoff was produced from a forested catchment of area A_f(ha). Then the runoff in mm is $\frac{0.146\ 100}{A_f}$, where the factor of 100 reflects that 100 mm = 1 ML ha^{-1}. More generally, the runoff in mm per annum required is $\frac{v\ 365}{10,000A_f}$ where v is the daily water per head consumption in litres.

To determine the area of forested catchment necessary as a function of P, we can state this as an equation:

$$\frac{v\,365}{10,000\,x\,A_f} = P - \left(\frac{1 + 2,820/P}{1 + 2,820/P + P/1,410}\right)P \tag{11.3}$$

It is then a simple matter to derive A_f as a function of P for forest land by transposition.

$$A_f = \frac{v365}{\left(P - \left(\frac{1+2,820/P}{1+2,820/P+P/1,410}\right)P\right)10,000} \tag{11.4}$$

By similar logic for pasture:

$$A_p = \frac{v365}{\left(P - \left(\frac{1+550/P}{1+550/P+P/1,100)}\right)P\right)10,000} \tag{11.5}$$

An alternative presentation is the number of people served per square kilometre of the catchment. This is given by $\frac{100}{A_f}$ and $\frac{100}{A_p}$ respectively.

Figure 11.2a shows the two curves in which the area per head is shown as a function of the mean annual rainfall and a daily consumption of 400 L. For ease of comparison, Fig. 11.2b, an alternative form, shows the number of people served per kilometre^2 as a function of the mean annual rainfall. Table 11.1 presents a table showing these values. It is to be noted that these curves are very general but do allow a basic quantification of the amount of catchment. Of particular note is:

1. The curvilinear increase in the number of people served by a catchment as its mean annual rainfall increases.
2. The differential between pasture catchments and forested catchments in terms of the water yield. In general this is compensated for by the higher water quality and sustained outflow of the forested catchments.
3. The diminishment of yields when rainfall is lower than anticipated. This highlights the vulnerability of cities relying on finite catchments to sustained drought.

Given this, estimating the population that a given forest area can supply with water is, in principle at least, simply a matter of working out the water yield of small blocks – “tiling the catchment.” The procedure is as follows:

1. Establish the estimated consumption per head of population, taking into account sources such as recycled water.
2. Derive a rainfall isohyet map using whatever long-term data are available.
3. Establish catchment boundaries such that any water flowing into the stream can be collected by a mechanism such as a dam or diversion weir.
4. “Pixelate” the area passing water into the diversion point into appropriately sized units (usually 1 km^2 blocks is adequate for most purposes).
5. Compute the rainfall for each “pixel”

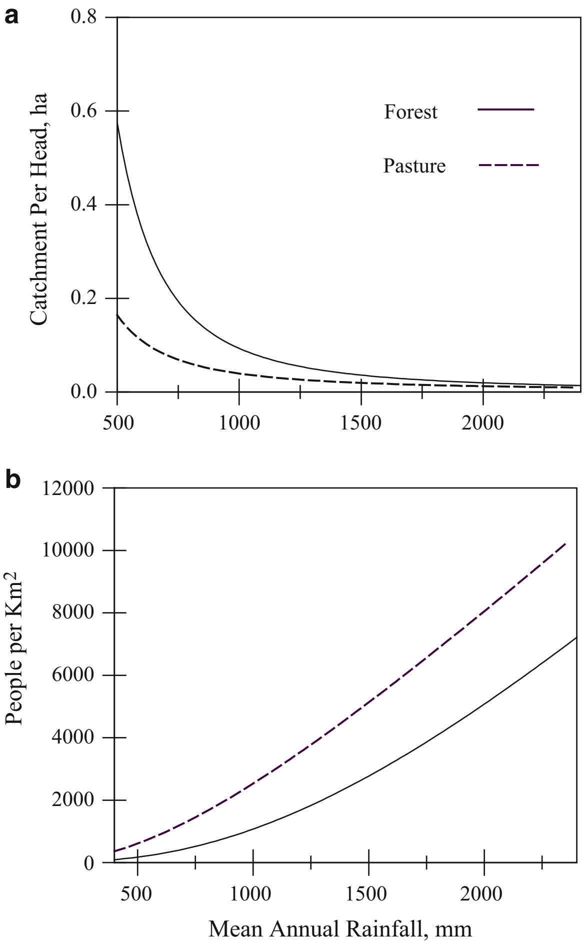

Fig. 11.2 (**a**) Area of land per person as a function of mean annual rainfall. (**b**) People per km^2 as a function of mean annual rainfall

6. Decide the land use (pasture or forest). For the level of such preliminary planning a binary subdivision is usually adequate.
7. Use Eqs. 11.4 or 11.5 to compute the contribution of each "pixel" to the population served.

