Appendix 8.

Ecohydrological classification based on landscape and climate data

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Summary

We grouped rivers and streams continent-wide on the basis of their multi-variate similarities using attributes that we expected would characterise the principal climatic and landscape factors that ultimately controlled ecologically relevant aspects of stream hydrology. A number of alternative classifications were generated using the ALOB non-hierarchical clustering method by varying the sets of attributes, weightings and transformations and numbers of groups. A 30 group classification was selected based on its greater capacity to recover the flow regime classes produced by the multi-metric classification of 830 gauges (Appendix 5) and explain meaningful variation in ecologically relevant descriptors of flow and for ease of communication. This 30 group ecohydrological environment classification was based on a set of 48 attributes describing the catchment climate, water balance, topography, substrate and vegetation cover of each of the 1.2 million stream reaches. No explicit weighting was applied to the attributes in this classification.

Stream reaches are not distributed evenly among the groups, the length of stream they contain varying by an order of magnitude between the smallest and largest groups. The diversity of types was also shown to vary greatly at a range of spatial scales. The groups are primarily differentiated by attributes describing the catchment climate and water balance and secondarily by attributes characterising the catchment morphology, substrate and vegetation cover. Ten spatially coherent meta-groups were recognised from a hierarchical clustering of the group means. There are broad similarities between this classification and an agroclimatic classification reinforcing the overriding influence of climate on the observed patterns. In contrast, there was little concordance between the ecohydrological environment classification and the Australian Water Resources Council Drainage Divisions.

The performance of the classification was assessed using the flow data compiled for the flow regime classification described in Appendix 5. The results were mixed. The classification strength was relatively high (75% of that for a comparable empirical classification) and better than that for alternative national classifications including IBRA. The groups differentiated significant variation in many of the ecologically important descriptors of flow though less effectively for those metrics describing the frequency and duration of extreme events. However, the flow regime classes were only moderately well recovered by the ecohydrological environment groups.

We describe here the limitations and uncertainties in our classification. These might be addressed by alternative classificatory strategies and improved characterisation of some hydrological processes, notably those that control the groundwater contribution to streams. This would be the subject of future research. Despite these limitations, we expect the ecohydrological environment classification to effectively support applications at broad regional to continental scale. We suggested, for instance, that it might be applied to the task of designing a more representative network of gauging stations. It could also provide context for finer scale regional or catchment studies.

8.1 Introduction

The classification of 830 stream gauges Australia-wide, based on ecologically relevant attributes of their hydrology, enabled a detailed description and understanding of variability in the natural flow regime (Appendices 5 and 6) but is only applicable to gauged streams. Methods to extend flow parameters to ungauged streams are developing (see review in Croke, 2002), but are confounded by the effects of flow regulation and catchment development.

On the other hand, environmental or landscape classification based on continent-wide environmental data can be applied to all streams and all sections of streams. Environmental classifications can be derived by drawing boundaries around relatively homogeneous geographic areas with a characteristic association of ecosystems (Bryce and Clarke, 1996; Omernik and Bailey, 1997) or by multivariate classification of spatially referenced objects described by the principal landscape factors responsible for the characteristics of interest ("driving" or "controlling" variables) (O'Keefe and Uys, 2000; Bourgeron *et al.*, 2001).

Ecoregion classifications, including the Interim Biogeographical Regionalisation of Australia (IBRA) (Thackway and Cresswell, 1995), are examples of the former approach and are widely used to support an ecosystem based approach to natural resource planning and management (Clarke *et al.*, 1991; Warry and Hanau, 1993; Omernik, 1995; Bailey, 1996; Bryce and Clarke, 1996; Uhlig and Jordan, 1996; Harding and Winterbourn, 1997). However, ecoregion classifications have generally performed poorly when applied to freshwater ecosystems. Cited concerns include their inability to effectively partition variation in biological composition (Hawkins *et al.*, 2000) or flow regimes among rivers (Snelder and Hughey, 2005) and the often inconsistent application and poor communication of the decision rules for boundary placement(Kingsford *et al.*, 2005).

Environmental domain analysis (Mackey *et al.*, 1988; Mackey *et al.*, 1989; Nix, 1992, 1997; Mackey *et al.*, 2001; Mackey *et al.*, 2007) typifies the second approach to environmental classification using numerical clustering procedures to group spatial units on the basis of their shared multi-variate similarities across attributes describing meso-scale climate, substrate (regolith and soils) and topography that ultimately control landscape physical processes and biological function. Environmental domains are thus delineated in environmental rather than geographic space and do not necessarily form regions. While there are still subjective choices as to attributes, weightings, classificatory strategy and numbers of groups these are explicit and therefore transparent and repeatable. Commonly adopted to represent patterns of terrestrial biodiversity (Mackey *et al.*, 1989; Lewis *et al.*, 1991; Belbin, 1993a; Kirkpatrick and Brown, 1994; Mackey *et al.*, 2000; Nix *et al.*, 2000; Mackey *et al.*, 2001; Leathwick *et al.*, 2003; Trakhtenbrot and Kadmon, 2005) the environmental domain approach has only recently been applied to rivers (Jerie *et al.*, 2003; Stein, 2007).

Here we apply the approach to develop an ecohydrological environment classification for all of the rivers and streams of Australia. We describe the environmental characteristics of the derived groups and the relationships between them. We also explore spatial variation in the diversity of ecohydrological environment groups at different scales and compare this classification with other national classifications. The performance of the classification is judged by its ability to recover the flow regime classes identified by the empirical classification of gauging stations (Appendix 5) and to discriminate meaningful variation in the ecologically relevant flow metrics on which these classes are based. We conclude with discussion of the limitations of the classification and suggestions for future improvement.

8.2 Methods

8.2.1. Classificatory strategy

Stream reaches (Appendix 7) were individually classified based on description of the environmental characteristics of their upstream catchment and local valley morphology (Section 8.2.2). The ecohydrological environment classes were derived using a numerical clustering procedure (ALOB) (Belbin, 1993b). Classes are thus an emergent property of the data and reflect the shared similarities of key attributes (e.g. environmental domains Mackey et al., 1988). The alternative approach of specifying *a priori* the boundaries between classes as the outer limits of the features that characterise them (O'Keefe and Uys, 2000) (e.g. New Zealand's River Environment Classification`, Snelder and Biggs, 2002) was not used as it assumes all possible types are already known.

We chose the ALOB non-hierarchical clustering method because it is well suited to classifying very large numbers of objects (Mackey *et al.*, 1988; Mackey *et al.*, 1989; Lewis *et al.*, 1991; Nix, Stein and Stein, 1992; Nix, Stein, Stein *et al.*, 1992; Nix *et al.*, 2000) and produces results that are at least comparable with traditional agglomerative hierarchical methods (Belbin, 1987; Belbin and McDonald, 1993). ALOB employs a simple iterative procedure to allocate objects into groups (Box 8.1). As ALOB is relatively insensitive to the choice of starting configuration (Belbin, 1987) we applied the default option to use the first object (i.e. stream reach) as the initial group seed. Reaches that are more distant in data space than the specified allocation radius from this initial seed become the seeds for additional groups. We employed the Gower metric (Gower, 1971) to measure this distance as it is appropriate for quantitative data (Belbin, 1993b) and incorporates a range standardisation ensuring attributes with a larger range of values do not have undue influence on the classification. Thus the distance D_{ij} between reaches i and j for p variables x_k (k=1,….p) is given by:

$$D_{ij} = \sum_{k=1}^{p} \frac{|x_{ik} - x_{jk}|}{r_k}$$

Where r_k is the range of the kth variable (Belbin, 1993b). The allocation radius that determines the number of groups derived was automatically set to the value that produced the result closest to the desired number of groups.

We generated a number of classifications by varying the set of attributes, attribute weightings and transformations and numbers of groups (Section 8.2.3) recognizing that these choices are largely subjective. Our preferred ecohydrological environment classification was selected based on three criteria: 1) its ability to recover the ecohydrological flow regime types generated by classification of the gauged data (Appendix 5) as judged by the Hubert-Arabie adjusted Rand Index ; 2) discrimination of variation in ecologically relevant descriptors of the flow regime within and across groups, as measured by its classification strength (Van Sickle, 1997; Van Sickle and Hughes, 2000) and 3) ease of interpretation and use.

The Hubert-Arabie adjusted Rand Index is generally accepted as the most reliable for measuring cluster recovery (Steinley, 2004). It was calculated using the RIND module of the PATN software package (Belbin, 1993b) and takes values in the range zero to one. An index value of one indicates a perfect match between the two groupings while a zero value implies an association no better than chance (Belbin, 1993b).

Classification strength (CS) is calculated as the mean of all pairwise within group similarities $(\overline{W})$ relative to the mean of all pairwise between group similarities $(\overline{B})$ (Van Sickle, 1997; Van Sickle and Hughes, 2000). Average within group similarities are weighted by the number of objects within the group and only defined for groups with 2 or more members. CS may be expressed as the difference $(\overline{W} - \overline{B})$ or the unitless ratio $(\overline{B}/\overline{W})$. A large difference or a small ratio implies objects in the same group are substantially more similar to each other than they are to objects in other groups and hence is indicative of a strong classification (Van Sickle and Hughes, 2000). CS was computed for each of the classifications with a modified version (Stein, 2007) of the ASIM program from PATN version 3.6 (Belbin, 1993b). The Gower measure was used to calculate the similarity between flow gauges across all 120 metrics. A test of the null hypothesis of "no class structure" was also conducted using ASIM to randomly permute objects between groups and compare the randomized ratio ($\overline{B}/\overline{W}$) to that of the *a priori* classification. The test was applied by determining the number of times the ratio derived for the random grouping was less than that derived for the *a priori* classifications from the default 100 permutations.

To assist understanding of the relationships between the groups, the centroids of the groups generated with the ALOB non-hierarchical algorithm were themselves classified using the hierarchical agglomerative clustering routine, flexible UPGMA (Un-weighted Pair Group Mean Averaging), implemented in the FUSE module of PATN (Belbin *et al.*, 1992). This clustering strategy weights objects equally as groups are successively combined. Belbin and colleagues (1992) demonstrated that this approach recovered simulated clusters better than an alternative option, flexible WPGMA, that weights groups equally, implicitly varying the weight of the object with the size of the group. Input to FUSE was the association matrix containing the dissimilarity between all pairs of group centroids produced by ALOB using the Gower metric and the specified attribute groupings. The β parameter, controlling the degree of dilation or contraction of the distance between groups as they join ("fuse"), was set to the recommended value of –0.1 (Belbin *et al.*, 1992). A dendrogram depicts the fusion history graphically.

A 3-dimensional ordination of the group centroids was constructed with the semi-strong hybrid multi-dimensional ordination method available in PATN version 3.03 (Belbin and Collins, 2004) as before using the Gower metric. For mapping, the groups were assigned a colour based on its position in the configuration with each dimension aligned to a primary colour (Belbin *et al.*, 1983). Box and whisker plots were produced using the R statistical software package (R Development Core Team, 2004).

8.2.2 Attributing environmental characteristics

Stream reaches were attributed with data for a broad set of environmental variables that we believed characterised potentially important landscape controls on the flow regime. Attribute selection was informed by a review of the landscape attributes used for river environment classifications elsewhere (Stein, 2007) and professional judgement but was limited by the availability of suitable spatial data with consistent, continent-wide coverage. This set formed the basis for the final selection of attributes on which the ecohydrological environment classification was based.

Gridded data layers were derived for each of the selected landscape and climate attributes. Catchment average values were calculated by accumulating the values of all upstream grid cells according to the DEM-defined flow pathways and dividing by the number of upstream cells. Following Stein (2007), the accumulated totals and cell counts were distributed to anabranches in accordance with stream name in the ratio of 8 rivers: 4 creeks: 1

Box 8.1 The ALOB clustering algorithm (Belbin, 1987)

1. Define a set of seed objects to act as a starting configuration
2. Create additional seeds from objects that are further (in data space) than the allocation radius from existing seeds
3. Generate an initial classification by allocating each object to the closest seed
4. Compute the centroid of each of the groups as the average of the attribute values for all objects in the group
5. Sequentially extract each object from its group and re-compute the group centroid. Calculate the distance from the object to each group centroid and (re-) allocate the object to its closest group
6. Recompute all group centroids and repeat steps 5 and 6 until there are no more objects to reallocate

unnamed stream: 0.1 floodplain wetlands. Sub-catchment or reach scale attributes were derived by summarizing the grid cell values of the stream reach and/or its sub-catchment only.

8.2.2.1 Climate

Climate ultimately controls many stream processes. The amount of runoff available for stream flow is a function of the precipitation falling within the catchment and is reduced by losses due to evaporation (among others) (Williamson, 1998). Rainfall and temperature affect rates of weathering of rock and accordingly the rock's hydrogeological characteristics including its porosity and permeability (Ollier and Pain, 1996; Knighton, 1998; Nanson *et al.*, 2005). Climatic parameters supply indicators for the critical environmental regimes (light, moisture, thermal) that control plant growth (Nix, 1981, 1992, 1997) that in turn influence infiltration and runoff processes.

The climate of the catchment upstream of each stream reach was characterised by a sub-set of the bioclimatic parameters summarising annual and seasonal mean conditions, extreme values and intra-year seasonality (Nix, 1986; Hutchinson *et al.*, 2000). These were computed for each cell of the national 9 second DEM version 3 (Table 8.1). The rainfall erosivity R factor was included as an indicator of rainfall intensity, an important influence on processes of infiltration and runoff generation. It describes the potential for rainfall-induced soil loss based on storm kinetic energy and the maximum, 30-minute rainfall intensity (Lu and Yu, 2002). Catchment average values of long-term monthly mean rainfall, minimum and maximum temperature and potential and actual evapotranspiration that had been derived from the Bureau of Meteorology Climate Atlas grids (Walsh *et al.*, 2007) were also compiled to assist interpretation.

Table 8.1 Climatic attributes derived by calculating the average value of all grid cells upstream of the reach pour-point. Attributes indicated in bold were $log_{10}(x+1)$ transformed for classification. All were selected for the NOWEIGHTING, EQWEIGHTING and NOSTANDARDIZATION series classifications (see Section 8.2.30)

Attribute	Units	Source
Annual mean rainfall	mm	1
Annual mean temperature	degrees C	1
Driest quarter mean rainfall	mm	1
Wettest quarter mean rainfall	mm	1
Coldest quarter mean rainfall	mm	1
Warmest quarter mean rainfall	mm	1
Annual mean solar radiation	$MJ/m^2/day$	1
Hottest month mean temperature	degrees C	1
Coldest month mean temperature	degrees C	1
Rainfall erosivity R factor	(MJ mm)/(ha hr yr)	2

Source data:

1. ANUCLIM (Hutchinson *et al.*, 2000)
2. NLWRA (National Land and Water Resources Audit, 2000)

8.2.2.2 Catchment water balance

The catchment water balance attributes describe more directly the key aspects of the climatic influence on stream hydrology. They were derived from real time estimates of monthly runoff computed with the water balance module of the GROWEST program (Nix, 1981; Hutchinson *et al.*, 2004). This or similar models have been found to reasonably reproduce annual (Atkinson *et al.*, 2002; Stein *et al.*, 2002) or monthly flows (Lewis, 1998; Xiong and Guo, 1999; Jellett, 2005). Unlike more complex rainfall-runoff models catchment specific calibration of model parameters could be avoided by setting the two required parameters based on broadly known soil attributes. It was thus suitable for continent-wide application.

GROWEST operates on a weekly time step, converting the monthly input rainfall and pan evaporation data to weekly values via cubic Bessel interpolation. The water balance module is conceptualised as a single "bucket" model. It adds rainfall to the previous soil storage and removes it by means of evapotranspiration. The soil water surplus or "runoff" is the rainfall exceeding "bucket full" after allowing for actual evapotranspiration, calculated relative to potential evapotranspiration as a simple exponential function of the relative soil moisture content. For the purposes of a comparative study we assume that pan evaporation is the same as potential evapotranspiration achieved under a full canopy when water is non-limiting (Hutchinson *et al.*, 1992). Monthly rainfall and pan evaporation estimates were generated at a grid spacing of 0.01 degrees (approximately 1km) using elevation values derived by resampling the 9 second DEM version 3 with bilinear interpolation, and monthly climate surface coefficients (Kesteven *et al.*, 2004) for a 30 year period from 1971 to 2000. This period matches as closely as possible that used for the classification of flow regimes that extends back to 1965 (Appendix 5). Evaporation data collected up to the early 1970s were less reliable as evaporation pans were not all fitted with bird guards (Bureau of Meteorology, private communication). The impact on the calculated "runoff" was not significant.

Table 8.2 Catchment water balance attributes derived from the monthly accumulated soil water surplus values (1971 to 2000) calculated in units of ML/month for each stream reach pour-point grid cell. As required for classification, the attributes shown in bold were standardized by dividing by the catchment area at the reach pour-point and $\log_{10}(x+1)$ transformed. Attributes indicated in italics were selected for the NOWEIGHTING, EQWEIGHTING and NOSTANDARDIZATION series classifications (see Section 8.2.3)

Mean of the annual totals	Coefficient of variation of the annual maximum monthly
Coefficient of variation of the annual totals	Coefficient of variation of the annual minimum monthly
Minimum of annual totals	**Seasonal mean (summer, winter, autumn and spring)**
Maximum of annual totals	***Monthly means (January to December)***
Percentiles of annual totals	Coefficient of variation of the monthly totals
(*5*,10,20,30,40,*50*,60,70,80,90,*95*%),	
Mean of the annual minimum monthly	*Skewness (Median annual accumulated soil water surplus / mean annual accumulated soil water surplus)*
Mean of the annual maximum monthly	*Perenniality (proportional contribution to mean annual discharge by the six driest months of the year) (%)*
Proportion of mean annual accumulated soil water surplus generated above the snow line in south-eastern Australia (> 1400m elevation on the mainland, > 1100m in Tasmania) (%)	

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GROWEST requires information for two soil parameters: the maximum available soil water capacity and the soil texture category (one of sandy loam, clay loam or clay) used to infer the relative water retention capabilities of the soil. Soil texture category was defined by classifying the values in the Australian Soil Resource Information System (ASRIS) grid of percent of clay in the A horizon (National Land and Water Resources Audit, 2001d). Maximum available soil water parameters were derived by summing the ASRIS gridded values for the soil A and B horizons (National Land and Water Resources Audit, 2001b, 2001c). Summary statistics derived from the monthly catchment water balance values (Table 8.2) were calculated from the reach pour-point accumulated totals of the upstream grid cell runoff estimates, converted to a volume by multiplying by the cell area.

Delayed runoff from precipitation that falls as snow during winter can produce significant flood peaks in spring. A simple indicator of the potential influence of snowfall on stream hydrology (Stein, 2007) in south-eastern Australia was derived by calculating the proportion of the catchment long-term mean annual runoff generated above the snowline: 1400m on the mainland (Hennessy *et al.*, 2003) and 1100m in Tasmania (Parkinson, 1986). Only runoff generated in the alpine areas of south-eastern Australia (i.e. areas south of $34^{o}12'$S) was considered. Although snow falls occasionally elsewhere along the Eastern Highlands, it has little impact on stream flow characteristics (Warner, 1986).

8.2.2.3 Substrate

The hydrogeological properties of the substrate underlying the catchment plays a major role in shaping ecologically important properties of the stream hydrograph, such as the contribution from groundwater and the size of the peak flows (McMahon, 1977; Goodwin, 1996).

To characterise this influence the areal proportion of bedrock lithology classes within the upstream catchment and the catchment average values of key soil hydrological properties (Table 8.3) were determined for each stream reach. The lithological classes were formed by grouping the mapping units from the digital 1:1 million scale Surface Geology of eastern Australia (Whitaker et al., 2005) and the Northern Territory (Liu et al., 2006) according to the broad lithological composition of the unit as coded in the gross rock descriptor field in the

Table 8.3 Attributes describing the catchment and stream substrate. Attributes indicated in italics were selected for the NOWEIGHTING, EQWEIGHTING and NOSTANDARDIZATION series classifications (see Section 8.2.3)

Attribute	Source of data	Units	Description
Catchment average saturated hydraulic conductivity	1	mm/h	Average value of all grid cells upstream of the reach pour-point
Stream and environs average saturated hydraulic conductivity	1	mm/h	Average value of all grid cells upstream of the reach pour-point
Catchment average solum plant available water holding capacity	1	mm	Average value of all grid cells upstream of the reach pour-point
Catchment percentage old bedrock	2,3,4	%	Areal proportion of all upstream grid cells overlying old rocks (>570My)
Catchment percentage siliciclastic/undifferentiated sedimentary rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying siliciclastic/undifferentiated sedimentary rocks (includes sandstones,conglomerate,mudstone,siltstone)
Catchment percentage carbonate sedimentary rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying carbonate sedimentary rocks (includes limestone,marl,dolomite)
Catchment percentage other sedimentary rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying other sedimentary rocks (includes volcanogenic sediments, non-carbonate chemical sediment, organic-rich rocks)
Catchment percentage igneous rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying igneous rocks
Catchment percentage mixed sedimentary and igneous rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying mixed sedimentary and igneous rocks
Stream and environs percentage unconsolidated rocks	2,3,4	%	Proportion of DEM derived stream reach grid cells and associated valley bottom cells overlying unconsolidated material (regolith)
Catchment percentage unconsolidated rocks	2,3,4	%	Areal proportion of all upstream grid cells overlying unconsolidated material (regolith)

Source data:

1. Soil Hydraulic Properties of Australia (Western and McKenzie, 2004)
2. Surface geology of eastern Australia (Whitaker *et al.*, 2005)
3. Surface geology of the Northern Territory (Liu *et al.*, 2006)
4. Geology of Australia (Bureau of Rural Sciences, 1991)

digital coverage. In Western Australia and South Australia where coverage of geology at this scale is not yet complete, the lithological classes were assigned based on the digital version of the 1976 Edition of Geology of Australia, 1:2,500,000 scale (Bureau of Rural Sciences, 1991).

