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A new stream and nested catchment framework for Australia

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Abstract

Nationally framed assessment and planning assists coordination of resource management activities across jurisdictional boundaries and provides context for assessing the cumulative effects of impacts that can be underestimated by local or regional studies. However, there were significant shortcomings in the existing spatial frameworks supporting national assessment and planning for Australia's rivers and streams.

We describe the development of a new national stream and nested catchment framework for Australia that includes a fully connected and directed stream network and a nested catchment hierarchy derived using a modified Pfafstetter scheme. The directed stream network with associated catchment boundaries and Pfafstetter coding respect all distributary junctions and topographically driven surface flow pathways including across the areas of low relief and internal drainage that make up over half of the Australian continent. The Pfafstetter coding facilitates multi-scale analyses and easy tracing and query of upstream/downstream attributes and tributary/main stem relationships. Accompanying the spatial layers are 13 lookup tables containing nearly 400 attributes describing the natural and anthropogenic environment of each of the 1.4M stream segments across the Australian continent at multiple spatial scales (segment, sub-catchment and catchment).

The database supplies key spatial layers to support national water information and accounting needs and assists a wide range of research, planning and assessment tasks at regional and continental scales. These include the delineation of reporting units for the Australian Water Resources Assessment, the development of an eco-hydrological environment classification for Australian streams and the identification of high conservation value aquatic ecosystems for northern Australia.

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1 Introduction

A continental framework for natural resource planning and assessment enables management activities to be coordinated across jurisdictional boundaries (Corkum, 1999; Jensen et al., 2001). Continental assessment provides unambiguous evidence of the cumulative impact of human activities (Boulton and Brock, 1999; Ormerod, 1999; Frissell et al., 2001) that are often underestimated by local or regional studies (Hughes et al., 2000; Australian State of the Environment Committee, 2001). This is especially important for cross-border rivers and streams where local decision-making can undermine broader goals of environmentally sustainable management (Kingsford et al., 1998, 2005; Australian State of the Environment Committee, 2001). A national framework can also guide priority setting for national funding programs and provide context for more detailed and specifically-targeted planning and assessment (Veitch and Walker, 2001).

However, the continental frameworks that have been available for planning and assessment of Australia's water resources have significant shortcomings. The most widely adopted of these, the Australian Water Resources Council (AWRC) River Basins and Drainage Divisions (Fig. 1) (Australian Water Resources Council, 1976; AUSLIG, 1997; Geoscience Australia, 2003a) has served for several decades, but does not always adhere to topographically defined hydrological boundaries and does not recognise the distributaries that link many major river systems. The Murray River, for example, divides River Basins within the Murray Darling Basin Drainage Division while the boundary between the Paroo and Warrego River Basins intersects a distributary that connects the two (Kingsford et al., 2001). The AWRC River Basins confuse a number of spatial scales and are too coarse for many water resource assessment needs. They include topographically defined basins (e.g. the Fitzroy River in Queensland), the catchments of major rivers (e.g. in the Murray-Darling Basin) and sub-catchments (e.g. the lower Avon River in Western Australia). The nested sub-catchments that supported the National Land and Water Resources Audit (Hutchinson et al., 2000) supplied a finer

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sub-division of topographically derived catchments. However, these catchments also fail to recognize distributary drainage structures, and the patterns of drainage density, derived by application of uniform area thresholds, are inconsistent with observed patterns, especially in areas with low topographic relief or extreme aridity. These areas make up over half of the Australian continent (Hutchinson et al., 2008).

A national catchment framework requires an underpinning spatially-consistent streamline network. However, the streams comprising the 1 : 250 000 scale Geodata TOPO 250K series 3 watercourse lines (Geoscience Australia, 2006), the most accurately located national stream layer, are not consistently directed downstream. The more recently published Australian Hydrological Geospatial Fabric (AHGF) cartographic streams (Bureau of Meteorology, 2010), based largely on the Geodata TOPO 250K series 1 watercourse lines (AUSLIG, 1992), are consistently directed but display major disparities in drainage density across mapsheet boundaries. Both are cartographic products that are not readily amenable to spatial analysis tasks such as catchment delineation and network tracing.