Although the procedure is conceptually simple, there are a number of real difficulties when this is done in real life. The first is the question of obtaining adequate rainfall information over large and sometimes remote forest blocks. Secondly is the question of how streamflow is to be "picked up" and transported to the town in question. Thirdly, the use of the curves of Zhang et al. (2001) assumes mean values, but takes no account of "bad years." Thus it is assumed there is adequate storage and a margin for safety for such years. In principle, an automated procedure and use of past rainfall records could produce likely highs and lows of such catchment outputs. The major difficulties are, of course, "ownership"

Table 11.1 Derived table showing catchment per head of population and people per km^2 of catchment for forested and pasture catchments as a function of mean annual rainfall

	Catchment per head, ha		People per km^2 of catchment	
Annual rainfall, mm	Forest	Pasture	Forest	Pasture
400	1.07	0.27	93	363
600	0.35	0.11	285	910
800	0.16	0.06	610	1,650
1,000	0.09	0.04	1,072	2,532
1,200	0.06	0.03	1,665	3,517
1,400	0.04	0.02	2,376	4,578
1,600	0.03	0.02	3,191	5,696
1,800	0.02	0.01	4,095	6,858
2,000	0.02	0.01	5,075	8,052
2,200	0.01	0.01	6,119	9,273
2,400	0.01	0.01	7,217	10,514

of water already in the streams and the political issues of capturing water from country areas to divert to cities. Thus, although the procedure gives a solid basis for planning, the exercise of planning may be major, onerous, and difficult, and involve a major interface with the public at large.

11.7 The Concept of Payment for Catchment Services

Ernst et al. (2004) looked at the relative economics of raw water from the catchment and the treatment costs necessary to bring the water to a suitable standard. They presented Table 11.2 below showing that a forested catchment was very effective in providing clean, drinkable water. This reflects the infiltration and "natural filtering" by the catchment slopes. They argued that although water treatment was useful, use of it had contributed to a movement away from protecting and managing our source areas.

Ernst et al. (2004) and Postel and Thompson (2005) have concluded that catchments provide many ecosystem services that were not priced or were underpriced in a "marketplace" society. In many cases the issue was that there was no market for essential services such as providing clean water. This led to the concept of "payment for catchment services".

The logic of this? Suppose water from a catchment is of a quality that requires water treatment before being suitable for consumers. An analysis shows that catchment conservation works including reafforestation could bring the water quality to a suitable standard at a lower price than treatment using a conventional plant. Then the land-holder could be paid to implement this, thereby achieving a net community benefit.

Table 11.2 Contribution of forested catchment cover to achieving lower water costs

Percent of catchment forested	Treatment and chemical cost per million gallons
10 %	$115
20 %	$93
30 %	$73
40 %	$58
50 %	$46
60 %	$37

Although the concept has long been recognized, there are relatively few working cases. In particular:

1. Although many communities recognize the benefits of catchment conservation, they would often prefer to have a water treatment plant as a “backup” or an additional layer of security because of the shorter time period to implement and the greater certainty of outcome.
2. There is a fear that such payment might recognise or encourage “bad practises” in which poor land use is rewarded but good land use attracts no such payment.
3. Mechanisms for valuing both the utility of clean water and the success rate of conservation programs are not well-developed, making it difficult to assess what “reasonable” payments should be.
4. It would be unusual for the problem to be associated with a single land owner. More usually, there would be a large group of land-holders and some form of equitable payment to the group would need to be negotiated.

Commonly, where some success has been achieved, there have been elements of both “Payment for Catchment Services”, together with some threat of compulsory acquisition of land if various goals were not met. In many cases the “payment” has been delivered in the form of cheaper goods and services (e.g. subsidized fencing) rather than a direct cash payment.

In the case of forestry, improved practice usually works to stop road drainage passing into waterways and improved stream crossings to avoid logs being pulled through flowing water. In agricultural land, works may include planting of sensitive areas, restrictions on cultivation and weed control using herbicides, and provision of watering points for stock to avoid stock polluting streams.

Postel and Thompson (2005) note that “a rich variety of institutional mechanisms exist to encourage higher levels of protection of watershed hydrological services.” In Australia this includes a bewildering array of water distribution networks and catchment management agencies with overlapping responsibilities. They note that the menu of options consists of four broad categories: governmental ownership and control of catchment lands; broad-based government incentive payments to encourage ecologically sound land-use choices; government regulations to protect catchment health, and negotiated payments by the beneficiaries of improved natural water supply services to the upstream providers of these.

Analysts such as Postel and Thompson (2005) recognise that "great opportunities" lie in the potential integration of rural development with protection of catchment and hydrological services. However there are formidable obstacles to be overcome before this becomes a day-to-day reality. In particular:

1. In many cases the upstream areas are managed by different agencies from downstream areas. There is usually little incentive for the various organisations to work together.
2. Quantification of the benefits and costs is difficult, particularly since they occur at different places over long time periods and the benefits accrue to different landholders.
3. Organisations fear "setting a precedent" in which they will be expected to pay landholders for providing clean water where-as, hitherto, this has been provided by landholders at no cost to the water authority.