An additional class, based on the age of the rocks underlying the catchment, was derived to reflect the increased porosity and permeability that accompanies weathering and fracturing of rocks over time (Table 8.3) (Le Moine *et al.*, 2005; Le Moine *et al.*, 2007). The hydraulic conductivity of the materials in the immediate environs of the stream is also an important influence on stream and aquifer connectivity (Ransley et al 2007). Accordingly, the proportion of coarse grained unconsolidated materials in the immediate vicinity of the stream and its associated environs was taken to be an indicator of the potential for groundwater recharge. These materials generally have high conductivities (Cook, 2003). We defined the stream and its environs to include the stream reach and any adjacent grid cells coded as valley bottom flats. Valley bottom flats were identified according to the Flatness Index of Gallant and Dowling derived from the values of their multi-resolution Valley Bottom Flatness Index and associated multi-resolution Ridge-top Flatness Index (Gallant and Dowling, 2003).

8.2.2.4 Catchment and valley morphology

Eleven terrain parameters (Table 8.4) were computed from the national 9 second DEM to account for the influence of catchment and valley morphology on stream hydrology.

Measures of slope and relief are indicative of the energy available for the movement of water. Runoff is usually quicker in steeper catchments so hydrographs have larger and spikier peaks (Thorne, 2004). Two measures of catchment relief were derived (Table 8.4). Catchment Relief (Stewardson *et al.*, 2005) considers the ratio of the average upstream relief relative to the total range in elevation while the Relief Ratio (Gordon *et al.*, 1992) measures the total elevation range relative to the catchment length. Catchment length is the longest upstream path length, estimated by summing the distance to move across the surface, allowing for the change in elevation, from the centre of the grid cell to the centre of the next grid cell downstream in the direction of flow. The catchment average slope was computed from the grid cell estimates of slope calculated from the 9 second DEM using biquadratic spline interpolation with the SLPGRD program (Hutchinson, unpublished).

Valley slope has a direct influence on channel slope and hence stream power and velocity (Knighton, 1998). It was calculated by dividing the difference in elevation between the highest and lowest cells of the stream segment by its length. The length of the segment was computed as the sum of the distances to move to the next cell in the direction of flow for all cells in the segment. Very short stream segments of just one cell were assigned the average of the segment slope values computed for the upstream and downstream segments.

The size and shape of the catchment influence the water yield and its timing and distribution. The catchment elongation, for example, has a large bearing on the timing and magnitude of peak flows during flood events (Bárdossy and Schmidt, 2002; Moussa, 2003). A commonly used measure of catchment shape is the Elongation Ratio (R_e) (Gordon *et al.*, 1992; Brierley *et al.*, 1996; Davies *et al.*, 2000; Parsons *et al.*, 2002). It was calculated at each segment pour-point by dividing the diameter of a circle with the same area as the catchment above the pour-point by the maximum length of the catchment. The more elongated the catchment, the closer the value of this ratio is to zero. Catchment size is described by the total area that drains to the catchment outlet (Gordon *et al.*, 2004). It was computed by accumulating the area of all grid cells upstream of the segment pour-point. The total area

Table 8.4 Terrain attributes describing the catchment and valley morphology. Attributes indicated in italics were selected for the NOWEIGHTING, EQWEIGHTING and NOSTANDARDIZATION series classifications (see Section 8.2.3). Catchment area and catchment length, $\log_{10}(x+1)$ transformed, were also included in the NOSTANDARDIZATION series classifications.

Attribute	Units	Definition
Indicator of valley confinement	%	Percentage of stream reach grid cells and their immediate neighbours that are not valley bottoms as defined by mrVBF and mrRTF indices
Valley Slope	%	Stream reach slope: computed as the difference in elevation between the highest and lowest cells of the stream reach divided by its length
Catchment area	km^2	The contributing area upstream of the reach pour-point
Catchment length	km	Maximum flow path length upstream to the reach pour-point, calculated by incrementing the maximum upstream length of neighbouring contributing cells. Flow path distance is the distance to move across the surface, allowing for the change in elevation, from the centre of the grid cell to the centre of the next grid cell downstream in the direction of flow.
Maximum upstream elevation	m	Maximum elevation value of all upstream grid cells
Mean upstream elevation	m	Mean elevation value of all upstream grid cells
Minimum reach elevation	m	Minimum elevation value of all cells in reach
Catchment relief		(mean upstream elevation-pour point elevation)/(max upstream elevation-pour point elevation).
Catchment relief ratio		(maximum upstream elevation-pour point elevation)/(flow path distance from source)
Catchment shape (elongation ratio)		$R_e = D_c / L$ where: D_c = the diameter of a circle with the same area as the catchment area upstream of the segment L = the maximum length of the catchment along a line basically parallel to the main stem (Gordon et al., 1992)
Catchment slope	%	Mean slope of all grid cells upstream of the reach pour-point (both valley and hillslope cells)
Stream density	km/km^2	Accumulated length of DEM derived stream upstream of the reach pour-point cell / upstream area

upstream of a flow bifurcation was included in the area of all downstream segments (i.e it was not divided at the bifurcation).

Hydrograph properties including those related to baseflow and the timing and magnitude of stormflow events, have been shown to be strongly correlated with drainage density, the length of channel per unit area (e.g.Mwakalila *et al.*, 2002; Brandes *et al.*, 2005). Drainage density was calculated here by dividing the total length of all upstream reaches by the catchment area at the reach pour-point.

A primary differentiating criteria in many river classification schemes is valley confinement (e.g. Whiting and Bradley, 1993; Rosgen, 1994; Brierley and Fryirs, 2000). The width of the valley relative to that of the channel controls the energy of inundating flows (Fagan and Nanson, 2004). Confinement must be described relative to the width of the channel (Jerie et al., 2003), but neither valley nor channel width can be estimated reliably with the available continental scale data. Instead, an indicator of valley confinement (Stein, 2007) was derived by considering the Flatness Index class values derived from the values of the multi-resolution Valley Bottom Flatness (mrVBF) and multi-resolution Ridge Top

Flatness (mrRTF) indices (Gallant and Dowling, 2003) of the grid cells neighbouring the channel cells. It was computed as the percentage of the cells in the immediate 3 x 3 cell neighbourhood of the channel cell that were not classified as valley bottoms (i.e. cells that were classified as hillslope, ridge top flat or indeterminate). Small values of this indicator thus identify unconfined channels on wide floodplains. Intermediate values suggest the presence of smaller floodplain pockets.Valley confinement is indicative of the depositional environment and the potential for stream aquifer connectivity (Ransley *et al.*, 2007) at the reach scale. The final terrain parameter, catchment storage, describes the relative proportion of depositional areas in the catchment, calculated simply as the proportion of grid cells in the catchment upstream of the segment pour-point that are valley bottoms.

8.2.2.5 Vegetation cover

The type and cover of vegetation in the catchment has an indirect but significant influence on stream hydrology through its effect on processes of infiltration and evapotranspiration. The catchment vegetation cover was described by the areal proportion of the catchment in each of three broad structural classes: trees, grasses and others, the latter including shrublands. These classes were formed by grouping the 23 major vegetation types of the National Vegetation Information System (NVIS) Version 3 pre-European vegetation layer supplied as a grid at 100m resolution (National Land and Water Resources Audit, 2001a). Pre-European vegetation, rather than present vegetation, was used to avoid confounding the classification with the effects of recent (post European) industrial society (see Appendix 3).

8.2.3 Assigning stream gauges to the DEM derived stream network

To aid evaluation of the ecohydrological environment classifications, each of the 830 high and medium quality gauging stations compiled for the classification of flow regimes (Appendices 4 and 5) were assigned the identifier of the stream reach on which they were located. This enabled gauges to be allocated to an ecohydrological environment group and thus the flow characteristics of the group to be described. Kruskal-Wallis rank sum tests were used to test the null hypothesis that the distribution of the flow metric values was the same in each of the ecohydrological environment groups (R Development Core Team, 2004). Kruskal-Wallis is a non-parametric statistic that is more robust to departures from normality than the F-statistic (Belbin and Collins, 2004).

The reach assignment of each gauging station was verified by comparing the gauge name and supplied catchment area with the name and DEM-derived catchment area of the assigned stream reach. These comparisons uncovered occasional errors in gauge location as well as incorrect matching due to differences in mapping scale and generalization of the DEM derived stream network, particularly for gauges located close to a confluence. Automatic procedures were developed to relocate these gauges to the closest position on a stream reach of the same stream name. Gauging stations for which matching locations could not be found automatically within 1 km of the given gauge location or those for which the DEM derived catchment area differed from that supplied by more than 5% were manually checked.

8.2.4 Classification series

Four series of classifications were generated with varying sets of attributes, weightings and transformations and numbers of groups (Table 8.5). Six classifications were generated for each series with the numbers of groups broadly between 10 and 60. In some cases, no value of

Table 8.5 Classification series from which the ecohydrological environment classification was chosen.

Classification name	*Number of groups*	*Attributes*	*Transformations*	*Standardization*	*Weighting of attributes*
MANTELSELECTED	10 20 29 41 51 61	As indicated in Table 8.6	As selected using the procedure of Snelder et al. (2007)	As per Table 8.2	Implied by the number of times an attribute was selected
NOWEIGHTING	10 20 30 40 51 59	As indicated in tables 8.1 to 8.4 + vegetation cover attributes (Section 8.2.2.5)	As per tables 8.1 and 8.2	As per Table 8.2	None
EQWEIGHTING	10 20 31 40 49 58	As for NO-WEIGHTING	As per tables 8.1 and 8.2	As per Table 8.2	Equal weighting applied to each attribute group
NOSTANDARDIZATION	11 18 30 41 49 57	As for NO-WEIGHTING plus catchment area and catchment length	As per tables 8.1, 8.2 and 8.4	None	Equal weighting applied to each attribute group

the allocation radius would produce exactly the desired number of groups and so the numbers of groups tested incremented only approximately by ten.

The first ("MANTELSELECTED") was based on a set of attributes and transformations selected using the method of Snelder et al. (2007) described below and the 830 gauges compiled for the ecohydrological classification characterised by a set of 120 ecologically relevant flow metrics (Appendix 5.1). Each gauge was also attributed with a corresponding set of the 75 environmental attributes compiled for the stream reach. Following Snelder et al. (2007), a set of environmental variables was selected from this candidate set

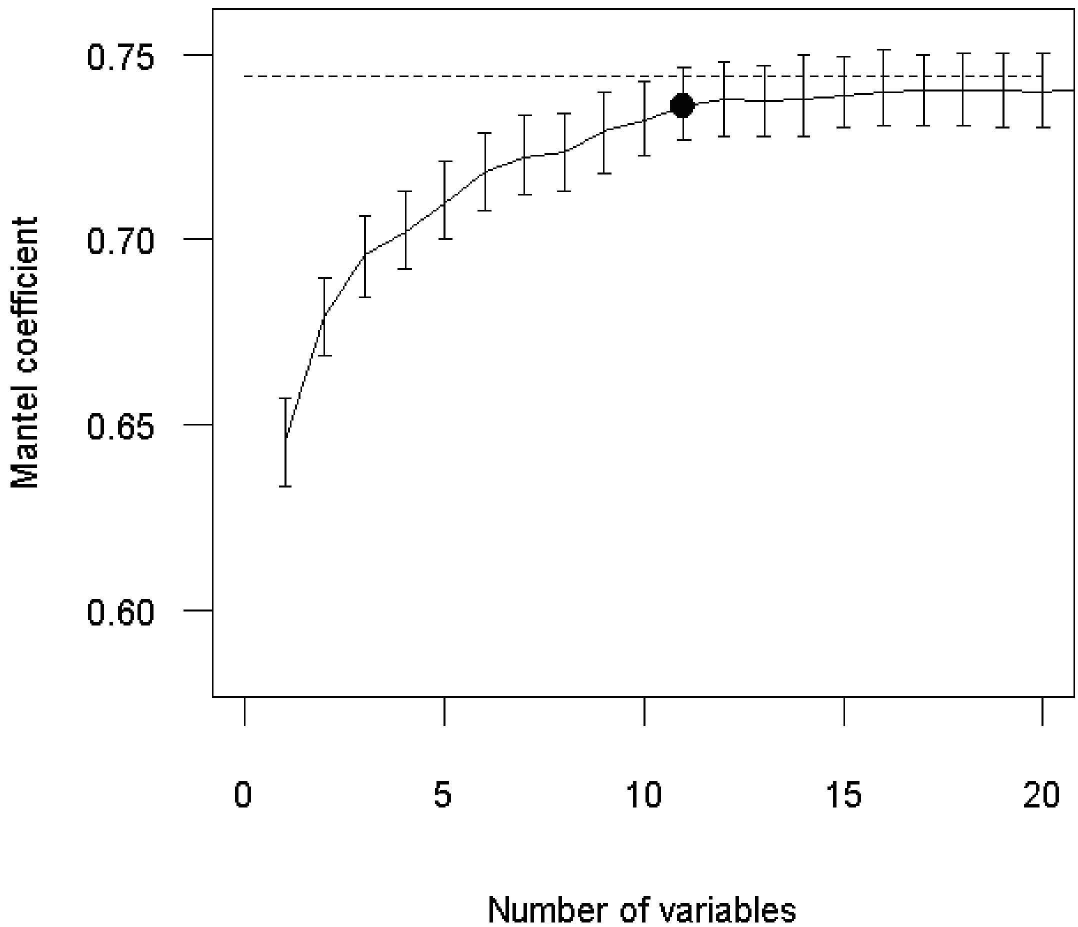

Figure 8.1 Mantel coefficient values with number of selected variables for the first 20 iterations. Error bars represent the 95% confidence limits while the dashed line show the maximum coefficient value obtained after 63 iterations. The circle indicates the minimum number of variables for which the confidence limits include the maximum coefficient value

such that the pairwise distances between gauges in environmental space was maximally correlated with the pairwise distances based on the observed flow metrics. Both environmental and flow distances were calculated by the Manhattan distance after applying a range standardization as for the Gower metric (Gower, 1971). In a manner akin to forward stepwise regression, the variable that produced the largest increase (or smallest decrease) in the correlation between the distance matrices, as measured by the Mantel r statistic, was added iteratively (Snelder et al., 2007). A single variable could be added more than once as all were considered for selection at each step. A range of transformations of the variables was also tested: raising them to the power of 2, 0.5, 0.25 and $\log_{10}$. The procedure was implemented in R using the ecodist package (Goslee and Urban, 2007) and allowed to run for 63 iterations. By this stage the change in the mantel r statistic for each additional attribute was very small (Figure 8.1) and no new attributes were being selected. To generate the MANTELSELECTED classification series we used the set of attributes that produced a Mantel r statistic value with confidence limits that included the maximum achieved over the 63 iterations (0.744) (Table 8.6).

The attributes selected by the Mantel tests are based on a set of gauging stations that sample just 830 of the 1.2 million stream reaches and so may not be representative of those that influence stream hydrology in other environmental settings. Accordingly, a second series of classifications (“NOWEIGHTING”) was generated based on attributes selected from literature review and our professional judgement. We excluded some of the reach scale attributes such as valley slope that we expected would be less important discriminators of the spatial variation in flow regimes and retained just five of the substrate attributes – those most

Table 8.6 Mantel test results for the first 15 iterations. The attributes shown in bold were selected for the MANTELSELECTED classification series.

Iteration number	*Mantel coefficient*	*Selected attribute*	*Transformation*	*Lower confidence limit*	*Upper confidence limit*
1	0.646	**C_v of annual runoff**	log_{10}	0.634	0.657
2	0.679	**Catchment average annual mean temperature**	log_{10}	0.669	0.690
3	0.696	**C_v of annual runoff**	0.5	0.685	0.706
4	0.702	**Stream density**	0.25	0.692	0.713
5	0.710	**Catchment average driest quarter rainfall**	none	0.700	0.721
6	0.719	**C_v of annual runoff**	0.5	0.708	0.729
7	0.722	**Catchment average saturated hydraulic conductivity**	log_{10}	0.712	0.733
8	0.723	**Mean September runoff**	0.25	0.713	0.734
9	0.729	**Proportion of catchment under natural tree cover**	0.25	0.718	0.740
10	0.732	**Skewness of annual runoff**	0.25	0.722	0.742
11	0.736	**Catchment average warmest quarter rainfall**	log_{10}	0.727	0.747
12	0.738	Catchment average driest quarter rainfall	2	0.728	0.748
13	0.738	Catchment average solum plant available water holding capacity	log_{10}	0.728	0.747
14	0.738	C_v of annual runoff	0.5	0.728	0.750
15	0.739	Catchment maximum elevation	log_{10}	0.730	0.749

likely to be indicative of greater potential for significant groundwater contributions to stream flow. A log_{10} (x+1) transformation was applied to attributes with particularly skewed distributions. In this series of classifications, no weighting was applied to attributes so correlated attributes would have a greater influence on the outcomes. The same set of attributes was selected for the third series of classifications (“EQWEIGHTING”) but in this case the five attribute groups (climate, catchment water balance, catchment/valley morphology, substrate and vegetation) were equally weighted in the calculation of the dissimilarity measure regardless of the number of attributes in the attribute group. The final series (“NOSTANDARDIZATION”) also weighted the attribute groups equally but allowed for a catchment size effect, using the catchment water balance attributes expressed as volumes (i.e not standardized by catchment area) and including additional attributes of catchment area and catchment length.

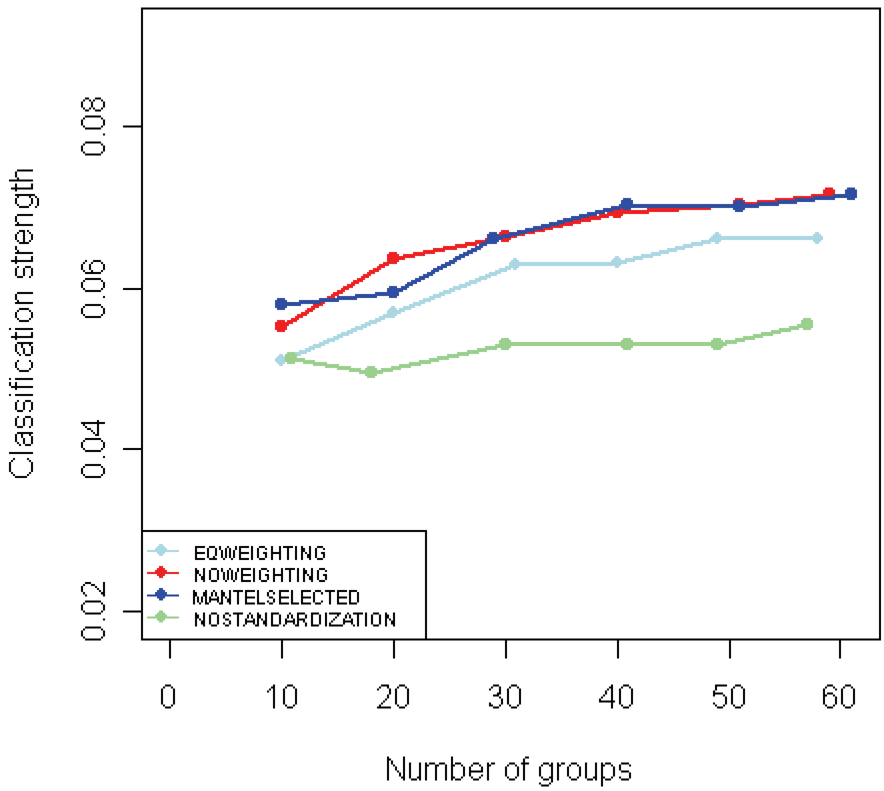

Figure 8.2 Classification strength of environmental classifications evaluated using 120 ecologically relevant flow metrics derived for 830 gauging stations. Classification strength is expressed as the difference between average within and between group similarities $\left(\overline{W}-\overline{B}\right)$

8.3 Results

8.3.1 Classification selection

Twenty four classifications were generated grouping the 1.2 million stream reaches into between 10 and 61 classes. The different classification series varied in both their ability to recover the flow regime types generated by the classification of gauging stations (Appendix 5) and their classification strength as measured by the similarity of flow metric values within and between groups.