Global drainage datasets also have serious shortcomings as national frameworks for planning and assessment. The earlier of these were developed from Digital Elevation Models (DEMs) at relatively coarse spatial scales of 30′ to 1° to provide a basis for continental and global scale modelling of water and sediment transport (Renssen and Knoop, 2000; Vörösmarty et al., 2000; Döll and Lehner, 2002). The HYDRO1k dataset (US Geological Survey, 2001) includes streams, drainage basins and ancillary layers (e.g. slope, aspect, contributing area) derived from the USGS' 30 arc-second DEM of the world (GTOPO30). HYDRO1k delivers a nested hierarchical catchment framework by successively sub-dividing drainage basins according to the Pfafstetter scheme (Verdin and Verdin, 1999). The most recent of the global hydrological databases, known as HydroSHEDS (Lehner et al., 2008), supplied a river network and a basin layer for Australia at 15 s grid cell resolution. These global datasets, however, map only the larger streams. Thus the contributing area thresholds applied to delineate the HydroSHEDS and HYDRO1K stream networks exclude streams with a contributing area of less than 20 and 1000 km^2 respectively. Importantly, none of these databases recognize distributary and anabranching drainage structures.

Here we introduce a new national stream and nested catchment framework for Australia that overcomes many of these limitations. We begin with an overview of our approach, and the encoding of surface flow pathways on which it depends. This is followed by a description of the framework components and their development. Applications of the new framework across a range of disciplinary areas, as well as limitations of the framework, are also described. The paper concludes by comparing key aspects of the new framework with other national catchment networks and discussing future developments.

2 Drainage analysis methods

The spatial framework that underpins the National Stream and Catchment database has been developed using new methods of drainage analysis of a DEM that are especially suited to application at continental scale (Stein and Hutchinson, 2014; Stein, 2006). In particular, these methods recognize the extensive distributary drainage structures and natural variability in drainage density that occurs across the Australian continent. Analyses were undertaken using raster based methods both for reasons of computational efficiency and for compatibility with the raster DEM on which many of the attributes characterizing the land surface depend. However, for ease of display and mapping, each of the spatial layers in the database is also supplied in vector format by converting the raster outputs.

All components of the database fundamentally depend on the surface flow pathways encoded in the national 9 s flow direction grid as calculated in 43 rectangular tiles by version 5.2 of the ANUDEM program (Hutchinson et al., 2008; Hutchinson, 2011). This version includes a multiple-flow extension that incorporates flow to an anabranch at each distributary point in the stream network. Infrequent shortcomings in the grid, including loops at tile edges, spurious sinks, spurious multiple flow directions, flow

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directions that produced catchment “tails” or crossing flow paths, and flow pathways that connected from the mainland to close islands (in an adjacent grid cell), were corrected using a combination of automatic procedures and manual editing. Supplementary flow directions were also added to a grid cell where the two directions coded by ANUDEM were insufficient to ensure the connectivity of flow pathways in the more complex braided or anastomosed sections of the channel network.

3 A nested stream and catchment framework

The new framework includes three closely linked components (Fig. 2):

1. A fully connected and directed stream network that recognizes distributary drainage structures, derived from the national 9 s DEM and flow direction grid version 3 (Hutchinson et al., 2008).
2. A nested hierarchy of catchments and associated Pfafstetter coding that respects these distributary junctions.
3. Readily interrogated lookup tables that provide attributes describing the natural and anthropogenic characteristics of the stream and catchment environment.

3.1 DEM derived stream network

The stream network was derived by tracing the flow pathways encoded in the multiple flow direction grid from the gridded channel heads of the AusHydro cartographic streams (the foundation layer for the AHGF mapped streams) to an outlet on the coast or an inland sink. The distributary points encoded into the flow direction grid ensure that the derived network connects streams and their anabranches.

Unlike the more commonly adopted method based on the application of a constant contributing area threshold (Montgomery and Foufoula-Georgiou, 1993; Hutchinson et al., 2000; Jenson, 1991; Verdin and Verdin, 1999) this method (Stein and Hutchinson, 2014) delineates a continent-wide steam network with a variable drainage density that is consistent with the mapping scale of the streamlines used to support the construction of the DEM, which in this case is about 1 : 250 000. The resolution of the DEM, however, limits the extent of the stream network and the size of the drainage features that can be extracted (Garbrecht and Martz, 1994). Thus, source channels with a contributing area of less than 1.25 km^2 at their pour-point were removed while retaining main stem segments, being the segments draining the larger upstream contributing area, to their source.

The raster stream network was divided into uniquely identified segments by inserting breaks at all tributary confluences and distributary points, where a channel flows into or out of an AusHydro waterbody or over a cliff and where the traced network connects gaps in the AusHydro watercourse lines (a "DEM connector") (Fig. 3).