This author concludes that there will need to be a number of major crises involving poor catchment management before the community will support and demand this sort of scheme.

11.8 Economics of Forested Catchment Issues

Clearly the management of a catchment must have an economic base; this provides money to pay workers, pay for the upkeep of facilities, and the capital cost of facility "improvements." For most water authorities the major source of revenue is supplying water. In Australia this is commonly a tax to supplied properties in which the fixed cost of the bill often far exceeds volumetric charges. Hence even linking the revenue of a water authority to the underpinning flow of water (without which the utility could not exist) is an interesting challenge in itself. Taylor et al. (2004) suggest that in such a case the marginal price of water to the consumer is the best indicator. However this is often kept relatively low to keep the household water bill within politically-acceptable levels.

Although there is a voluminous literature on aspects of water economics, the literature on evaluating the economic performance of alternative strategies for water catchments is less fulsome. A number of issues laid out below appear to bedevil all analyses.

11.8.1 Without Water, There Is No Economy!

A city or town cannot exist without a water supply, and an advanced economy is a major user of water for industrial production (e.g. one estimate is that it takes 250 tonnes of water to make a tonne of steel). Thus, without an adequate flow of water, a modern city cannot exist. Aspects of this are shown in severe droughts when local economies sometimes collapse because of lack of water. The result is that cities will, ultimately, do what-ever is needed to ensure an adequate water supply; although this may well be costed and alternatives evaluated, the rationale of obtaining the supply is unquestioned. Having an inadequate water supply is not an option for an Australian city or town.

11.8.2 Long Time Periods Bedevil Compound Interest

Albert Einstein (Box 11.2) is reputed (falsely it is now thought) to have quipped "Compound interest is man's greatest invention." Compound interest involves a small multiplier, periodically applied. If a cost or return occurs in the future then the amount is periodically "discounted" by periodically dividing rather than multiplying. The benefit of the technique is that it gives a methodology for considering the contributions of costs and benefits which occur over considerable periods of time. The concept works well over small time periods of a few years, but when applied over long periods, ultimately leads to a huge growth in the compounding/discounting factor. Added to this is an uncertainty not found in shorter terms – all sorts of disasters may impede the collection of benefits. The result is that benefits which appear many years in the future are worth little. Similarly a small amount, compounded into the future over long periods may become huge.

Because forests may take a century or more to mature, the application of compound interest becomes particularly critical, with the result very sensitive to the rate chosen. Classically a low rate favours investments and returns a long way into the future. A high rate devalues the future. For forests, there is the question of when, in the future, the analysis should stop (see Creedy and Wurzbacher (2001) for a consideration of this). Many analyses curtail their computations after about one century (Box 11.2).

Box 11.2: Albert Einstein and Relation to Catchment Hydrology

Albert Einstein is famous for his work in Relativity physics. However he wrote an early piece (Einstein 1926) on the cause of river meandering. His first son, Hans Albert Einstein (1904–1973) was a leading researcher on river sediment transport, with a doctorate on probability issues of sediment transport. Einstein (senior) attributed meanders due to the balance between inertial and frictional forces in a direction perpendicular to the water motion. He is reputed (again probably falsely) to have advised young Hans that there was nothing more complex than sediment transport and that he should find a simpler field.

11.8.3 Valuation of Water and Other Products

Pattanayak (2004) contends that unreliable information regarding the value of services from tropical forests can partly cause the rapid disappearance of the world's natural forest cover, and thereby endanger the flow of socially-useful goods and services from catchments. He notes that catchment services are "public good" resource in which the benefit is spread across the community and for which it is difficult to exclude an individual from the benefits. His analysis provides an example of how substantive, economic benefits can be ascribed to catchment protection, and argues that ecosystem valuation can provide critical input into the design and evaluation of conservation policies, thereby allowing us to "give the invisible hand of free market economics a green thumb" (Wilson 1993).

Analyses of water catchment options may involve ascribing values to water, wood, and other forest products. In the case of wood there may be some form of market that can be used to give a reasonable estimate of price. Although water may be collected and sold, the marginal value of additional forest water is difficult to fix. In particular, in Australia, water from the same dam may be purchased for irrigation or town water supplies. Different prices apply to each of these, reflecting historical development of the water resources. In addition, the value of the water depends on recent flow history. Thus at times of high flow, additional water may have no value or even (at times of flooding), a negative value.