Classification strength (CS), expressed as the difference $\left(\overline{W}-\overline{B}\right)$, generally increased with the number of groups in the classification across all classification series (Figure 8.2). In all cases, the randomized ratio ($\overline{B}/\overline{W}$) was greater than that for the environmental classification so the null hypothesis of "no class structure" could be rejected. However, with increasing numbers of groups the proportion of groups sampled by the gauges decreases as does the number of gauges within each group (Table 8.7) increasing the likelihood that CS values are affected by random sampling effects associated with small sample sizes (Hawkins *et al.*, 2000; Heino *et al.*, 2004; Snelder *et al.*, 2005). The CS values of the MANTELSELECT and NOWEIGHTING series are consistently higher than those of the

Table 8.7 Classification strength as measured by the similarity of flow metric values within and between groups for environmental classifications. A higher difference ($\overline{W} - \overline{B}$) or lower ratio ($\overline{B}/\overline{W}$) indicates a stronger classification

Classification	*No. groups*	*No. groups tested (i.e. > 1 gauge)*	*No. groups with less than 5 gauges*	*Mean no. gauges / group*	$\overline{W} - \overline{B}$	$\overline{B}/\overline{W}$
NOWEIGHTING	10	9	1	83.0	0.0551	0.937
	20	18	2	41.5	0.0637	0.928
	30	26	3	28.6	0.0663	0.925
	40	34	6	23.1	0.0692	0.923
	51	40	8	19.3	0.0702	0.922
	59	49	13	15.7	0.0715	0.920
EQWEIGHTING	10	9	1	83.0	0.051	0.941
	20	16	4	46.1	0.0569	0.935
	31	23	5	31.9	0.0629	0.929
	40	25	10	25.9	0.063	0.929
	49	31	11	22.4	0.066	0.926
	58	37	15	18.9	0.0661	0.926
NOSTANDARDIZATION	11	11	2	75.5	0.0512	0.940
	18	11	5	46.1	0.0495	0.943
	30	11	9	33.2	0.0529	0.939
	41	11	14	25.2	0.053	0.939
	49	8	18	21.3	0.053	0.939
	57	8	18	20.8	0.0555	0.937
MANTELSELECTED	10	9	1	83.0	0.0578	0.934
	20	17	5	43.7	0.0595	0.932
	29	24	8	33.2	0.066	0.926
	41	32	7	24.4	0.0704	0.921
	51	37	18	19.3	0.07	0.922
	61	43	17	16.6	0.0716	0.920

EQWEIGHTING series classifications. Not surprisingly, all are higher than the values for the NOSTANDARDIZATION series where stream size has a direct influence on the groupings.

Similarly, the Hubert Arabie Rand Index values indicated the environmental classifications derived using the standardized catchment water balance attributes, better recovered the 12 group classification of gauging stations based on standardized flow metrics (Figure 8.3). The index reached a maximum value of 0.23 for the 31 group EQWEIGHTING classification. This is only slightly higher than that for the 30 group NOWEIGHTING and the 29 group MANTELSELECTED classifications though much lower than the value of 0.8 suggested by Steinley (2004) to be indicative of good recovery of given clusters. However, it compared reasonably with the Hubert Arabie Rand Index value of 0.37 for an alternative 12 group classification of the gauges that was generated using the UPGMA hierarchical agglomerative clustering strategy and the Gower dissimilarity measure based directly on the flow metrics. Communicating the characteristics of more than thirty groups is unwieldy whether by graphical or other means. A greater number of classes will also be more difficult to comprehend (DeVellis, 1991 in Schunemann *et al.*, 2003). We chose therefore to focus our analysis on a 30 group classification, the 30 group classification from the NOWEIGHTING series, henceforth referred to as the "ecohydrological environment classification". Although performing comparably, the MANTELSELECTED classifications were based on a limited number of attributes (Table 8.6) omitting many that our literature review had indicated played an important role in shaping flow regimes. In particular, geology is known to be a major control on the magnitude of the groundwater contribution to a stream yet none of the attributes that described the catchment geology were selected.

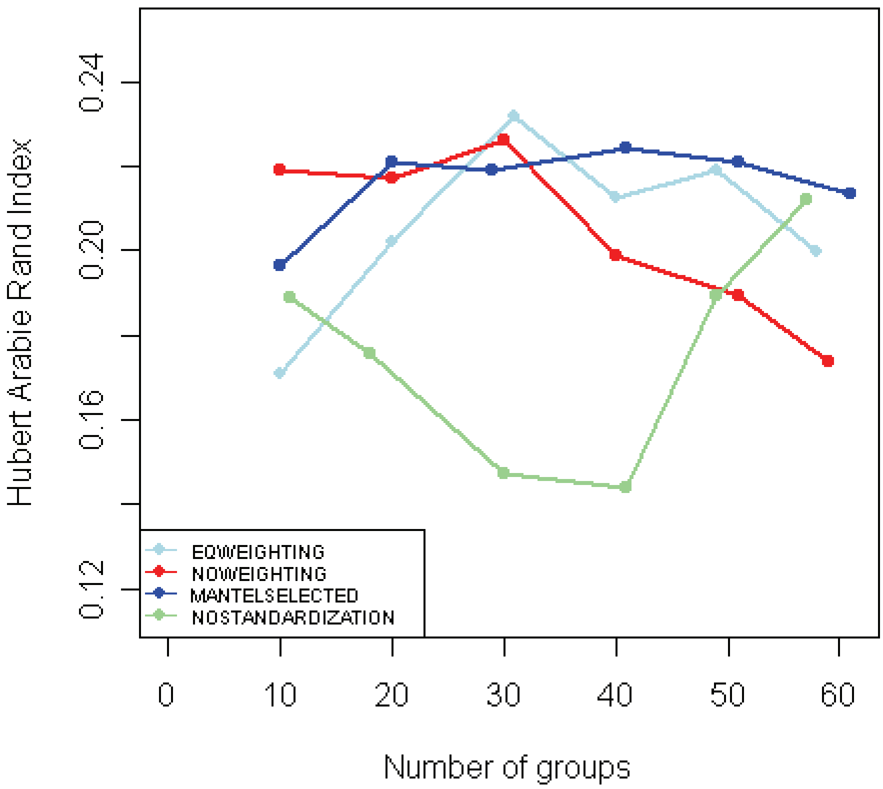

Figure 8.3 Recovery of the 12 groups generated by classification of gauging stations by the environmental classifications as measured by the Hubert Arabie Rand Index

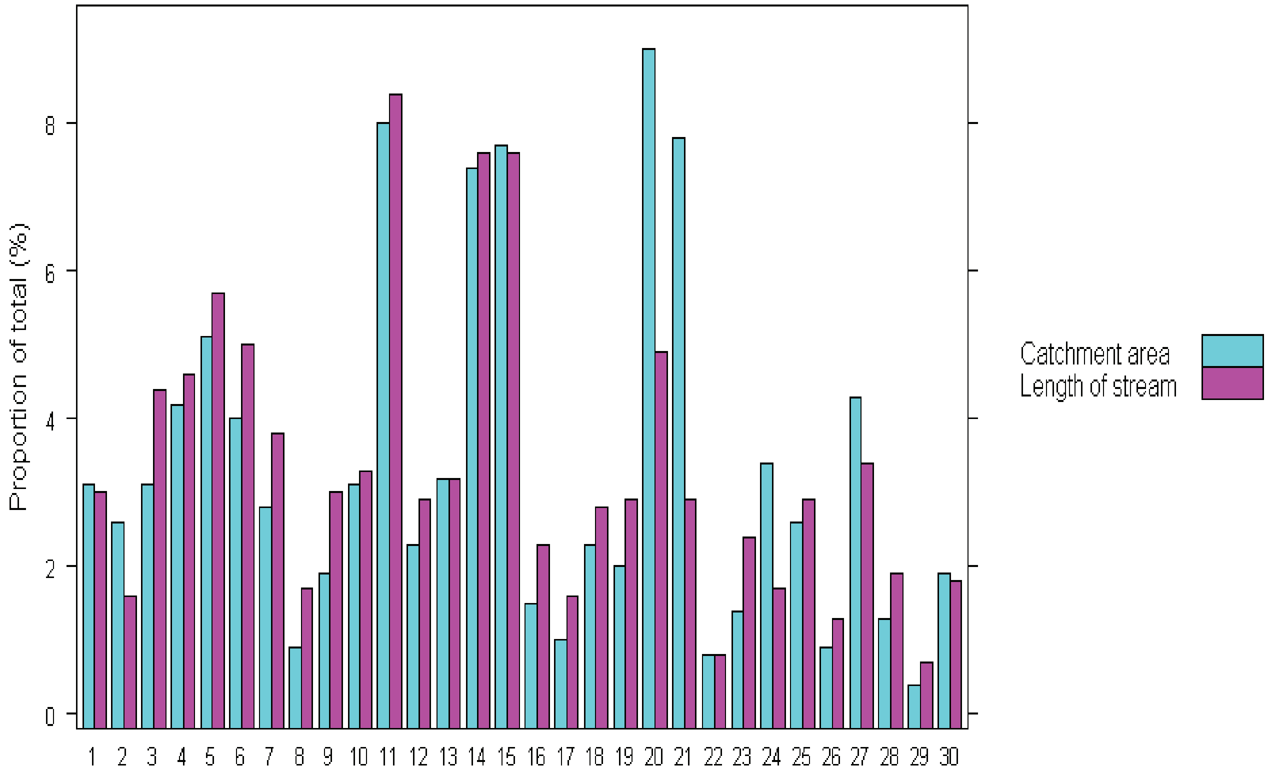

Figure 8.4 Total length of stream and catchment area (stream reach contributing area) by ecohydrological environment group.

8.3.2 The ecohydrological environment classification

Streams reaches are not evenly distributed among the ecoecohydrological environment groups (Figure 8.4). The number of stream reaches, their total length and catchment area vary by an order of magnitude. The largest group (20) includes reaches totalling more than 246,500 kilometres of stream and drains a total area of 516,437km^2 while the reaches within the smallest group (29) total just 20,508 km and have a catchment area of 25,573 km^2. A few groups (20, 21 and 24 in particular) drain proportionally more area than the length of channel they contain reflecting a lower drainage density while the reverse is true for some other groups (e.g. 6 and 7) that contain a relatively higher proportion of the channel length than of catchment area. The groups include streams with a wide range of catchment sizes (Figure 8.5) though five groups (numbers 2, 21, 24 and 27 and to a lesser extent, 4) more often contain stream reaches of larger catchments.

The groups are displayed in colours that reflect their shared similarity (Figure 8.6) highlighting the strong north-south latitudinal gradient in the distribution of the ecohydrological environment groups and a clear separation of streams along the coastal fringe from those inland.

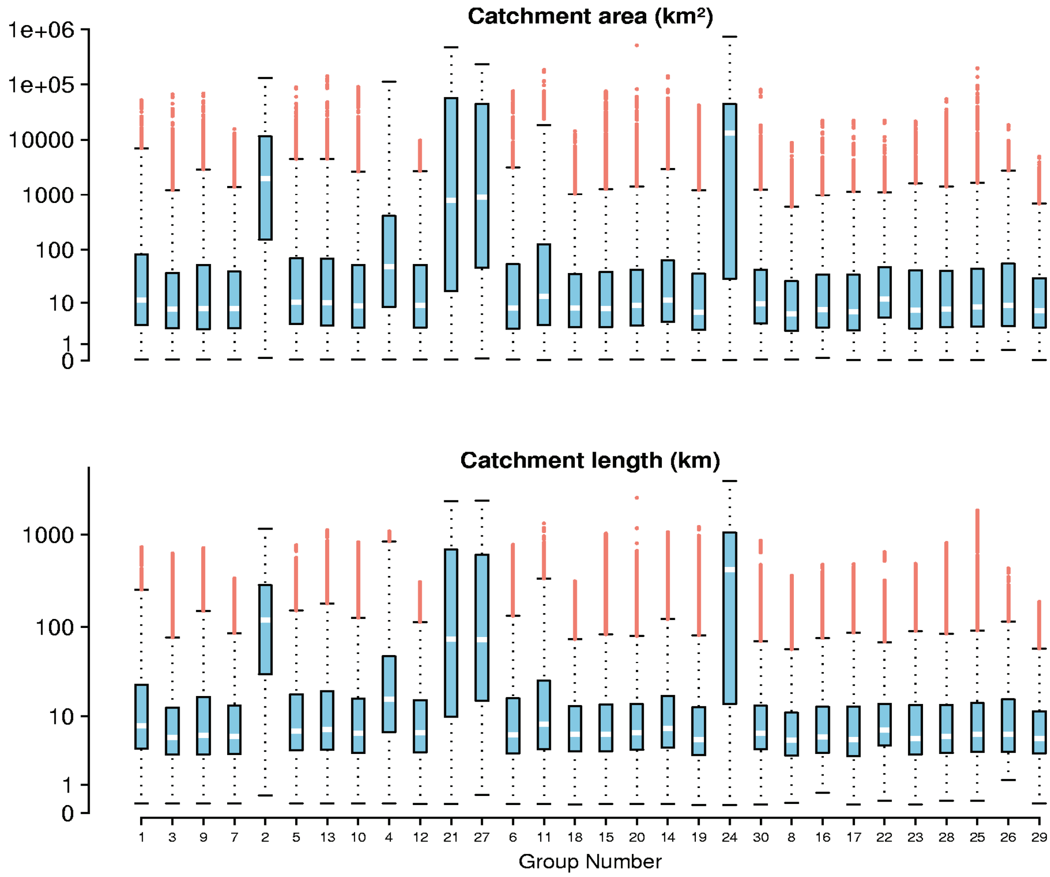

Figure 8.5 The catchment size of stream reaches by ecohydrological environment group. The boxes indicate the inter-quartile range with the central bar signifying the median value. Whiskers are drawn to include all data points that are not more than 1.5 times the inter-quartile range from the box with outliers portrayed in red.

A single river may traverse more than one of the ecohydrological environment groups. The main stem of the Darling River in western New South Wales, for instance, flows through five of the groups (20, 21, 24, 26 and 27) and even more if its tributaries are also considered. The Murray Darling Basin, in fact, contains some of the greatest diversity of ecohydrological environment groups at spatial scales ranging from drainage divisions (Figure 8.7a) through drainage basins (Figure 8.7c) and 1 degree grid cells (~110x110km) (Figure 8.7b). High flow regime diversity in the Murray Darling Basin was also a feature of the empirical classification (Appendix 6) although in this case, the larger streams were not included due to regulation. However, when considered as a function of drainage basin area, it is the higher relief, coastal draining basins that exhibit the greater diversity (Figure 8.7d). The Snowy River basin for instance contains 11 of the ecohydrological environment types, compared to the 20 found in the Murray Darling Basin, though occupying less than 2% of the area. The small, internally draining basins that occur across much of the Western Plateau Drainage Division and the lower reaches of the Murray Darling Basin Drainage Division also display a relatively high diversity in comparison to their area though in absolute terms the number of types is very low.

There are broad similarities between the ecohydrological environment classification and the agroclimatic classification of Australia (Hutchinson *et al.*, 2005), modelled from a

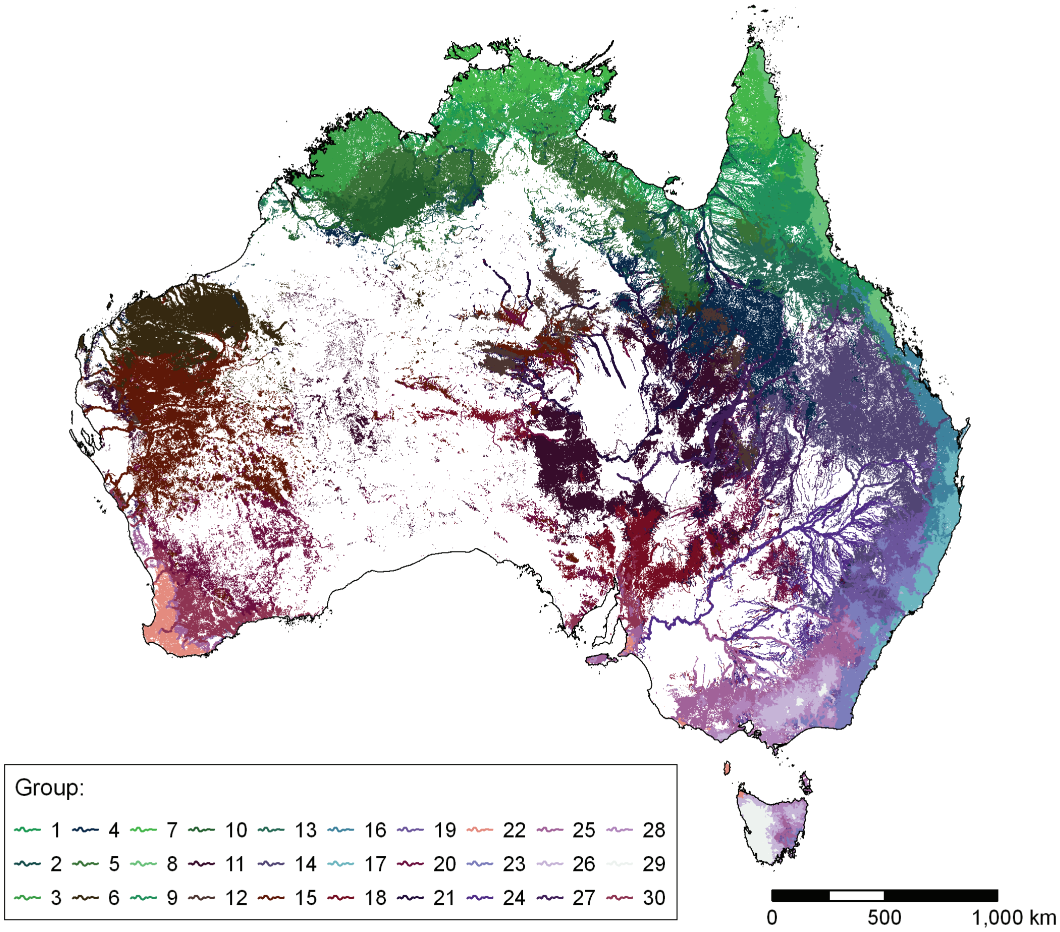

Figure 8.6 The ecohydrological environment classification. Colours used to map the groups were derived by aligning the ordination axes of a 3-dimensional ordination of the group centroids with the three primary colours and assigning a colour to each group based on its position in the configuration (Belbin et al., 1983). Thus groups that are similar in environmental space share similar colours.

global classification of agro-climatic data (Hutchinson *et al.*, 1992) (Figure 8.8a). However, the catchment signal is clearly evident when compared to the smoothed boundaries of the agro-climatic regions. Thus, the agro-climatic class that coincides with the ecohydrological environment grouping of a stream reach is that of its upper catchment rather than the agro-climatic region in which it flows. Similarly, a number of the Interim Biogeographical Classification of Australia (IBRA) regions (version 6.1) (Department of Environment Water Heritage and the Arts, 2007) are aligned with major groupings in the ecohydrological environment classification though other regions (e.g the Brigalow Belt North in Queensland) encompass quite dissimilar ecohydrological environment groups (Figure 8.8b). IBRA was developed for the National Reserves System program (Pigram and Sundell, 1997). It is a regionalisation delineated from regional and continental scale data on climate, geomorphology, landform, lithology and expert knowledge of characteristic flora and fauna (Thackway and Cresswell, 1995). In contrast, there is little concordance between the ecohydrological environment classification and the Australian Water Resources Council (AWRC) Drainage Divisions (Australian Water Resources Council, 1976; AUSLIG, 1997; Geoscience Australia, 2003) (Figure 8.8c) derived by aggregating the catchments of the major river systems and neighbouring small coastal or inland drainage systems according to geographic proximity or shared discharge points.

The ecohydrological environment groups are primarily differentiated by climatic and catchment water balance attributes and secondarily by attributes describing the catchment morphology, substrate or vegetation cover. This is shown in the box and whisker plots presented in Appendix 8.A (Figures.A8.1 to A8.8). For any group the values of climatic and catchment water balance attributes occupy a reasonably narrow range. However, the range of values for the attributes describing the catchment morphology, substrate and vegetation cover is generally much wider and often overlapping.