An AusHydro identifier was assigned to each segment to link it to the corresponding AusHydro watercourse line feature based on their shared topological relationships. The attributes associated with the AusHydro cartographic streams (stream name, hierarchy and perenniality) were then transferred to the corresponding DEM derived stream segment. Occasional shortcomings in the attribution, such as missing names or an inconsistent hierarchy assignment, were corrected as far as possible, using automatic procedures to trace the network to ensure that attribution followed expected downstream conventions. Thus, it was assumed that major hierarchy status was maintained along the main channel to the stream network outlet. Similarly, attribution was traced downstream to the DEM connectors that were not associated with a cartographic stream.

The derived stream network comprises nearly 1.4M stream segments and has a total length of 3.3M km. About 90 % of these segments are bounded by tributary confluences or distributary points. The remainder comprise 122 578 DEM connectors that join gaps in the mapped stream network, just over 64 000 waterbody connectors (of which 89 % are located within a natural lake and 11 % within a reservoir) and 2700 segments that break the stream at a cliff.

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Segments vary in length from that of a single grid cell (about 270 m) up to 243 km, with an average segment length of 2.4 km. This variation reflects the natural variability in drainage density across the continent, as mapped at a scale of 1 : 250 000, while removing some of the discrepancies between map tiles due to differences in cartographic interpretation.

The locations of the streams derived from the DEM accurately reflect the locations of the input map streams. A random sample of 1000 points along the DEM derived stream lines (excluding DEM connectors) on each of the 44 tiles that correspond to Geoscience Australia's 1 : 1 million scale map series were found to be on average 61 m from an AusHydro watercourse, the expected difference due to gridding and generalization of the vector stream lines to the grid cell resolution of 9 s of latitude and longitude (about 270 m). Just 5 % of the sample points were located more than 125 m from an AusHydro watercourse and all were less than 500 m distant.

3.2 Hierarchically nested catchments

The nested hierarchy of catchments (Fig. 2) was formed by first aggregating, then successively sub-dividing, drainage basins using a modified version (Stein, 2013) of the Pfafstetter scheme of Verdin and Verdin (1999). The Pfafstetter scheme labels each catchment unit with a code that conveys useful information about stream topological characteristics and higher level relationships. It stands out among other methods for delineating and coding catchment units for its efficient use of digits, its ease of implementation, the ready interpretation of its coding scheme and its widespread use globally (Stein and Hutchinson, 2008).

Guided by the topology of the stream network and the size of the drainage area, the Pfafstetter scheme sub-divides drainage basins into successively smaller catchment units that are coded with the digits zero to nine: the four largest tributary catchments coded with the even digits, five inter-catchment units taking the odd digits and a single closed (internal draining) basin, that being the largest in area, that is assigned a Pfafstetter code of zero.

3.2.1 Drainage basins

Drainage basins delineate the entire connected drainage areas of each outlet to the sea and inland sink such as a natural depression or lake. The same identifier was assigned to drainage areas that were connected by a distributary or drained to multiple sinks within a single lake so that these connected areas were together recognized as a single drainage basin. For example, the Norman, Staaten, Gilbert and Flinders Rivers, draining to the Gulf of Carpentaria, are linked by distributaries and so their drainage areas delineate a single basin (Fig. 4). Small drainage basins flowing to a connected group of grid cells in the sea but not drained by a DEM derived stream were similarly aggregated and treated as a single drainage basin.

Nearly 90 000 (88 434) drainage basins were so delineated, each basin draining to one or more outlets on the coast (44 % by area) or to inland sinks (56 % by area) (Fig. 5). However, only 722 basins have an area greater than 1000 km^2. More than 80 % of the basins are very small (less than 10 km^2). These include the areas draining to clusters of clay pans or small dry lakes inland or directly to the sea rather than through a river mouth on the coastal fringe. Just 49 of the basins with an area less than 10 km^2 are drained by an AusHydro named stream. In contrast, the largest basins are typically drained by a major river system or terminate in a large lake (Table 1). The new drainage analysis recognises substantial areas of internal drainage within the Murray-Darling Basin. Consequently the total area draining to the mouth of the Murray River is calculated to be nearly 270 000 km^2 less than the usually quoted area of 1 059 000 km^2 (http://www.mdba.gov.au/about-basin/basin-environment/georgraphy/geology-and-size).