Although there is a broad agreement on the need for incorporation of economic analysis, the number of good Australian examples are few. Creedy and Wurzbacher (2001) and Spring et al. (2005 both provide examples of the difficulties of deriving clear messages from economic analyses applied to water catchments. In both cases the most severe form of the Kuczera curve (see Eq. 6.4) was applied; the reader is reminded that this describes the response of a mountain ash forest to burning rather than harvesting. Both attempted to apply carbon pricing to the carbon sequestered in the forest. The optimal results proved highly sensitive to the price of carbon, and assumptions made about water use of the forest and fire protection.

11.8.4 Managing for Catchment Resilience

A major concern of catchment managers world-wide appears to be the resilience of the forest. One definition of forest resilience is the "capacity of a forest to withstand (absorb) external pressures and return, over time, to its pre-disturbance state" (Thompson et al. 2009). From the point of view of watershed management, it implies the ability of a water catchment to resume supplying high quality water after some form of ecological disturbance. Major concerns in this regard appear to be:

1. Impacts of fire on catchment water quality and quantity with the possible effects lasting a long time in human terms.

2. Possibility of major wind-throw, insect attack, or some other form of "ecological disaster".
3. Possibility of large areas of even-aged forest occupying catchments suddenly becoming "senescent."
4. "Climate change" altering the regional climate parameters such that the forest type in a particular area is no longer "in equilibrium" with the climate.

The concept of resilience appears to be difficult to apply to specific cases. Thus, for instance, experience has shown that mature mountain ash forests, when burnt severely, will go through a life-cycle change in which the mature trees will die and be replaced by dense regeneration. Although this may be resilient from an ecological view, it is not necessarily the catchment manager's favourite form of resilience since the forests will have a new yield function as discussed in Chap. 6. Thompson et al. (2009) specifically examines this ecosystem and concludes that mountain ash generally meets criteria of resilience in conservation terms but not in water production terms. They also note that not all forest ecosystems are equally resilient.

Hansen et al. (2003) provides a list of strategies for maintaining forest resilience in the face of climate change. This includes maintenance of fire regimes, protection from insect attack, and "silvicultural techniques to promote forest productivity." This stated that the forest manager should have a "straightforward, no-regrets" policy of maintenance of a diversity of age of stands and mix of species (Krankina et al. 1997). It is argued that these measures will contribute to maintaining the productivity of the forest system as climate changes, since different age and species combination will show a diversity of sensitivity to climate change. This author believes that there would be considerable community resistance to modification of existing, healthy forest stands to meet a possible (but hypothetical) future change.

At the time of writing, the term can only be viewed as an interesting concept to be explored in catchment management. It may be conceptually possible to maximise the "resilience" of a catchment by changing the vegetation structure over large areas and maintaining forest health by thinning, but it is unlikely that this would be met with acclaim by the customers of the catchment. It is likely that the concept of a catchment which is "resilient" from a water supply point of view would not be viewed as optimal from an ecological point of view, and this would create a long-lasting conflict in Australia.

11.9 Dealing with Disasters to the Catchment's Forests

For catchment owners, it is inevitable that sooner or later some form of disaster will impact on some or all of the forest estate. In Australia, the most likely of these is fires. Other common forms of forest disaster may include insect attack or wind-throw. Although each such incident will have its own unique features, the possibilities of such incidents are usually reasonably predictable in a statistical sense or by examining past forest records. Aspects of fire recovery are dealt with in Chap. 8.

Opinions on what should or might be done post-disaster vary. Robichaud et al. (2000) examined the effectiveness of post-fire rehabilitation treatments, and noted the large expenditure on sediment control. They found little literature then (or now) on the effectiveness of such measures, and noted that the amount of protection afforded by any treatment was small. After such fires there is usually a desire by catchment managers to "get out and do something." Given the widespread sediment movement after Australian forest fires, it would seem that there is little point in working on small areas. Notwithstanding this, such projects are an excellent public-relations ploy and give people the feeling of "doing something" or "helping the land recover".

Pre-disaster planning can help avoid statistically predictable disasters, but the question of what is "reasonable" bedevils this. Thus, in Australia, fire presents a statistically predictable disaster. Catchment management could, in principle, minimise the occurrence of fire in the catchments by a large road network, increased fuel reduction burning around the catchments (both internally and externally), and the presence of fire-fighting infrastructure such as dams, tanks, helipads, roads, firebreaks, personnel accommodation, etc. The question of "what is reasonable given the hazard?" is difficult. If the catchments are "closed" or "national parks" then the above infrastructure is often against National Park management policies. The public relations strategy of the past has been to say "We did our best; who would have thought that the fires could be so intense?" This will probably be less acceptable in the future.

For larger water supplies there are a number of valuable strategies associated with isolating a source which may suffer contamination, thereby substantially avoiding the issues. This is a major advantage of multiple catchments and cross-linking.