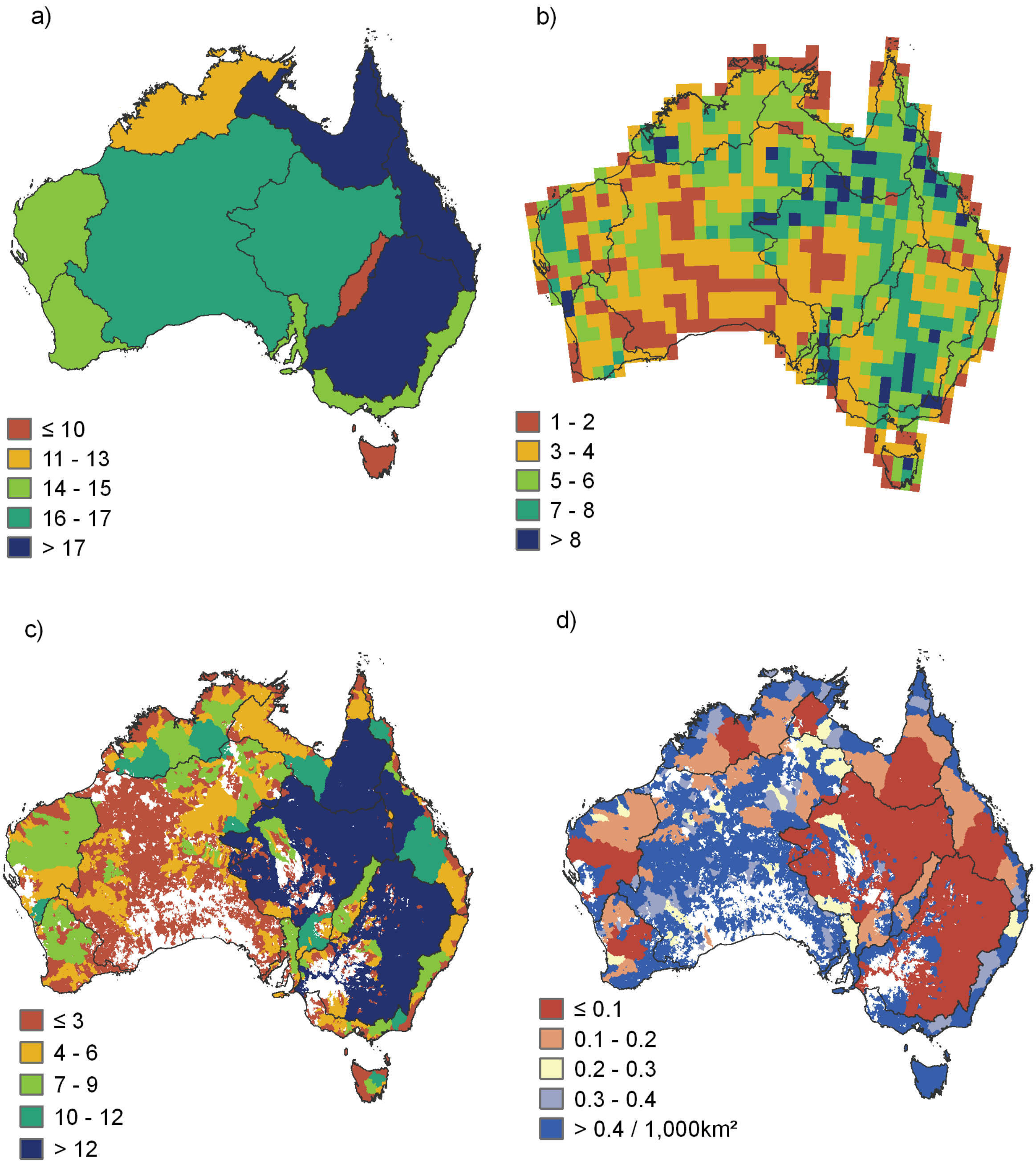

Figure 8.7 Number of ecohydrological environment types per (a), AWRC drainage division, (b) 1 degree grid cell, (c) topographically defined drainage basin and (d) relative to drainage basin area (number / 1,000km^2)

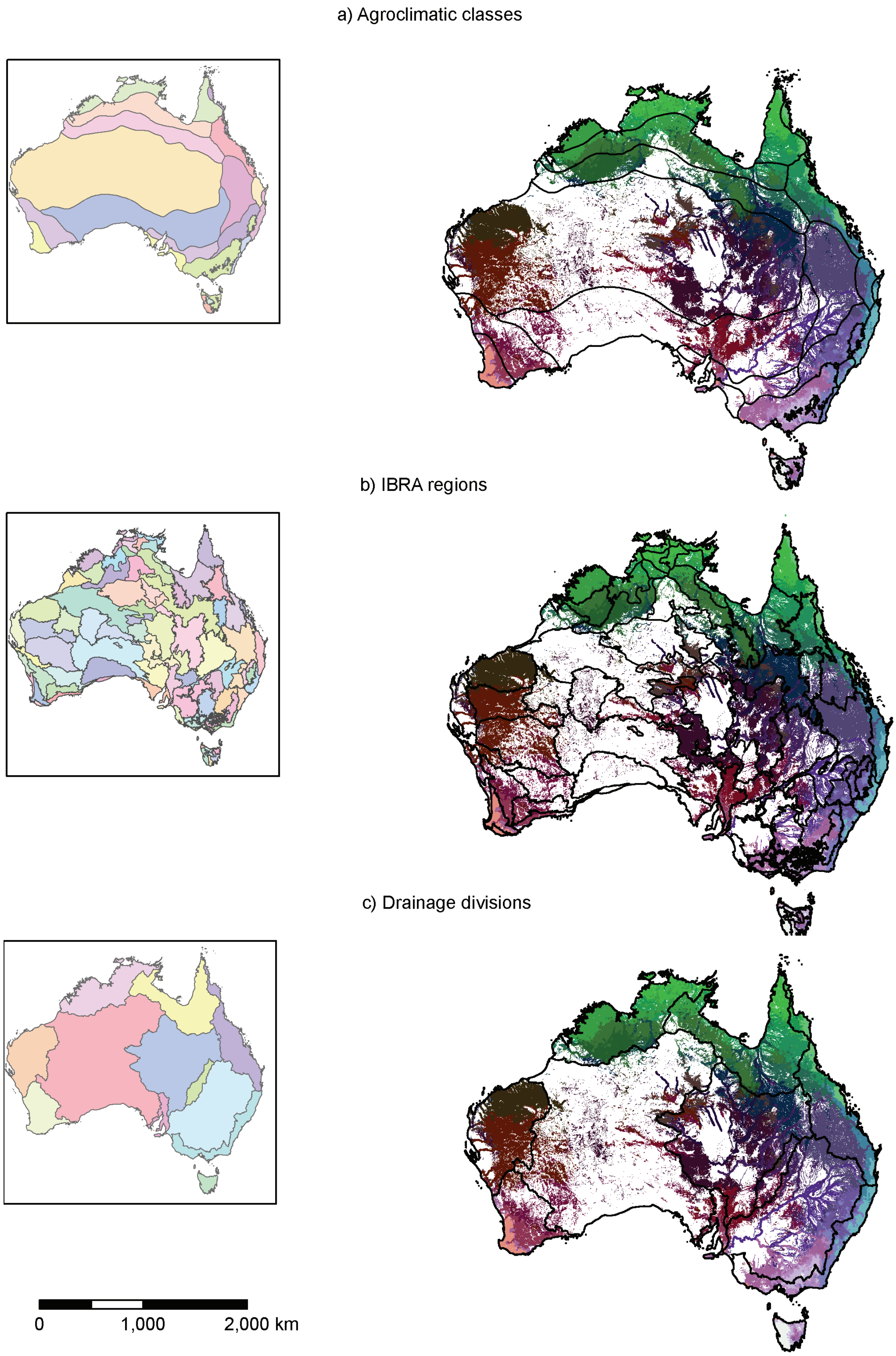

Figure 8.8 Concordance between the ecohydrological environment classification and the boundaries of regions delineated by other national classification schemes: a) Agroclimatic regions (Hutchinson et al., 2005); b) IBRA 6.1 regions (Department of Environment Water Heritage and the Arts, 2007) and c) Drainage Divisions (Geoscience Australia, 2003). Inset maps show the alternative classification.

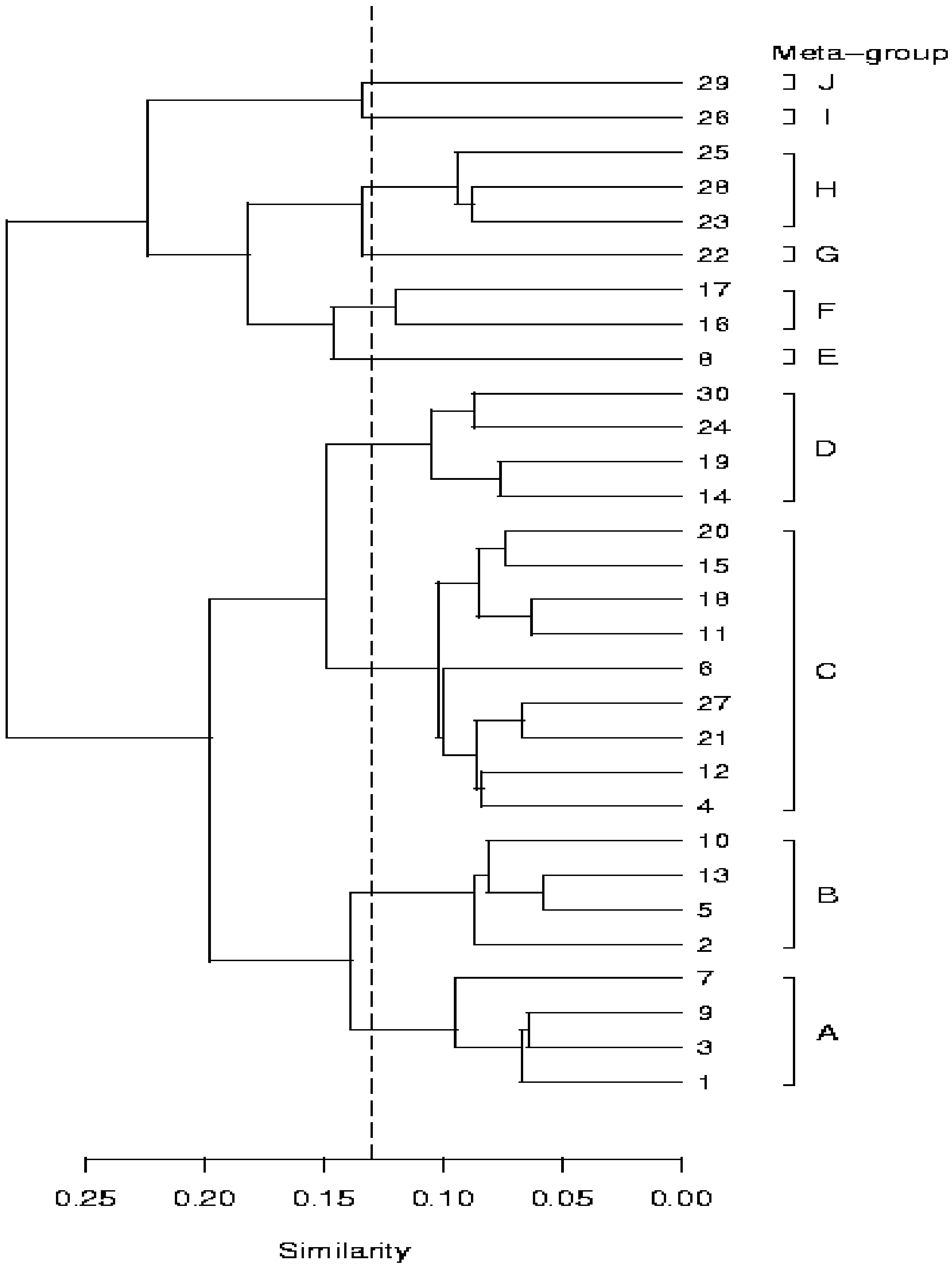

Figure 8.9 Dendrogram showing the relationship among the ecohydrological environment groups derived by clustering group centroids. The dashed line shows the 10 meta groups delineated by cutting the dendrogram at a similarity value of 0.13.

The hierarchical clustering of the group centroids indicates the 30 ecohydrological environment groups form 10 distinct meta groups (Figure 8.9) with strong spatial coherence (Figure 8.10). At the broadest scale these cluster into three broad regions: i) a northern cluster with strong seasonal wet / dry rainfall and runoff patterns (meta-groups A and B); ii) a much drier cluster of streams across inland Australia with highly variable runoff characteristics (meta-groups C and D) and iii) streams draining wetter catchments with less variable runoff along the east coast, in south-eastern and south-western Australia (meta groups E to J). The major gradients are summarized in the 3-dimensional ordination (Figure 8.11). It shows a clear separation of the 10 meta-groups.

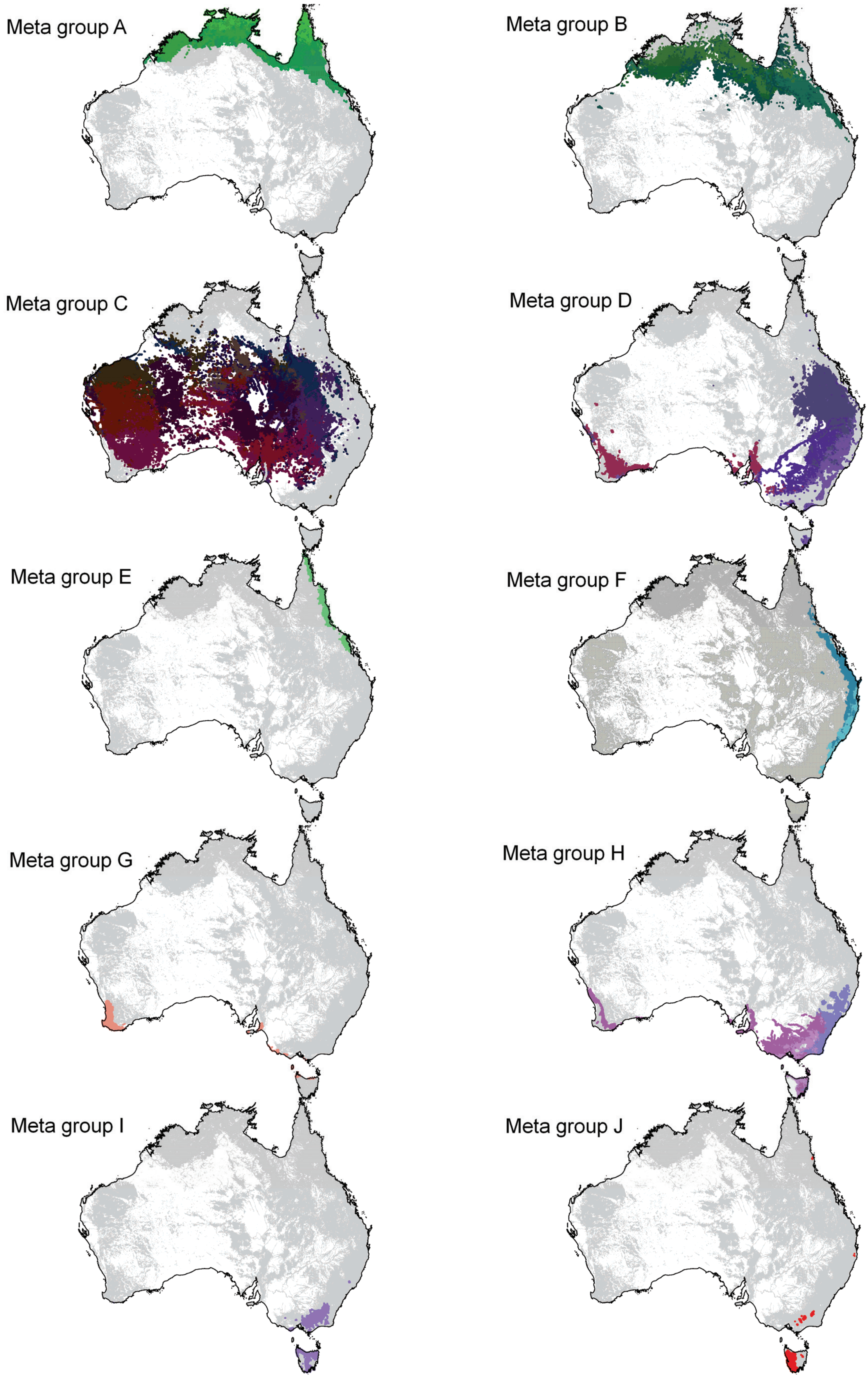

Figure 8.10 Geographic extent of ecohydrological environment meta groups. Individual groups are coloured as in Figure 8.6 with the exception of the single group (29) that comprises meta group J here shown in red for easier discrimination.

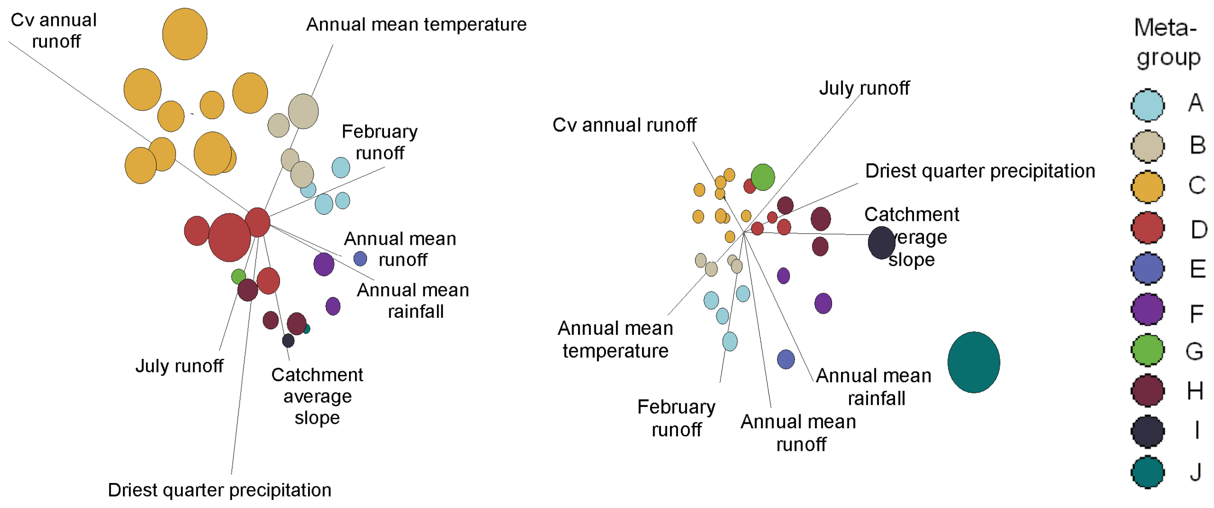

Figure 8.11 Two rotated views of the 3-dimensional ordination of ecohydrological environment groups with groups coloured according to meta-group membership. Vectors indicate a gradient of increasing values of the labelled attributes from the centroid of all the groups in the ordination space.

Meta group A includes four of the groups (1, 3, 9 and 7) distributed across the top end of Australia (Figure 8.10). The catchments of streams in these groups experience high temperatures throughout the year and a strong seasonal wet-dry rainfall pattern. Rainfall tends to be highly erosive and leads to high annual runoff totals generated almost entirely over the period December to April. Group 9 streams are distinguished from others in this meta group by slightly cooler minimum temperatures in the colder months and less marked differences in precipitation between the wettest and driest quarters. Group 7 streams exhibit less variability and higher minimums in annual totals of runoff. In contrast to the other meta-group A streams, the ecohydrological environment group 1 streams typically have a low proportion of the catchment underlain by siliclastic sedimentary rocks but a high proportion of unconsolidated sediments while group 3 streams more often have a large proportion of old rocks underlying the catchment.

Stream reaches found in a band lying immediately to the south and inland of those in meta group A belong to the four groups (2, 5, 10 and 13) that form meta group B (Figure 8.10). They too experience strongly seasonal rainfall patterns though tend to be drier and cooler in the colder months than those in meta group A and have more variable runoff. Group 2 streams are distinguished by catchment morphological descriptors. They typically have a lower elongation ratio implying a more elongated catchment but relatively larger proportions of flat depositional areas as indicated by the catchment storage values and reflected in the lower catchment relief. These streams also have lower annual runoff totals. Vegetation cover is the primary attribute discriminating group 10 streams from others in meta group B. Grasses, not trees, dominate the catchment of these streams. Group 13 streams are generally draining catchments that are cooler during the hottest months and have lower radiation while group 5 streams differ most from others in this meta group by the geology that underlies the majority of their catchments most often comprising older rocks.

Meta group C contains nine member groups from the ecohydrological environment classification. It is the largest of the meta groups representing a total length of 1,248,652 km of stream and occupying a catchment area of 2,836,723 km^2 across central Australia (Figure 8.10). These are the streams in the most arid parts of the continent with the lowest precipitation and high radiation. They experience a greater temperature range than streams in either meta group A or Bwith high temperatures in the hottest months and cool to warm temperatures in the colder months. Runoff is highly variable. While average monthly runoff is low all year round, annual totals are highly skewed. Runoff may be substantial in some years, most notably for streams in groups 4 and 12, but negligible in many others. Member groups can also be distinguished by their dominant vegetation cover (trees: groups 12, 20 and 27; grasses: groups 4, 6, 21, 11 and 18; shrublands: group 15) and catchment average soil hydraulic conductivity. Groups 21 and 27 also have lower values of catchment relief.