11.10 Catchment Protection Issues

11.10.1 Road Drainage Management

The presence of roads in a catchment is a fact of life. These are linear strips of compacted earth, sometimes with an impervious surface. From the point of view of the catchment manager they can generate substantial volumes of contaminated water. Contamination is substantially sediment and organic matter but may also include materials from spills, and more exotic chemicals derived from vehicle mishaps. The reader is referred to road design manuals such as Ryan et al. (2004) which provide methods for dealing with road drainage and stream protection.

From the catchment manager's point of view, the principles of road design are:

1. Avoid stream crossings as far as possible.
2. Keep roads as far from streams as possible.

3. Divert road drainage into energy dissipaters (splash pavements etc.) and then pass into infiltrating surfaces (usually native forest) well upslope from streams.

Particular attention needs to be paid to the runoff from roads near stream crossings. Ideally runoff should be diverted from the road frequently to avoid large concentrations of flow during rainfall. A common strategy is paved surfaces for the energy of the water to be dissipated on.

11.10.2 Buffer Strips and Stream Protection

A basic method of protecting a stream from the impacts of land use is a "buffer strip" – ideally a strip of forest which protects the stream. Thus a common rule in Australia is that logging should not be closer to a stream than 20 m This gives a buffer strip of about 42 m (allowing 2 m for the width of the stream) if the harvesting surrounds the stream. Figure 11.3 illustrates the application of a buffer strip at Croppers Creek. This was found to give excellent protection to the stream. Most forest management regulations stipulate use of buffer strips as a fundamental tool of stream protection.

Why Do They Work? The common view is that they provide an infiltrating zone of high hydraulic roughness such that minor surface flow (generated from compacted surfaces) that passes into the zone are held by the roughness and given time to infiltrate. The buffer zones protect the stream from radiation which

Fig. 11.3 A buffer strip used to protect the riparian environment at the time of plantation conversion on Clem Creek in 1980. Width of the buffer (indicated by the *arrow*) was 30 m either side of the stream. Plantation formation by clearing native forest is now illegal

may alter its stream temperature (and hence the riparian environment), provide refugia for native fauna, and provide a “corridor” for fauna to move along the stream without being as subject to the predation they might encounter in open areas.

There are ample studies testifying to their effectiveness in protecting streams. The usual logic is along the lines of “the catchment was logged; no deterioration of water quality parameters were observed; hence the buffer strip worked.” Properly-designed experiment which actually tests the limits of buffer strips or determines the threshold limit at which the buffer strip won’t work on sediment intrusion are uncommon. A case where this was done for protecting the stream from insolation was Wilkerson et al. (2006). In this, 15 streams were assigned to test five different logging treatments using stream temperature variation as the measureable criterion. Results showed no change in stream temperatures with a 23 m buffer, small changes with an 11 m buffer, and the greatest increase without a buffer. Water temperatures below the treatment in the no-buffer case were elevated above pre-treatment levels, although the temperature was never above the known thermal limit. The study concluded that an 11 m buffer was adequate for stream protection.

Buffer strips are admirable practice. However they cannot deal continuously with concentrated, sediment-laden runoff from roads coursing into and across a buffer strip. Over time this will reduce hydraulic roughness, clog infiltration pathways, and provide a smooth, non-infiltrating passage to the stream.

How Wide Should Buffers Be? Commonly the recommendation is 20 m width (horizontal distance) from the edge of the stream; this appears to be based on the fact that it generally works. However examples of buffer strips as narrow as 2 m protecting stream quality can be found. In forest-harvesting debates many people make suggestions as to what the widths should be, with suggested values of many tens of metres common.

Bren (1995) examined the properties of a buffer strip network in a mountainous area of Victoria. This work was undertaken in response to a variety of claims being made as to how wide buffer strips should be, and examined both the proportion of land and the proportion of harvestable resource that was placed into buffer strips as a function of buffer strip width. The equation derived was:

$$y = -0.489 + 0.650\,w - 0.001\,w^2 \tag{11.6}$$

where

y = percentage of the catchment occupied by buffer strips, and
w = width of the buffer strip from the stream centre-line, m.

This relation is shown in Fig. 11.4a as applied to the mountainous Tarago catchment in Eastern Victoria. The area had a dense stream network, and it was found that nowhere was more than about 250 m from a stream. A related study (Bren 1997) examined the loss of economic value as a function of buffer strip width. The equations derived were:

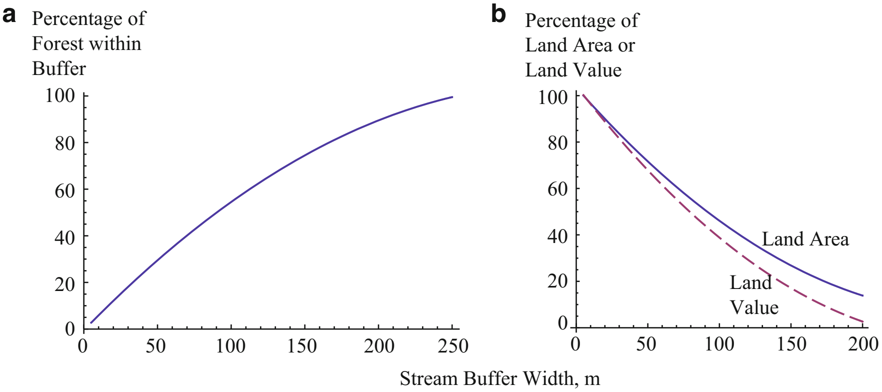

Fig. 11.4 (**a**) Percentage of forest in a catchment within a buffer as a function of stream buffer width (Bren 1995), and (**b**) Percentage of land area and land value available for forest management as a function of stream buffer width (Bren 1997)

$$R_{area} = 1.035 - 0.007w + 0.00001259w^2 \tag{11.7}$$

$$R_{value} = 1.042 - 0.008w + 0.00001462w^2 \tag{11.8}$$

R_{area} is the ratio of land area available for forest management for a given value of w to the land area given by a 5 m buffer. R_{value} is the ratio of economic value available for forest management. Figure 11.4b show these for the same area as Eq. 11.6. Because lower land tends to be more fertile than upper land, the economic value of the land is extinguished faster than the relative area as buffer width increases. The results also showed that because of the ramifying network of streams, at about 100 m buffers would overlap, thereby creating islands of land that could not be accessed without passing through a buffer strip.

Buffer Design Algorithms The simplest and the recommended design procedure is to mark a buffer a set distance from a stream. In most forestry situations the stream will be a first or second order stream, although occasionally forestry operations may be adjacent to higher order streams. Richardson et al. (2012) bemoans such a simple approach, but notes that few experiments have been done to test the efficacy of buffers of a particular width or of site-or-landscape-specific modifications.

Bren (1998, 2000) considered deficiencies of this simple approach, and concluded that the "buffer loading" (the ratio of the area of land upslope per unit area of buffer) differed widely, depending on whether the upslope catchment could be classed as concave, convex, or parallel. In particular, buffer areas downslope of concavities had particularly heavy loadings, and buffers downslope of convexities had low loadings. There is a case for increasing and decreasing the widths of the buffer respectively in such cases. However application of more formalised design rules for buffers which did give uniform buffer loadings led to variable buffer widths along an otherwise uniform reach of stream. Since there is no evidence of deficiencies in performance of the simple buffer design, there would seem little to be gained by more complex methods.

Bisson et al. (2013) provide an interesting account of evaluating the effectiveness of buffers in field trials, noting that these were "fraught with difficulty." Based on this it was suggested that trials be viewed as "interventions" rather than true experiments, noting that it was impossible to obtain a complete and balanced experimental design. In particular, the interpretation of what was a "control" and dealing with natural variation (combined with the small sample size) proved to be particularly difficult.

It is likely in the future that buffer designs will become more complex to meet demands of ecologists rather than hydrologists.

11.10.2.1 Buffer Strip Issues

Section 3.5 notes that life for a low-order stream is a battle between the forces of erosion to carry away sediment against colluvium filling-in stream channels. In many parts of Australia, probably as a result of past wetter climates, there is a network of "drainage lines" which were once streams but rarely or possibly never carry streamflow now. Often these are referred to as "drainage lines." These may pass directly into a stream or eventually develop enough groundwater flow to form a spring. Advocates of buffer protection commonly argue that these should have defined buffer strips in forest management issues, and this causes passionate advocacy. Since there is virtually no flow under common circumstances there are no water quality issues. The suggested criteria for whether an area should be given buffer protection is whether the flow it has had in the recent past has been enough to develop an armoured stream bed.

The traditional rationale for a stream buffer was to protect a stream from the depredations of logging equipment and possible pollution associated with overland flow. More recently they have been viewed as a method of preserving biodiversity in streams in areas subject to logging. The question then raised has been whether the width is adequate to make the light regime of the stream similar to that which existed before logging. Dignam and Bren (2003a, b) studied the effect of logging on the understorey light environment in forested, riparian buffer strips in mountainous forest. They found that the influence of light penetration from a cut edge extended for about 50 m. Creation of a sharp edge by logging of the upslope forest resulted in major changes in light penetration.

11.11 Two Case Studies of Catchment Management

With the exception of logging on catchments, management is usually uncontroversial, supported by the public, and held to be in the public good. Two uncontroversial examples are given below. In both cases the catchments are mixtures of forest and agriculture, and in both cases sustain commercial forestry. Notwithstanding the much larger size of the second water supply, there are many similarities.