Clustered with the meta group C streams are the four ecohydrological environment groups (14, 19, 24, and 30) that form meta group D (Figure 8.9). They are common across the northern areas of the Murray Darling Basin and include group 30 streams in south-west Western Australia, the latter group corresponding with the ancient or old drainage zone identified by Mulcahy and Bettenay (1972) . Meta group D streams experience moderate to low precipitation similar to that of streams in meta group B but with less marked seasonality and cooler temperatures. Monthly runoff magnitude is highest in winter but generally low. Although less variable than meta group C streams, annual runoff totals vary considerably from year to year though consistently higher for group 14 and 19 streams than others in this meta group. Group 14 is distinguished further by catchments with a high proportion of unconsolidated sediments while those in group 19 experience cooler temperatures and drain catchments with higher average slopes and greater relief. Group 24 stream reaches are usually in lower catchment positions distant from their source and drain large, elongated catchments (Figure 8.4). Catchment storage values indicate that more of their catchment is classed as a valley bottom flat reflected also by their typically lower catchment relief.

Ecohydrological environment group 8, the sole member of meta group E, is distributed along the coastal fringe in Queensland (Figure 8.10). It is distinguished by high summer rainfall that is highly erosive and temperatures that are warm to hot all year. Annual runoff totals are also high with low year to year variability though considerable intra-year variability with a strong seasonal wet/dry pattern in average monthly runoff totals.

Most similar to this group are the two ecohydrological environment groups (16 and 17) that comprise meta-group F (Figure 8.9).They are found along the east coast of Australia and represent a transition zone between the streams with a summer dominant rainfall/runoff pattern in the north and those with a winter dominant pattern in the south (Figure 8.10). Rainfall is high even in the driest period of the year and temperatures warm. The northern streams in this meta-group belong to ecohydrological environment group 16 and differ from the southern group 17 streams principally in the magnitude and seasonality of rainfall and runoff. Group 16 streams are wetter overall though group 17 streams experience more winter rainfall. The runoff of group 16 streams is also more variable both inter- and intra-year and their catchments experience warmer temperatures.

Meta-group G is another with just one member group (22) and is found on the Fleurieu Peninsula in South Australia and in south-west Western Australia (Figure 8.10) where it overlaps with the “mature drainage” zone of Mulcahy and Bettenay (1972). This group has a typical Mediterranean climate with hot summers, mild winters and a strongly seasonal pattern of winter dominated rainfall and runoff. Runoff totals vary little from year to year. Streams in this group are most similar to those in meta-group H (Figure 8.9). They are differentiated primarily by a more pronounced rainfall seasonality and generally lower relief and average catchment slopes.

Meta-group H comprise three of the ecohydrological environment groups (23, 25 and 28) that are distributed across southern Australia (Figure 8.10). They are characterised by a cool, wet climate and the absence of a seasonal dry period. Group 25 streams are distinguished from the others in this meta group by lower values of catchment average slope and relief ratio and warmer temperatures while runoff is higher, especially in winter and spring in group 28 streams. Streams in both of these groups have lower values of pereniality but higher values of skewness than do streams in group 23.

Ecohydrological environment group 26 is the single member of meta-group I. It is found in areas of higher slope and relief in south-eastern Australia, including Tasmania. The catchments of these streams experience cool temperatures, lower radiation and winter dominant rainfall patterns like those in meta-group H, but are wetter and streams may receive a contribution to runoff from snow melt.

Streams in south-west Tasmania and the highest parts of the Great Dividing Range are members of the ecohydrological environment group 29 that forms the final meta-group, J. They share similar climate and runoff characteristics with those in meta-group I but typically are even wetter and colder and have the lowest year to year variability in runoff of all groups. They also differ in catchment vegetation cover. Unlike meta-group I streams, grasses and other non-tree vegetation types may cover a substantial portion of the catchment of these streams

8.3.3 Performance of the ecohydrological environment classification

8.3.3.1 Recovery of flow regime classes

The 830 gauging stations used to test classification performance are unevenly distributed across the ecohydrological environment groups. One group (11) is not represented at all while three other groups (12, 18, and 21) are gauged at just one location. Another eight of the groups are represented by less than 10 gauging stations. In contrast, more than 80 gauges are located on streams in ecohydrological environment groups 22 and 28.

The ability of the ecohydrological environment classification to recover the 12 flow regime classes generated by the classification of these gauging stations (Appendix 5) is mixed. While the streams of some ecohydrological environment groups are readily assigned a flow regime class others are shared among a number of flow regime classes (Figure 8.12). This is confirmed by the value of the Hubert Arabie Rand Index of 0.226 indicative of a fairly weak recovery of the flow regime classes (Steinley, 2004). None of the groups sampled by more than one gauging station are exclusively linked to a single flow regime class. However, for 19 of the 30 ecohydrological environment groups, a majority (> 50%) of the gauges were of a single flow regime class. In particular, gauging stations on streams in the cool, wet groups were predominantly of either the perennial flow regime class 11 or 5. Five of the six gauges on the group 29 streams were flow regime class 11 the other class 5. This situation was reversed for streams in the other closely associated cool, wet group 26 where 41 of the 61 gauges belong to flow regime class 5 and another 14 are flow regime class 11. Similarly, at the other ends of the environmental spectrum the arid group 6 streams were gauged at six locations of which five were of the extremely intermittent flow regime class 4 while all but one of the 34 gauges on streams in ecohydrological environment group 7 (hot, wet, summer rainfall) were of the flow regime class 2 (highly intermittent, summer dominant) (23 gauges) or 6 (perennial, summer dominant, high baseflow contribution) (10 gauges).

Other ecohydrological environment groups include gauging stations from as many as eight flow regime classes. This is the case for both groups 25 and 28, gauged at 48 and 86 locations respectively. Both are members of meta-group 8. This, however, is the meta-group containing the greatest variety of flow regime classes (Table 8.8). The majority of gauges of most other meta-groups are members of just two or three flow regime classes. Table 8.8 also shows that the flow regime classes typically occur across several of the ecohydrological environment meta-groups though the majority may be restricted to just one or two. For instance, 47 of the 56 gauges of flow regime class 8 (intermittent, winter dominant) are found on streams in ecohydrological environment group 22 (meta-group G) the remainder are scattered across three other meta-groups D, H and I. The Hubert Arabie Rand Index value of 0.232 is only slightly better than that for the comparison with the 30 group classification.

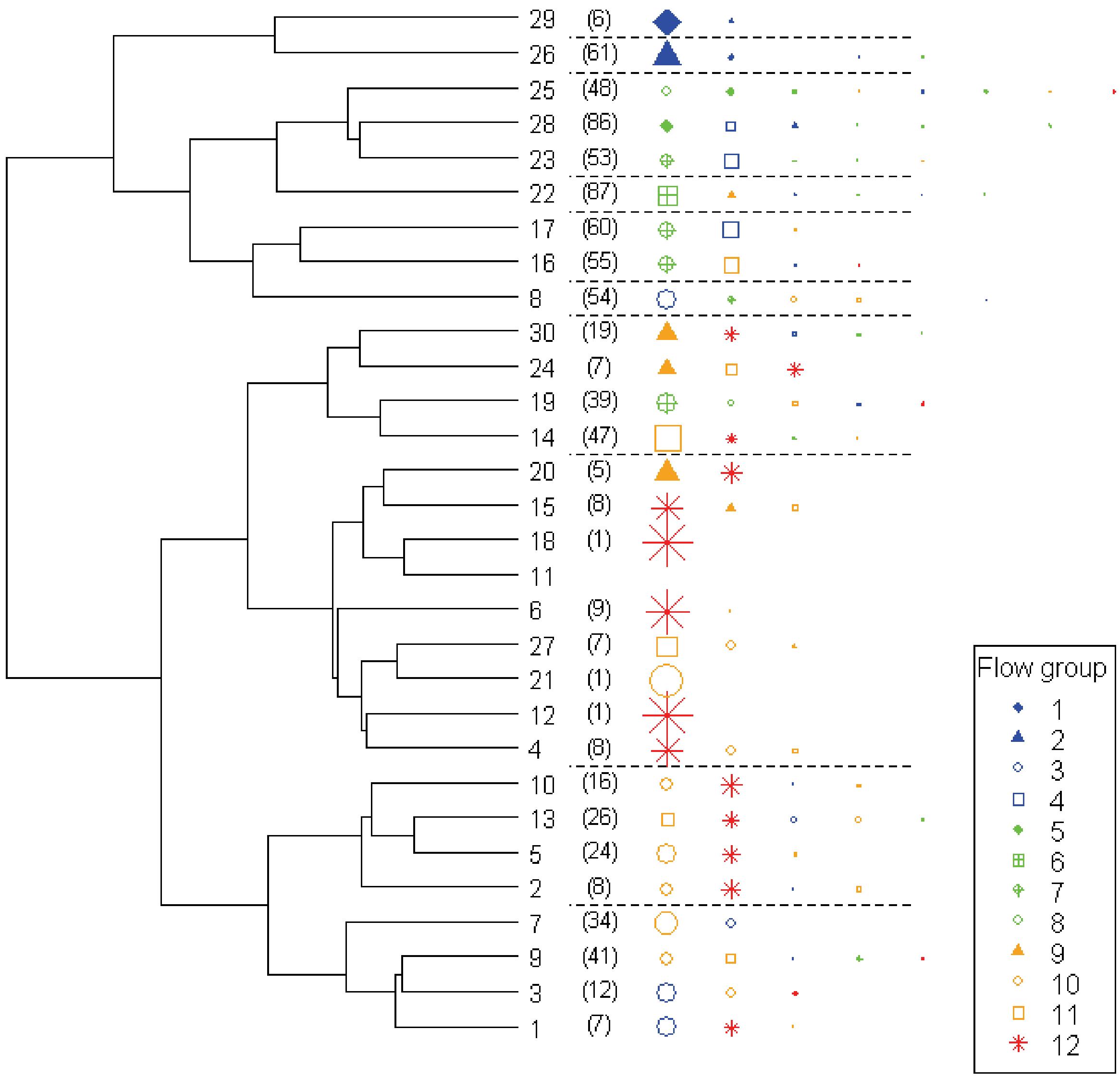

Figure 8.12. Flow regime class membership of the ecohydrological environment groups. The size of symbols is drawn proportional to the total number of gauges within each environment group (shown in parenthesis) while their colour and shape derives from their flow regime class as in Figure 5.9 in Appendix 5 (i.e. blue=Perennial, green=Intermittent, Orange=Highly intermittent, red=Extreme intermittent). Dashed lines show the 10 meta-groups formed by clustering of the ecohydrological environment groups. Environment group 11 streams were not gauged.

Table 8.8 Number of gauging stations by flow regime class and ecohydrological environment meta-group

Meta-group	Flow regime class											
	Perennial				Intermittent			Highly intermittent				Extreme intermittent
	1	2	3	4	5	6	7	8	9	10	11	12
A	1		27				6			46	10	4
B			6				1			28	13	26
C									6	6	6	22
D						1	25	7	14	1	42	18
E	1		30				10			8	4	
F	1			31			57				25	1
G	4	11			6	47		1	18			
H	1	18		45	54	7	26	25	6		3	2
I	14	41		2	3	1						
J	5	1										

8.3.3.2 Discriminating variation in flow regime characteristics

While not being able to consistently predict the flow regime class membership of a stream, the ecohydrological classification is able to discriminate meaningful variation among streams in a number of the ecologically relevant characteristics of the flow regime. This is shown by the box and whisker plots presented for selected flow metrics describing major facets of the flow regime (Figures 8.13 to 8.16). To assist comparison, the hydrologic indices selected are those used to show variation among the flow regime classes in figure 5.9 in Appendix 5, calculated for each of the 830 gauging stations.

The ability of the ecohydrological environment groups to differentiate the values of the hydrologic indices varies between the indices and among groups, though no group appears to be consistently more variable across all flow metrics. For instance, the mean number of zero flow days is well predicted by group membership for some groups including those at the extremes of the climate gradient (e,g the cool, wet groups 26 and 29 and the arid groups 6 and 27) but poorly so for many others (e.g. group 1) (Figure 8. 13). In contrast, within group variation in the values of the hydrologic index, predictability of mean daily flow, is similar for all groups and relatively modest.

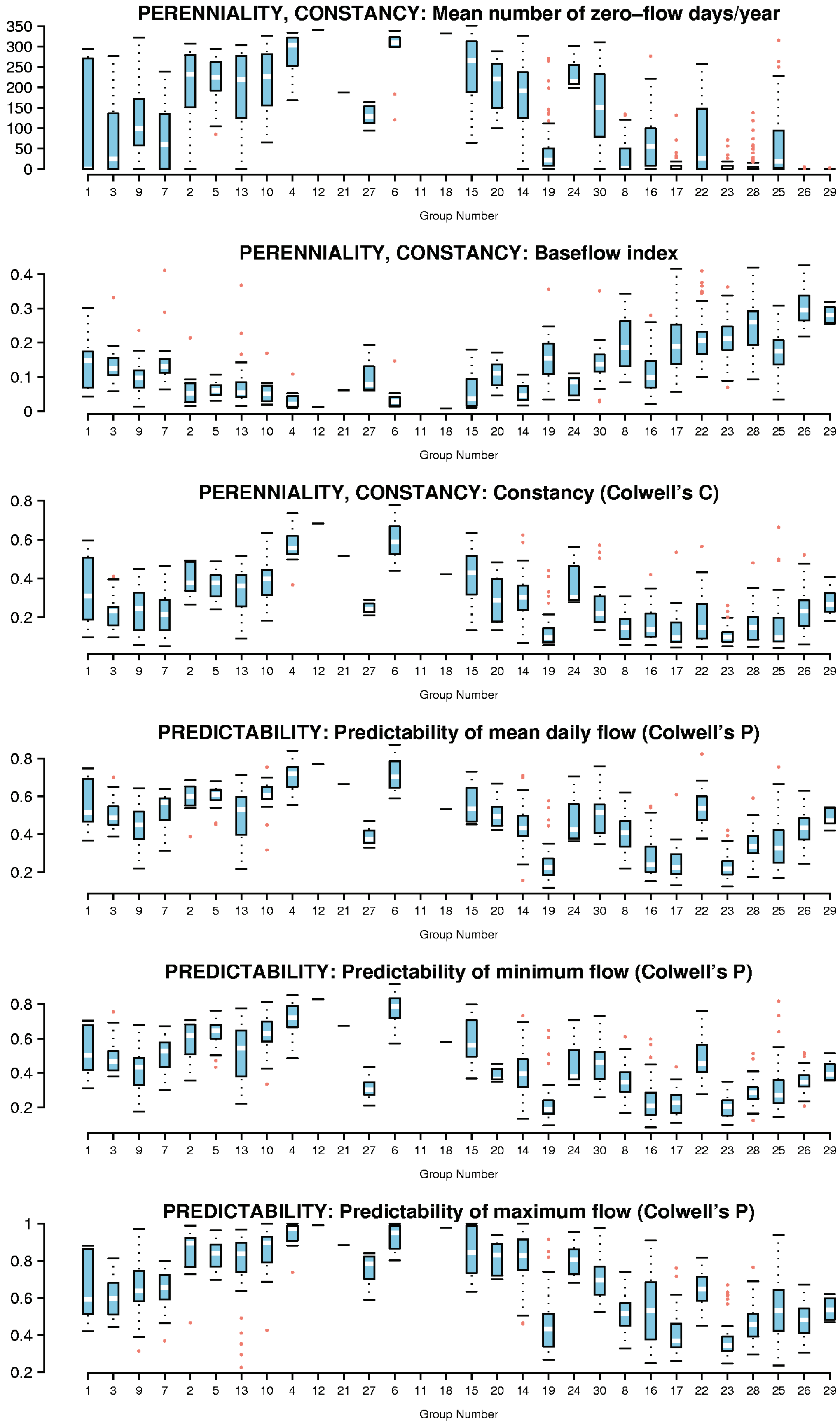

Figure 8. 13 Distribution of flow metric values by ecohydrological environment group (arranged in dendrogram order) for selected flow metrics 1: perenniality, constancy and predictability

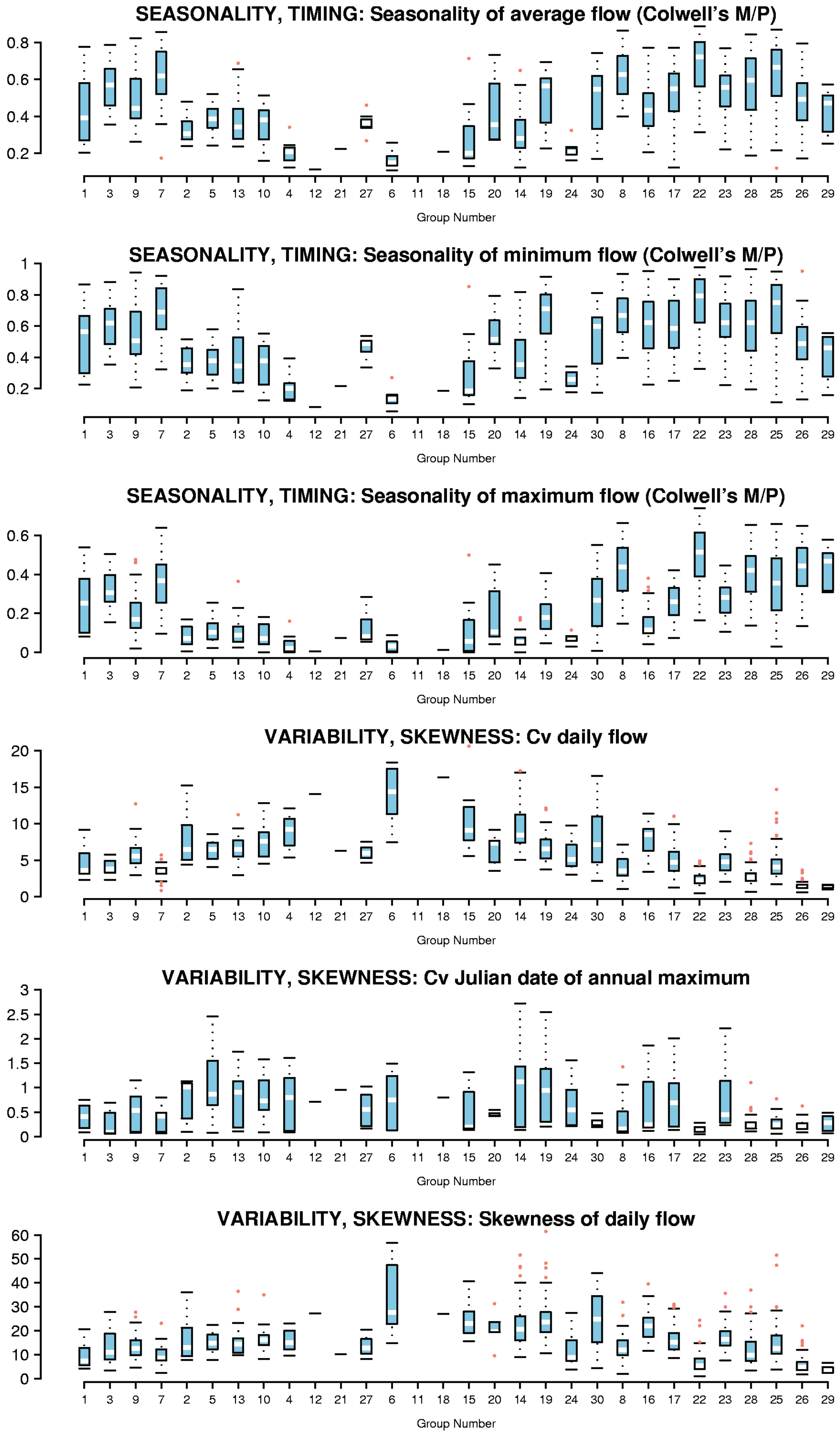

Figure 8. 14 Distribution of flow metric values by ecohydrological environment group (arranged in dendrogram order) for selected flow metrics 2: seasonality, timing, variability and skewness of flow