11.11.1 City of Ballarat (Australia)

Central Highlands Regional Water Authority provides water and waste-water services to approximately 100,000 customers in the Victorian city of Ballarat (Australia) and surrounding towns. In the 1850s the city had an explosive growth as some of the richest gold-fields of the world (both deep and alluvial gold) were tapped. The rapidly expanding city soon defined the need for a permanent water supply. This began initially by enlarging a local lake but by the 1870s a number of dams had been constructed. Since then there has been an expanding network of dams, groundwater supplies, pipelines for importation of water, and schemes to recycle water. A major advance was the introduction of water treatment plants in the early part of this century to overcome issues of colour in the water arising from the clay soils. This has given four levels of protection (catchment management, reservoir storage, water treatment, and chlorination).

Catchment management began with development in the 1870s when it was realised that both old mining activities and farming in the catchments were leading to poor water quality. The then Ballarat Water Board began purchasing land to avoid it being cultivated and to allow reclamation. An early decision was that this land could be planted to the commercial species *Pinus radiata*. It was hoped that this would both protect and water quality and could then be harvested to help finance catchment activities. Well over a century later, this is continuing with the Water Authority owning about 1,600 ha of commercial plantation and a similar area of native forests. Most plantation areas have had many cutting cycles pass over them. The plantations provide a continuing flow of revenue to finance catchment activities. As well, the forestry activities provide a resource of skilled operators and machines to undertake much catchment conservation work (weed control, removal of wind-throw along aquaducts, etc.). In particular, many non-commercial forests have been planted to protect water quality along streams and channels.

Overall, the forestry activities have been uncontroversial and become an accepted part of Ballarat's catchment management. The forest management has been proceeding for longer than any resident has been alive, so for most residents it has been a "constant factor." The issues of water quality from cultivated land near reservoirs has a long history of causing organisational concern; it is possible to find letters from a century or more ago expressing what appears to be surprisingly modern concern on this matter. However a program on education, a long-standing relationship between the Water Authority and the land-holders involved, and various forms of incentives has lessened the impacts. Over the years consideration has been given to “Payment for Catchment Services” and elements of this have been introduced. However the forms of payment tend to be in aspects such as assistance with fencing or provision of alternatives for stock watering rather than direct cash payments.

11.11.2 Quabbin Reservoir – United States of America

Quabbin Reservoir is a large impoundment on the Swift River and is a major supply for Boston, MA. The catchment is of around 50,000 ha. The catchment has an annual rainfall of around 1,200 mm, and is noted by Barten et al. (1998) as having a water-supply efficiency of 50 %. Average snow depth over winter over the catchment is 1.2 m. making it rather different from Australian catchments.

Overall the catchment has 87 % forest cover and 6 % wetland cover, with the balance being agriculture, residential, or other uses. The forest lands are neither wilderness nor unplanned but represent years of effort by the city to purchase land in a semi-agricultural catchment as it became available. Earlier land purchases at the start of the twentieth century were not without passions, but these have long since faded. The catchment managers have an active program of restructuring the forest to enhance watershed protection and ensure forest resilience. This often involves commercial harvesting of the forest.

Unusually, around 50 % of the catchment is owned by Government agencies, who note that “owning and managing forest lands surrounding a public drinking water supply source is recognized as the most direct and proven method of protecting the water source’s long term quality.” Thus the forest protects quality, land ownership prevents development and prevents problem activities, and the use of vegetated buffers allows stream protection. Barten et al. (1998) notes that “active management of watershed lands through proper forestry practices improves their pollution-attenuation ability while reducing fire risk”. An active land acquisition program is purchasing land as it becomes available.

Forest management on the catchment is multi-facetted, including wildlife habitat management, access control, harvesting, regeneration, and stand improvement activities. Silviculture occurs on about 600–800 ha per annum, including regeneration, thinning, enrichment, and other aspects of forest tending. For any given stand the frequency of return cutting is about 15–30 years. No measureable water quality degradation has been associated with the practices. The Australian experience is that presence of forestry working groups provides direct access to equipment and personnel for a range of non-forestry projects related to conservation control. The revenue generated by the forestry works also finances the cost of management. This appears to be the case at Quabbin as well.

Wildlife management has become of concern due to increasing awareness of the potential of wild populations of animals and birds to transmit pathogens – particularly *Salmonella*, *Cryptosporidium*, and *Giardia*. A "bird harassment" program aimed at modifying nesting behaviours has been effective but time-consuming. Controlled hunting is used to reduce deer populations. Access to the forests are allowed for a range of passive and active recreations (including boating and canoeing), but these are managed to avoid water supply risks. A "Citizen's Advisory Committee" provides input into decisions and actions on issues such as whether to allow motorized boats.