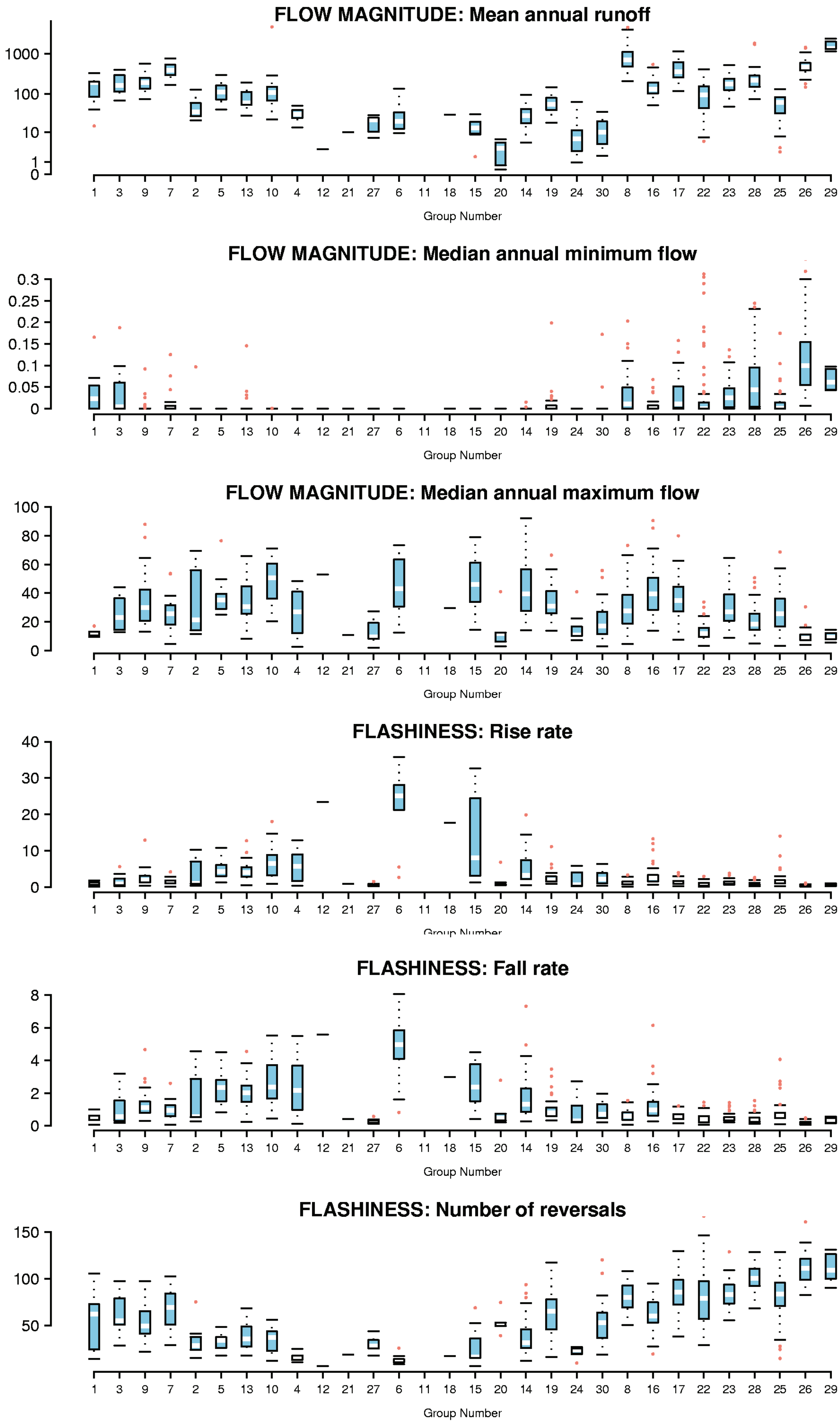

Figure 8. 15 Distribution of flow metric values by ecohydrological environment group (arranged in dendrogram order) for selected flow metrics 3: magnitude and flashiness

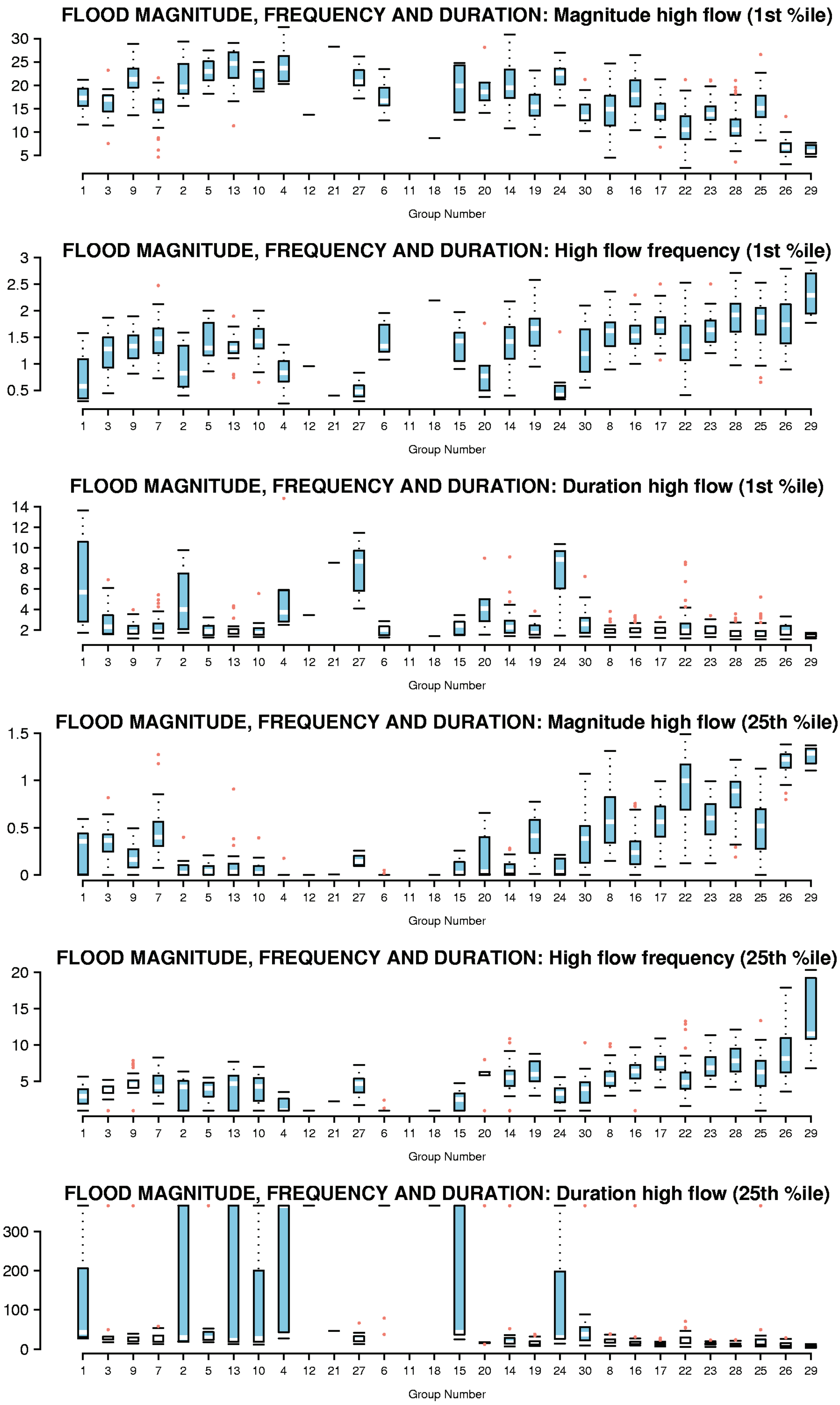

Figure 8. 16 Distribution of flow metric values by ecohydrological environment group (arranged in dendrogram order) for selected flow metrics 4: flood magnitude, frequency and duration

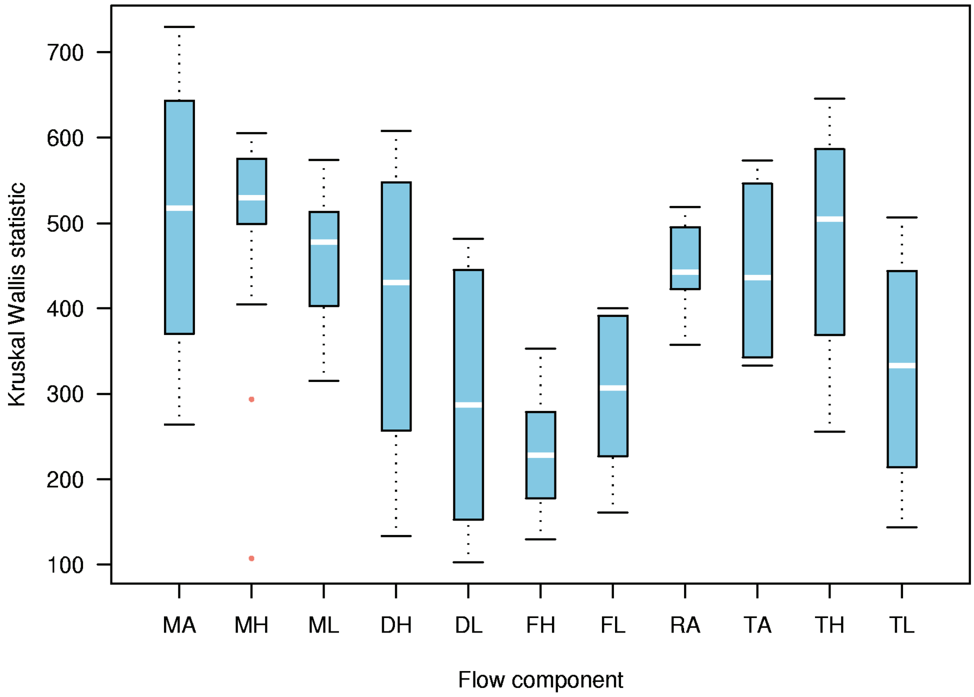

Figure 8.17 Ecohydrological Environment Types Kruskal Wallis statistic for hydrologic indices by flow component: MH-Magnitude average, MH-Magnitude high, ML-Magnitude low, DH-Duration high, DL-Duration low, FH-Frequency high, FL-Frequency low, RA-Rate of change, TA-Timing average, TH-Timing high, TL-Timing low

The results are similarly mixed for the indices describing the seasonality, timing and variability of flow (Figure 8. 14). Perhaps best discriminated by the ecohydrological environment classification among these indices, are the skewness of daily flow and the C_v of daily flow. In contrast, the gauging station values of the Cv of the Julian date of the annual maximum are quite variable for most groups with some notable exceptions for several groups of streams from the southern half of the continent. Interestingly, this hydrologic index also exhibited a wide range of values for five of the flow regime classes (0, 1, 3, 4 and 6) (see figure 5.9 in Appendix 5).

The gauged values of annual mean runoff are very well discriminated by all of the ecohydrological environment classification (Figure 8. 15) (though note log scale). The results are more inconsistent for the median annual minimum and median annual maximum flows. However, group membership reliably predicts where the median annual minimum flow is typically zero. Variation within groups for the hydrologic indices describing the rate of rise and fall is also less for streams in the cooler, wetter groups in southern Australia than it is for streams in meta-groups B and C in particular (Figure 8. 15).

Similarly, the groups differ in the level of within group variation for the flow metrics describing characteristics of the high flows (Figure 8. 16). While the indices describing the flood magnitude and frequency are, in most cases, reasonably well discriminated by the ecohydrological environment groups those describing the duration of high flows are very poorly differentiated by several groups in northern Australia.

For all hydrologic indices the probability value of the Kruskall-Wallis test was very close to zero, confirming that the ecohydrological environment classification did indeed discriminate significant variation in their values. However, as seen in the box and whisker plots, this varied between hydrologic indices (Figure 8.17). Indices describing flow components related to the duration and frequency of events (both high and low) and the timing of low flow events are typically less well discriminated than other components of flow.

8.3.3.3 Classification strength

The Kruskal Wallis statistic tested classification performance against each of the hydrologic indices independently. A more integrated measure of performance is provided by the Classification Strength (CS). We showed earlier (Section 8.3.1, Table 8.7) that the CS value of the 30 group ecohydrological environment classification derived from the NOWEIGHTING classification series was less than that of the flow regime classification of gauging stations, though better than any random grouping of gauging stations. Here we compare the CS of the ecohydrological environment classification with those of alternative landscape classification schemes: the IBRA regionalisation and sub-regionalisation (Department of Environment Water Heritage and the Arts, 2007), the AWRC Drainage Divisions (Australian Water Resources Council, 1976; Geoscience Australia, 2003) topographically defined drainage basins (all of the catchment area draining to a river mouth or inland sink) (Stein, 2007, unpublished) and the agroclimatic classification (Hutchinson et al., 2005). Gauging stations were allocated to a region in each classification by overlay. We also explore variation in hydrologic similarity within groups.

Classification strength was computed for each of the alternative classifications based on the hydrologic similarity of the gauges measured by the Gower metric across all 120 hydrologic indices. The classification strength derived directly from *a posteriori* classification of the gauges suggests an upper bound to that achievable by any landscape classification for the same number of groups (Van Sickle and Hughes, 2000). To compare the strength of different classifications the relative CS (Snelder *et al.*, 2004) was calculated by expressing CS as a percentage of the CS of *a posteriori,* spatially neutral classifications of the gauging station data. These *a posteriori* classifications were generated with the flexible beta UPGMA clustering algorithm (β = -0.1) (Belbin *et al.*, 1992) as implemented in PATN (Belbin, 1993b) for a number of groups equal to the number of landscape classification groups represented by at least two sites, that is, the number of groups included in the calculation of $\overline{W}$. For example, a 26 group classification of gauging stations produced a CS ($\overline{W} - \overline{B}$) value of 0.0887. Thus, the ecohydrological environment classification that also tests 26 groups has a relative CS value of 75% (0.0663 / 0.0887)

The ecohydrological environment classification provides the strongest landscape classification when expressed as relative CS (Table 8.9). The agroclimatic classification also performs well with a relative CS value of 69%. Topographically defined drainage basins provide the weakest classification with CS values just 35% of that achievable for *a posteriori* classification with an equivalent number of groups.

Table 8.9 Classification strength of alternative landscape classifications. Relative CS values are calculated as for *a posteriori* classifications of the gauges are also included

Classification	***Number of groups***	***Number of groups sampled by > 1 gauge***	$\overline{W}-\overline{B}$	$\overline{B}/\overline{W}$	***Relative CS (%)***
Landscape classification					
IBRA 6.1 regions (Department of Environment Water Heritage and the Arts, 2007)	85	56	0.0578	0.935	60
IBRA 6.1 sub-regions (Department of Environment Water Heritage and the Arts, 2007)	403	145	0.0674	0.925	62
AWRC Drainage Divisions (Geoscience Australia, 2003)	12	11	0.0379	0.956	49
Topographically defined drainage basins (Stein, 2007 unpublished)	1250[1]	93	0.0357	0.99	35
Agroclimatic classification of Australia (Hutchinson et al., 2005)	18	17	0.0579	0.934	69
Ecohydrological environment classification (this study)	30	26	0.0663	0.925	75
Classification of gauging stations					
Flow regime classes (Appendix 5)	12	12	0.0764	0.915	98

Notes:

1. Basins of named streams

Mean similarity dendrograms (Van Sickle, 1997) were produced using a routine written in the R statistical software scripting language (R Development Core Team, 2004) (Figure 8.18). Relatively long branches of the mean similarity dendrogram are indicative of a strong classification (Van Sickle and Hughes, 2000). However, while within group similarity W_i was greater than between class similarity for all but one of the Drainage Divisions (Bullo-Bancannia), none of the classifications presented, including the *a posteriori* classification of flow regime classes (Appendix 5) displayed the long arms that would suggest a strong classification. Moreover, W varies between groups. The values of the hydrologic indices were most similar among gauging stations in the cool, wet ecohydrological environment groups 26 and 29 (values of W of 0.914 and 0.917 respectively) and least similar for gauges in group 30, the drier of the south-west Western Australian groups (W=0.8346). The greatest variation in W is observed for groups gauged at less than 15 locations (Figure 8.19) suggesting at least some of the variation in W between groups may be attributed to sampling effects (Hawkins and Vinson, 2000; Heino et al., 2004).

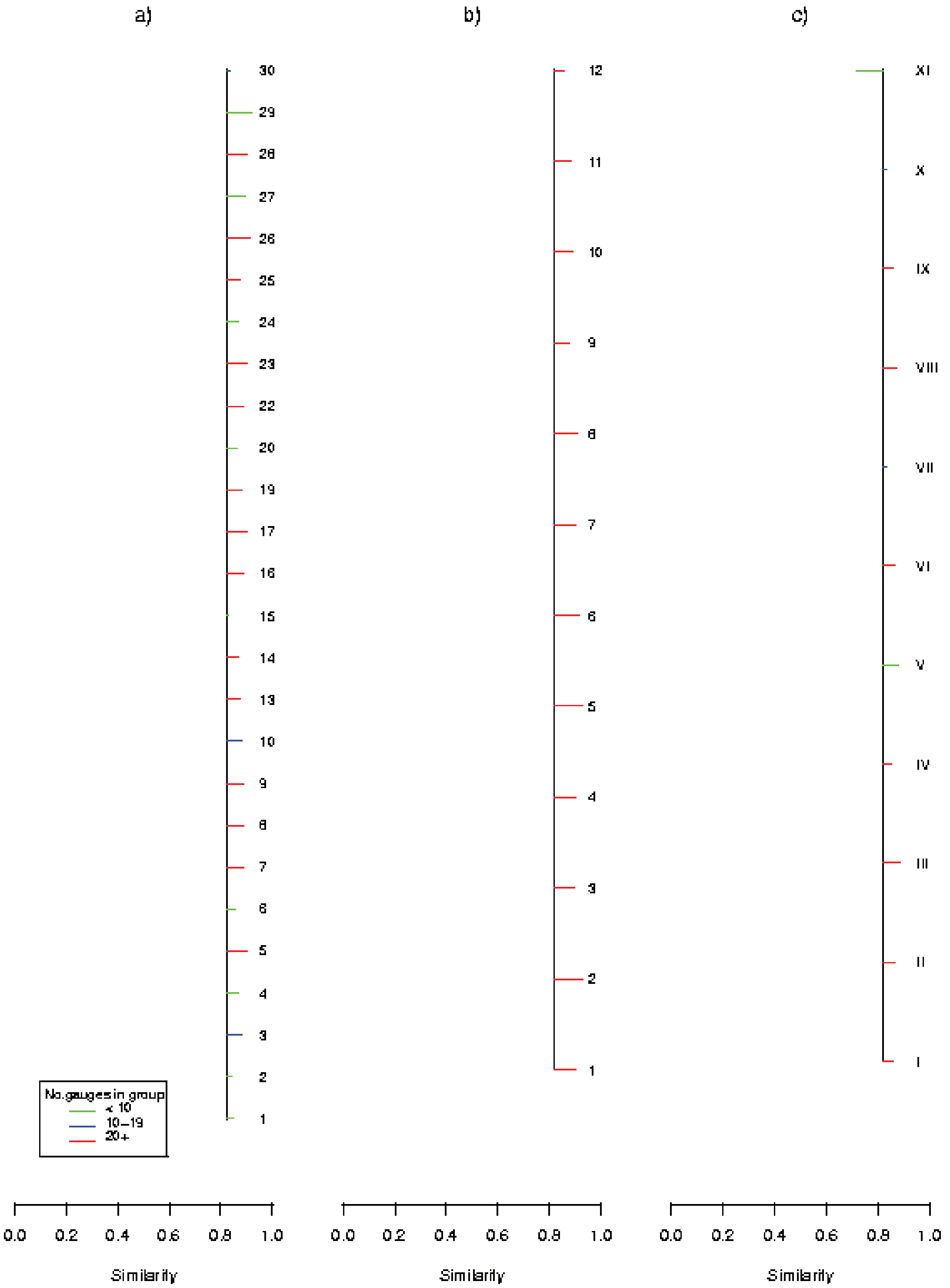

Figure 8.18 Mean similarity dendrograms for alternative groupings of gauging stations: a) the ecohydrological environment classification; b) Autoclass clustering of gauges (Appendix 5); c) AWRC Drainage Divisions (I- North-east coast, II:-South-east coast, III-Tasmania, IV-Murray-Darling, V-South Australian coast, VI-South-west coast, VII-Indian Ocean, VIII-Timor Sea, IX-Gulf of Carpentaria, X-Lake Eyre, XI-Bulloo-Bancannia) . The dendrogram node is plotted at $\overline{B}$, the average between group similarity, with branches for each group of length W_i where W_i is the within group mean similarity for group i

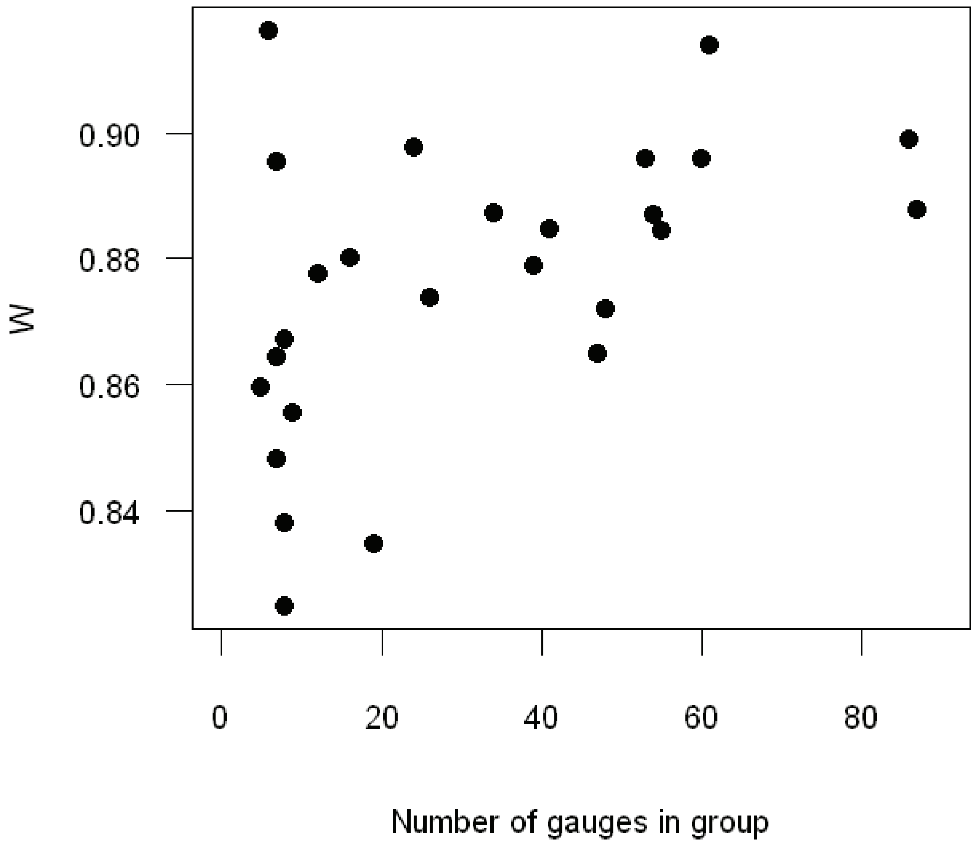

Figure 8.19 Within group similarity (W) for ecohydrological environment groups with number of gauging stations

8.4 Discussion

We classified all of the streams (that are mapped at a scale of 1:250,000) to derive an ecohydrological environment classification for Australia. The classification describes variation in the landscape and climate variables that shape the flow regime. Climate, both directly, and indirectly through the catchment water balance attributes, exerts a major influence on these patterns. At finer spatial scales, groups exemplify the separate and/or combined influences of substrate, terrain and vegetation cover.