In 2012 the managing agency announced a "relaunch" of its watershed forestry program. using a criterion of "the greatest good" in their deliberations (Barten et al. 2012). This aims to slowly build age and species diversity into the Quabbin forests. This is to increase the resistance and recovery from disturbances such as storms or insects. This followed an independent review of its watershed forestry program, which included revised size and shape standards for harvested openings, enhanced monitoring of water quality adjacent to harvests, and improvements in public information and outreach.

Their report noted the unease with which forest harvesting was viewed by members of the population. Barten et al. (2012) notes that "This heightened attention and concern happened to coincide with the recent transition from relatively innocuous thinning treatments to much less photogenic regeneration treatments. Most people are unpleasantly surprised by any kind of logging, especially when its purpose is unknown, unclear, or misrepresented. Few people have the opportunity to observe forest change over time".

In recent years there have been growing calls for the designation of the Quabbin Forest as some sort of "biosphere reserve" or as a "wild-land". The proposals do not explain how this designation would equal or exceed the efficacy of the current plan and risk management approach. Both proposals assert that active land management is, at best, unnecessary – that a decision to "let Nature takes its course" is the most prudent and conservative way to maintain or enhance the function of this watershed protection forests. Barten et al. (2012) notes that this notion is very appealing to the general public and many policy makers. However a *laissez-faire* approach is at variances with the time-tested principles and practices of water supply management. It is also noted that a "passive management" approach is also at odds with the diversification and risk management principles that have guided most other areas of economic endeavour for centuries.

The type of compromise management shown at Quabbin is probably the most suitable for water supplies of Australian towns in which their catchments have land uses other than water supply. However, as shown by the Quabbin experience, whatever the benefits of active land management, it is likely to be trenchantly resisted by a portion of the population – particularly if there is a logging component.

11.12 And Finally

Most cities of the world do not have the luxury of large areas of land which they can devote to water production; rather they must do the best they can with whatever catchments they have and import water under the best arrangements they can get. For those cities that do have large catchments, forests have traditionally been the favoured land cover because of the high quality and sustained supply.

Good catchment management is a fundamental protector of public health. It is easy to show that catchments with large areas of agricultural land are prone to suffer from increased human populations, which increases possibilities of impairment of water quality in physical and bacteriological terms. Forested catchments in Australia do not usually have such pressures. It is likely that future governments, both in Australia and around the world, will actively protect catchments from burgeoning subdivision. A part of that protection is likely to be conversion of hitherto agricultural areas to forest, with some cost offsets by managing these commercially.

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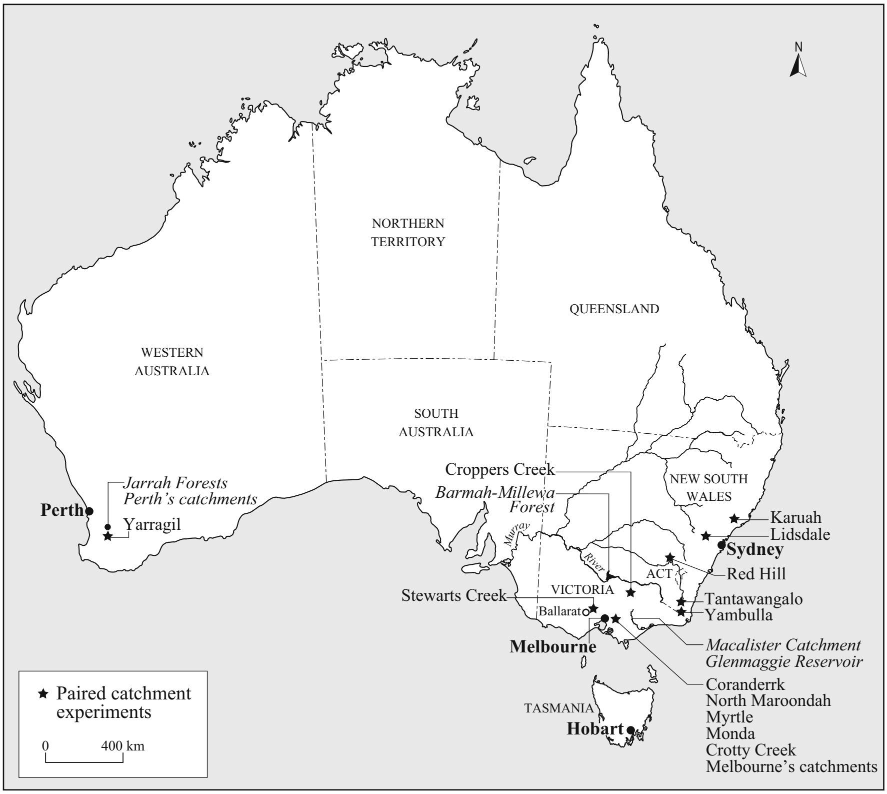
Appendix 1: Map of Australia Showing Locations Mentioned in the Text



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