8.4.1 Classification performance

Our classification is also able to discriminate meaningful variation in many of the ecologically relevant descriptors of the flow regime. It provides a stronger classification than other national classifications including the AWRC Drainage Divisions, IBRA and the agroclimatic classification. The CS value for the topographically defined drainage basins was particularly low suggesting there is considerable within basin heterogeneity in flow regimes relative to that between – a finding supported by the high diversity of ecohydrological environment types observed for many basins.

The relative CS value of 75% of that for a comparable *a posteriori* classification of the gauging stations compares favourably with that reported by Snelder et al. (2005) for New Zealand's River Environment Classification from an analysis of 335 gauges (a best CS of 60%). Like Snelder et al. (2005) we found between group similarities $(\overline{B})$ to be relatively large when compared to the within group similarities among gauging stations ($\overline{W}$). Accordingly, absolute CS values were reasonably low. This however, was also true of the classification of flow regime classes. The low $\overline{B}$ values implies that each pair-wise combination of gauging stations share similar values for at least some flow metrics, thus constraining the range of possible values of B. The distribution of the pair-wise similarity values confirms this to be the case. These have a mean value of 0.827 (standard deviation: 0.061, median: 0.834) on a scale of zero, indicating the gauging stations are maximally dissimilar, to one, implying identical values across all hydrologic indices. Even the most dissimilar gauges have a Gower metric value of 0.503 implying some overlap in flow metric values.

CS is an integrated measure of classification performance. However, it masks considerable variability in the classification's ability to discriminate meaningful variation between hydrologic indices. Interestingly, some of the components of flow least well discriminated (low flow magnitude, duration and timing) were also some of those that were found to be least accurately described by the gauged data (Appendix 4). Since baseflow characteristics are an important distinguishing attribute of the flow regime classes (Appendix 5) it was not surprising that the ecohydrological environment classification did not reliably predict class membership.

8.4.2 Classificatory strategy

The classification might have been tailored to better recover these flow regime classes by seeding it with the flow regime class means derived from the values of the environmental attributes at the gauging station location. Thus, each stream reach would be allocated to the flow regime class to which it was most similar in this environmental space. However, we were also interested to discover whether there was additional variation in the ecohydrological characteristics of streams that might not be captured by the reasonably limited set of gauging stations available. Accordingly, we derived our environmental classification independently and used the gauged data to test its performance. We thus identified four groups of streams with potentially different ecohydrological characteristics that were either not gauged at all, or gauged at only one location. Not unexpectedly, these streams are all found across the arid centre of Australia and hence have been of very little interest to hydrologists.

There are a number of other aspects of our classificatory strategy that will influence the outcomes. These include our choices of clustering method, attributes, weightings, numbers of groups and hierarchical organization.

We employed the ALOB non-hierarchical clustering procedure to generate the ecohydrological environment classification based on its successful application to many other environmental domain analyses and its ability to handle the very large data matrix that we generated (i.e. 1.2 million stream reaches x 48 attributes). The inter-group association matrix it produces also enables exploration of the relationship between groups and their higher level clustering. However, it does not explicitly incorporate data uncertainty into the algorithm though this might be approximated by appropriate variable weightings. More seriously, it produces hard boundaries between classes that may not reflect gradual change. Probabilistic methods such as that used to generate the flow regime classes overcome the problem of indeterminate boundaries and might be assessed for future revisions of the ecohydrological environment classification.

There are no widely accepted criteria for determining an appropriate number of groups (Belbin, 1993a). Moreover the different criteria may not agree (Mufti *et al.*, 2005). For ease of interpretation and use and because it better recovered the grouping of gauging stations we chose to focus our analysis on a 30 group classification. Classifications with a larger number of groups will differentiate greater variation in the environmental characteristics of streams and their catchments. However, as the number of groups increases, the differences between them increasingly approach the measurement error of the attributes or is so small as to be ecologically meaningless. Still, streams in the two most similar groups of the 40 group NOWEIGHTING classification series differed significantly across at least one attribute: the average proportion of natural tree cover in the catchment (values of 5 and 74% respectively). It remains to be tested, however, whether this explains any additional, ecologically meaningful, variation in their flow regime. Such testing would likely require additional gauging stations to ensure adequate sampling of each group.

Our attribute weighting was implicitly defined by the number of variables that we used to describe the major landscape controls on stream hydrology. These were heavily weighted to the climatic and catchment water balance descriptors, many of them highly correlated, so not surprisingly, these are the major discriminators of variation among the groups. This is, however, consistent with the wide recognition of the primary role that climate plays in controlling stream ecosystem patterns and processes at broad spatial scales (Bailey, 1996; Cleland *et al.*, 1997; Calvert *et al.*, 2001; Snelder and Biggs, 2002) but reduces the influence of other important controlling factors. This could be one of the reasons the classification was unable to discriminate those streams with a significant baseflow contribution associated with the geology of its catchment. Assigning equal weighting to each of the major attribute groups (climate, catchment water balance, catchment morphology, substrate and vegetation cover), however, produced a weaker classification.

A hierarchical classification structure provides an alternative method of organizing the classification that better reflects the different scales at which the controlling factors operate. Thus, for instance, one could derive five separate classifications, one for each of the major attribute groups, and then combine these hierarchically (e.g.Snelder and Biggs, 2002; Stein, 2007). The major disadvantage of this approach is the large number of combinations it can produce making validation and testing problematic. For example, there are 10^5 possible combinations for a five level hierarchical classification of ten groups though of course, many of the potential combinations may not exist.

The attributes selected by the Mantel tests raise some interesting questions about the nature of the landscape controls on stream hydrology. These too down-weighted the influence of substrate, selecting none of the attributes describing the catchment lithology. Similarly, the classification trees (CART) models (Appendix 5) did not include geological attributes as significant predictors of flow regime class membership. This, however, is likely to be more a reflection of the limitations of the geological data and the method of attribution than an indication of the relative influence of catchment geology on stream hydrology.

8.4.3 Characterisation of landscape processes

Categorical map data such as lithology are difficult to attribute in ways that suitably reflect their influence on stream hydrology. This task was made more difficult by the nature of the geological mapping. The new, 1:1 million scale, Geology of Australia mapping was not finished in time for this project. Differences in the mapping scale and the coding and lithological description of map units between this, and the older, 1:2,500,000 scale mapping used to complete the continental coverage, produced inconsistencies across state borders and potentially artefacts in the classification. The mapping units also combine lithologies with very different hydrogeological properties. For example, shales and other fine grained clastic rocks, typically with extremely low permeabilities, were mapped with highly permeable sandstones (Fitts, 2002). Moreover, a lithology's hydrogeological behaviour may vary considerably depending on the age of the bedrock and the degree of weathering and faulting (Le Moine et al., 2007). Even if expert assistance was available to characterise the hydrogeological properties of each of the many thousands of mapping units (a major undertaking) there remains the problem of integrating these values across the catchment.

Catchment averages may be uninformative and even misleading, especially in large catchments.

Catchment averages were also used to characterise the catchment climate and similarly, may not adequately represent the heterogeneous climatic conditions of a large catchment. This might be improved by weighting the average according to the potential contribution of an area to stream flow (e.g. as indicated by the monthly runoff estimates). An even better solution would be to model directly the physical processes that shape the character and behaviour of the stream hydrology although in many cases this is likely to be precluded by the coarse scale of national mapping of essential data layers.

The catchment water balance model attempted to do this. Clearly, it greatly simplifies the processes of converting rainfall into runoff. This avoided the need for calibration for individual catchments and complex parameterization with concomitant demands on data thus enabling continental scale application. It was computed from monthly rainfall totals rather than actual rainfall events and does not account for transmission losses in streamflow routing. Contributions to streamflow from surface (overland and interflow) and groundwater are not partitioned though work is now underway to introduce a slow flow component into the water balance model (M.Hutchinson, pers. comm. 31/1/08). The results will also be sensitive to the coarse resolution (~1km) of the soils data that sets the size of the soil water storage capacity and the way the accumulated runoff is apportioned in anabranching systems.

8.5 Conclusions

We recognized limitations and uncertainties in our classification. Some of these could be readily addressed by testing alternative classificatory strategies such as the use of probabilistic clustering algorithms or a hierarchical classification structure. Others relate to our ability to capture the critical landscape controls on stream hydrology and will require a greater investment in research. In particular, it will be important to address shortcomings in the methods available to characterise the influence of catchment geology and the geological mapping on which it is based. The inability of the classification to discriminate streams with a significant groundwater contribution might be largely attributed to these shortcomings.

Even so, we have shown that the consistent, continent-wide characterisation of climate and landscape variation that our ecohydrological environment classification describes differentiates many of the other ecologically relevant components of the flow regime, including those describing its magnitude, seasonality and variability. At the highest level, the classification splits streams into three broad clusters, differentiating streams in the north from those in the south and inland. Further divisions produce groupings of streams that are generally spatially coherent. The overriding influence of climate on these patterns is reinforced by the relative strength of an independent agroclimatic classification.

The ecohydrological environment classification will support applications at broad regional to continental scale while supplying the context for finer scale regional or catchment studies. We showed, for instance, how it might be used to explore patterns of diversity in the ecohydrological characteristics of streams at a range of spatial scales. We also identified several ecohydrological environment types that were very poorly gauged. Thus, our classification may also be applied to the task of designing a more representative network of gauging stations.

Acknowledgements

The maps shown in figures 8.6, 8.7, 8.8 and 8.10 incorporates data which is ©
Commonwealth of Australia Geoscience Australia 1997 and 2004

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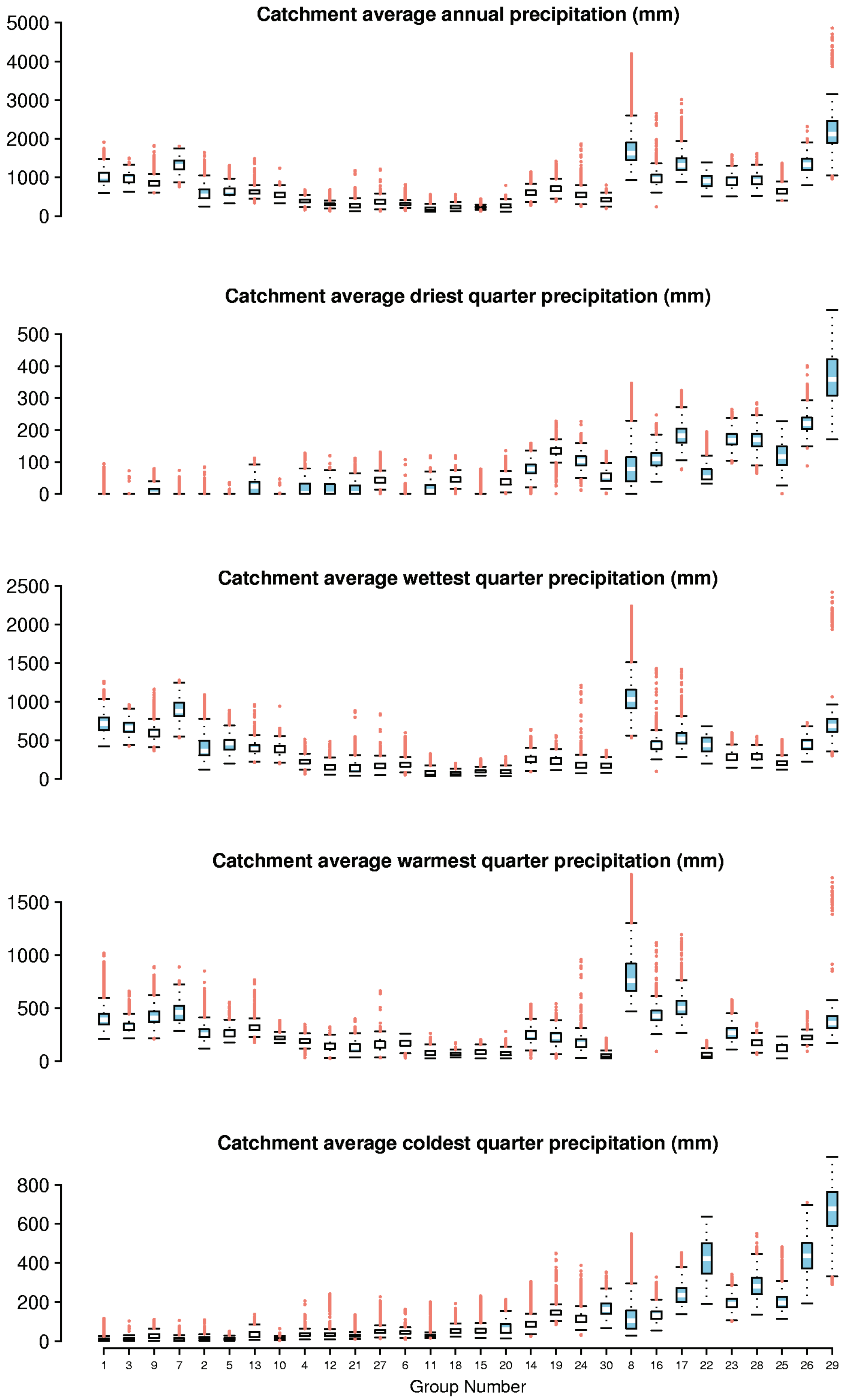

Figure A8.1 Distribution of rainfall attributes by ecohydrological environment group. Groups are arranged in dendrogram order (Figure 8.9)

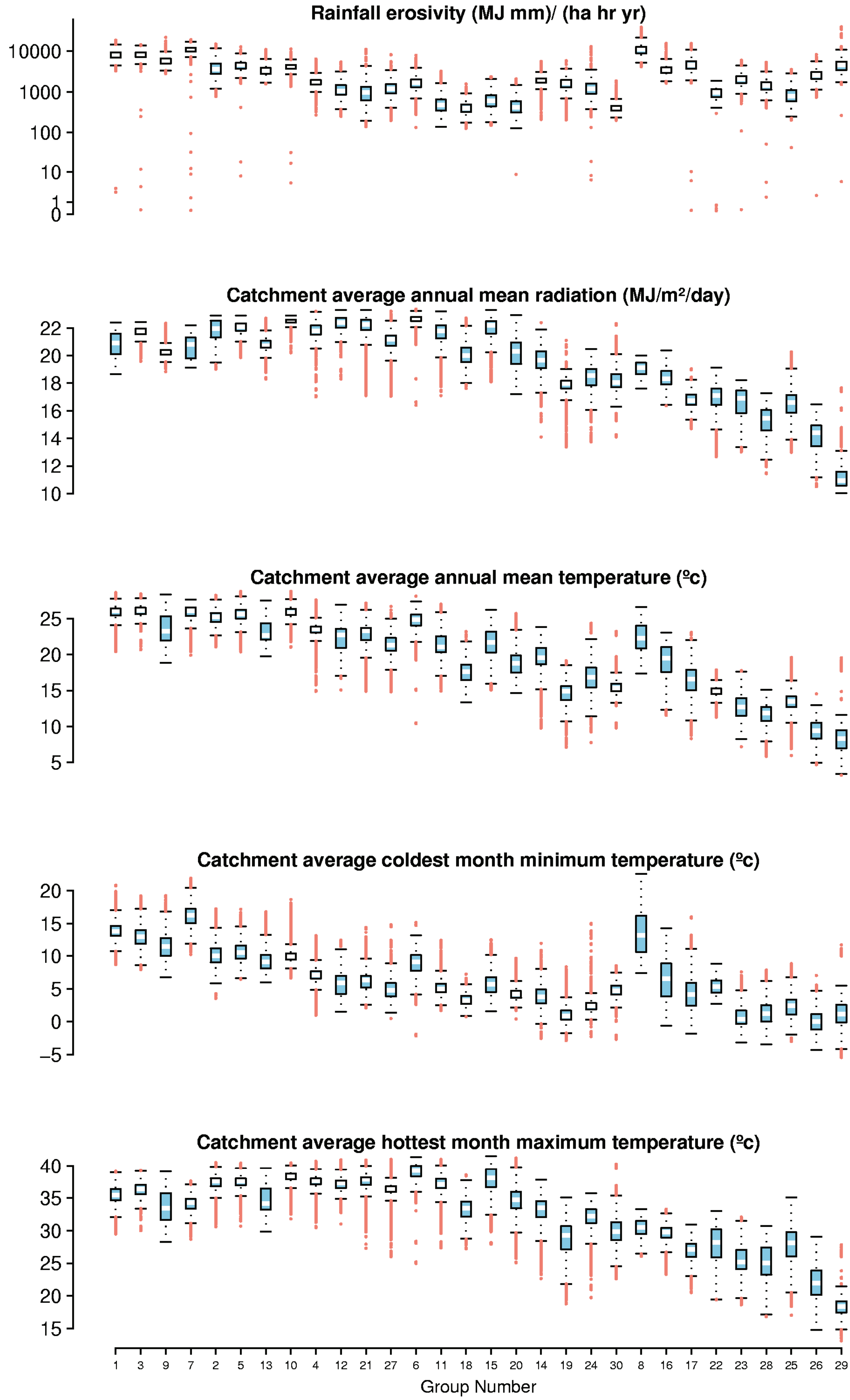

Figure A8.2 Distribution of other climatic attributes by ecohydrological environment group. Groups are arranged in dendrogram order (Figure 8.9)

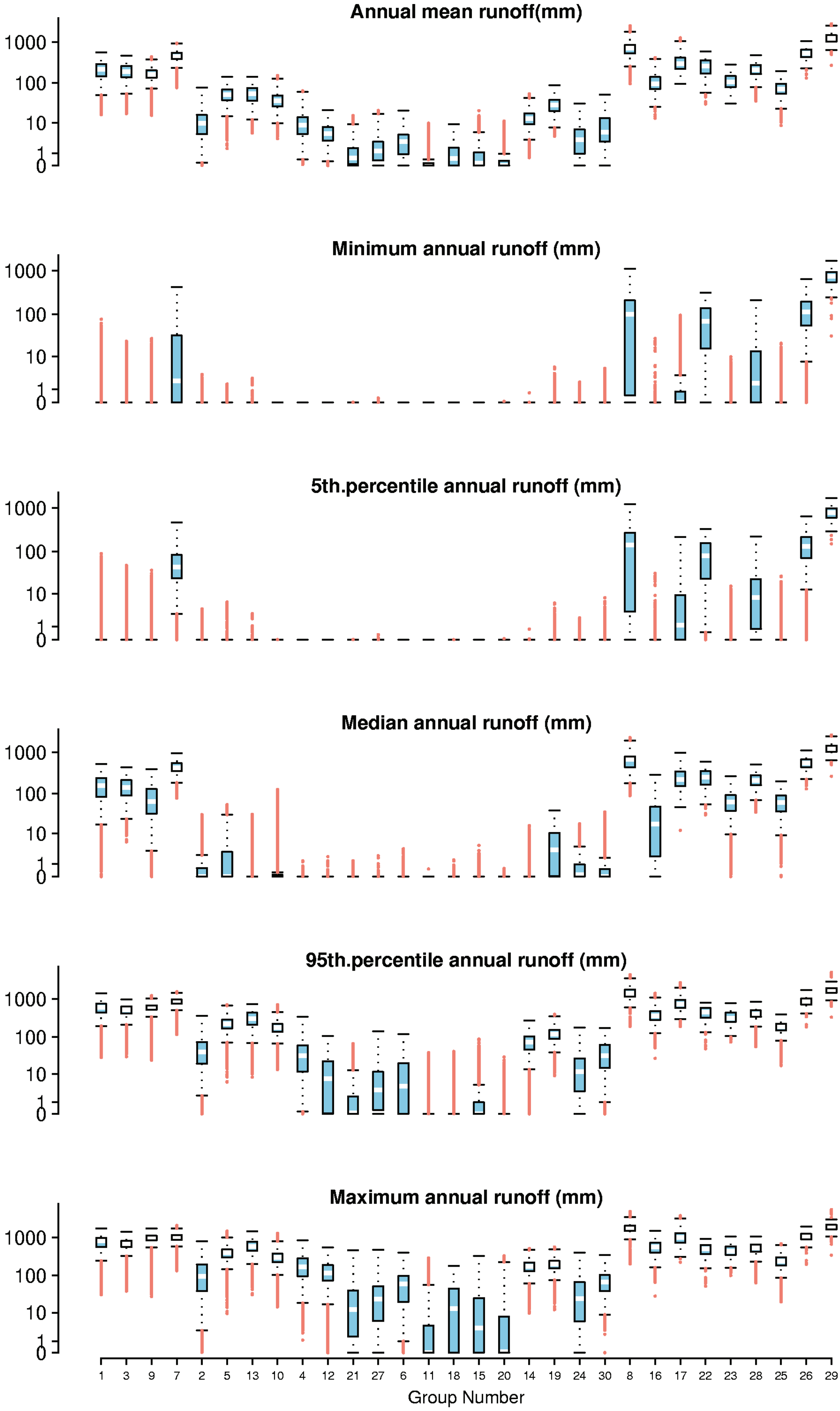

Figure A8.3 Distribution of values for catchment water balance attributes by ecohydrological environment group 2. Groups are arranged in dendrogram order (Figure 8.9)

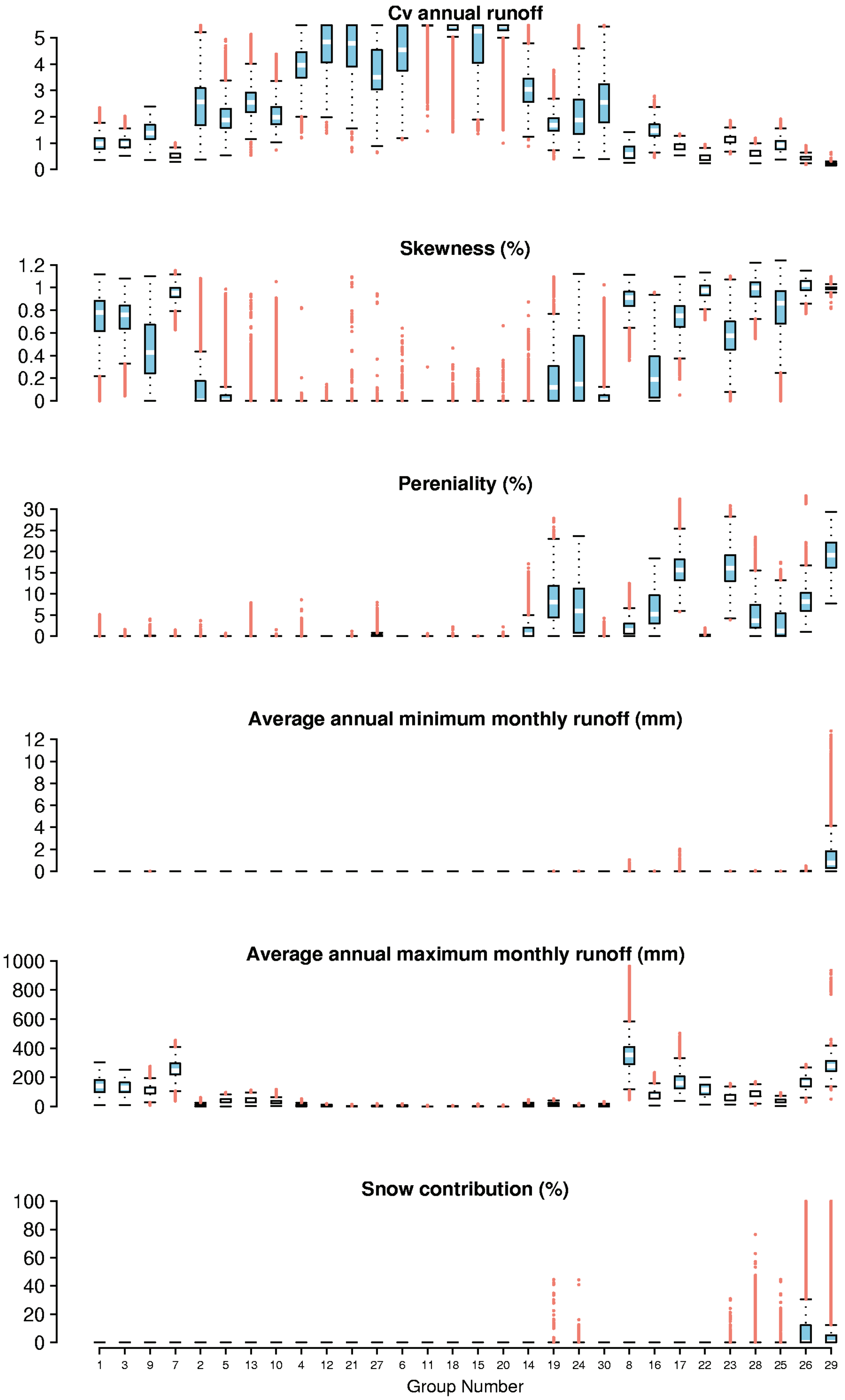

Figure A8.4 Distribution of values for catchment water balance attributes by ecohydrological environment group 2. Groups are arranged in dendrogram order (Figure 8.9)

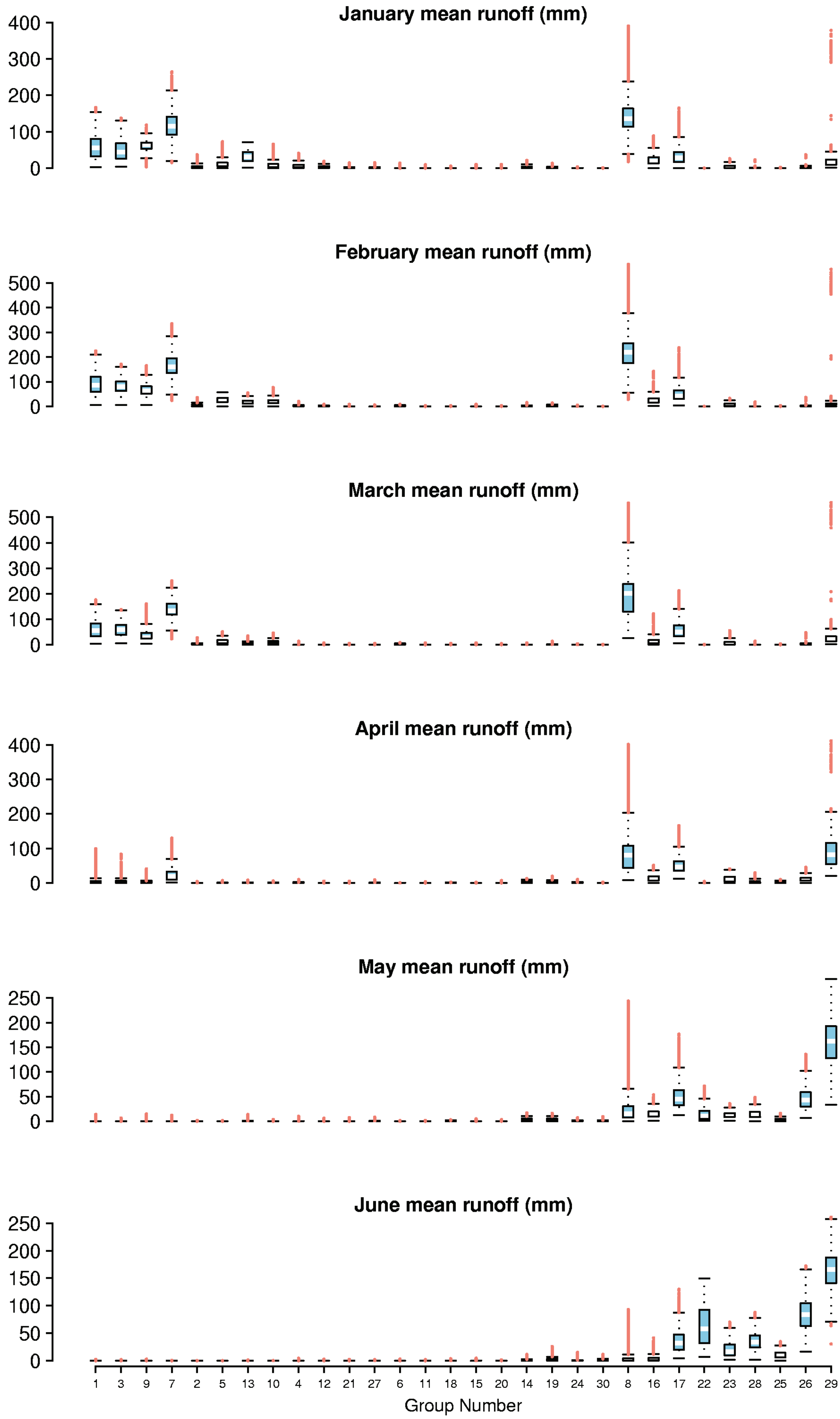

Figure A8.5 Distribution of monthly mean runoff values by ecohydrological environment group 1. Groups are arranged in dendrogram order (Figure 8.9)

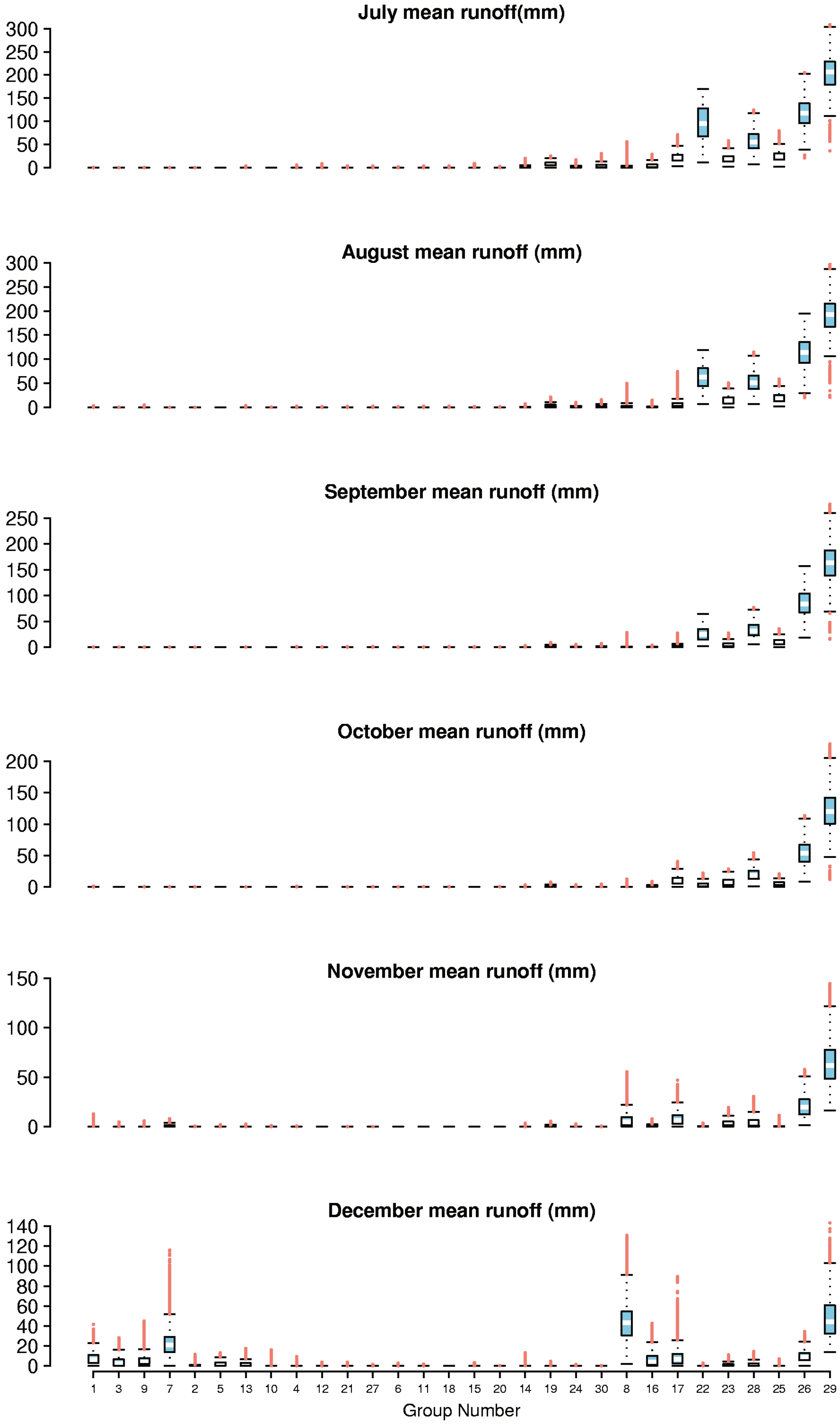

Figure A8.6 Distribution of monthly mean catchment runoff values by ecohydrological environment group 2. Groups are arranged in dendrogram order (Figure 8.9)

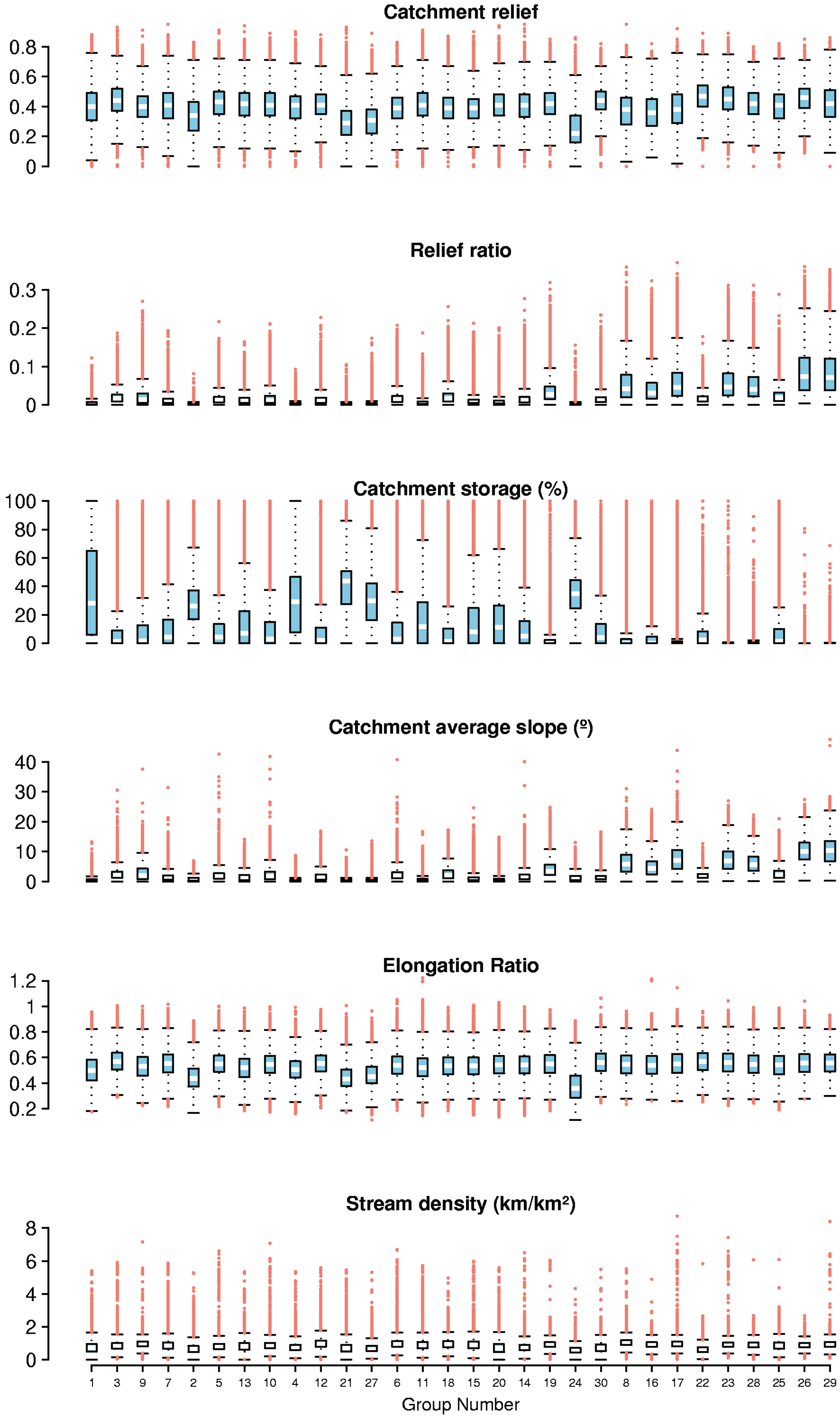

Figure A8.8 Distribution of values for catchment and valley morphology attributes by ecohydrological environment group 1. Groups are arranged in dendrogram order (Figure 8.9)

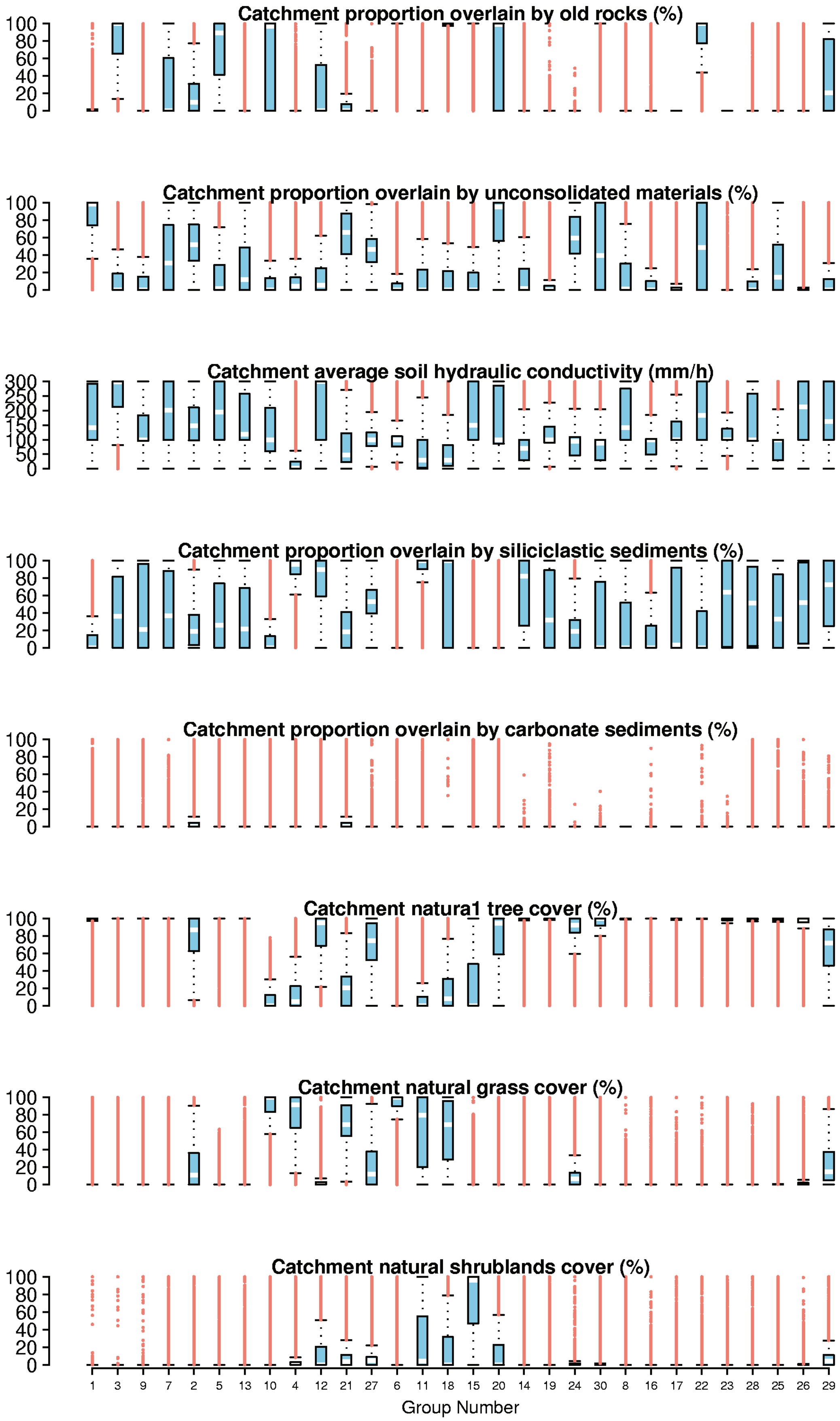

Figure A8.9 Distribution of values for catchment substrate and vegetation cover attributes by ecohydrological environment group. Groups are arranged in dendrogram order (Figure 8.9)