3.2.2 Level 1 and 2: aggregated drainage basins

Levels 1 and 2 of the nested catchment framework were derived by grouping the drainage basins based largely on the AWRC boundaries. This produced more evenly sized regions than would the Pfafstetter scheme when applied at the continental level

(Stein, 2006). Linking with the AWRC boundaries also facilitates the transfer of existing water resource information to the new framework.

The Level 1 Topographic Drainage Divisions (Fig. 6) were thus delineated by first allocating each of the coastal draining basins to the AWRC Drainage Division that occupied the majority of the drainage basin area. Internally draining basins were then associated with either a coastal draining AWRC Division or the interior Lake Eyre drainage basin by successively merging them with a lower neighbouring drainage basin via the lowest pour point on the basin divide. The derived Level 1 boundaries were compared with the AWRC boundaries, the topographically based analysis by Hutchinson and Dowling (1991), palaeodrainage systems established by van de Graaff and colleagues (1977) and divisions similarly derived from locally averaged 1 s SRTM data (Gallant et al., 2011). Major discrepancies were further checked by local inspection of the terrain features on Landsat imagery (Furby, 2002) and 1 : 100 K topographic mapping.

This review indicated that the group of 71 internally draining basins draining towards Lake Breaden in the Gibson Desert in Western Australia that had been merged with basins in the North Western Plateau Drainage Division should instead be grouped with the drainage basins draining to the southern Australian coast that form the South Western Plateau Drainage Division. The elevation of the competing pour-points on the drainage divide differed by less than 6 m, within the elevation error of the 9 s DEM (Hutchinson et al., 2008). Thus, supported by the additional evidence, we reassigned these basins to the South Western Plateau Drainage Division.

The drainage divisions derived from analysis of both the 1 and 9 s DEMs indicated an expansion of the Murray-Darling Basin (MDB) Division in the south-east to include internally draining basins from the northern half of the AWRC Millicent Coast Basin, South-east Drainage Division. However, for compatibility with the legislated administrative boundaries for the MDB that are based on the old AWRC boundaries, the Level 1 boundaries were modified so that this group of internally draining basins was placed in the Level 1 South-east Coast Drainage Division.

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Level 2 in the catchment hierarchy was delineated by sub-dividing the Level 1 drainage basin groupings based on the AWRC River Basins (Fig. 6). Thus, the 9 s topographically defined drainage basins were associated with an AWRC River Basin draining to the sea or in the case of the internally draining Lake Eyre Drainage Division, into Lake Eyre (North). The associated AWRC River Basin was the one that occupies the majority of the 9 s drainage basin area or, if an internally draining 9 s basin, the AWRC River Basin that it would be associated with if the 9 s basin were to overflow successively into lower neighbouring basins via the lowest pour-points.

3.2.3 Level 3 and beyond: application of a modified Pfafstetter scheme

The Level 2 basin groups were sub-divided into successively smaller basin and sub-basin units using a modified version (Stein, 2013) of the Pfafstetter scheme of Verdin and Verdin (1999). The continental scale Pfafstetter scheme of Verdin and Verdin was applied to initially divide and code Level 2 basin groups. The Verdin system was then modified to successively sub-divide these drainage basins into tributary catchments and main stem "inter-basins", using a modelled estimate of runoff volume rather than contributing area to discriminate the tributary and main stem. The Pfafstetter system was also extended to include a coding method for distributary and anabranching drainage systems and catchments that drained stream networks with less than four tributaries.

Only distributary channels that drained to an alternative outlet or into a different tributary basin were coded separately from the main stem. Other multi-channel streams were assigned a Pfafstetter code as if a single channel. The identifier of the upstream main stem segment (in the case of an anabranch off-take) or the downstream anabranch segment (if a main stem segment that is an anabranch off-take) and the level in the catchment hierarchy at which the anabranch is coded separately from the main stem channel are recorded in the database. This allows the user to optionally include these relationships in network tracing and catchment delineation tasks.

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The original Verdin and Verdin scheme codes only the largest of the internally draining basins at each level. This was modified so that a Pfafstetter code was assigned to each of the numerous internally draining basins that were delineated from the 9 s DEM. Each of these smaller, internally draining basins was assigned the Pfafstetter code of the catchment unit to which it would flow if it were to overflow into the lower neighbouring basin via the lowest pour-point on the drainage divide, a process akin to that used to associate the internally draining basins with a Level 1 or 2 unit.

A 13 level Pfafstetter sub-division of the Level 2 basin aggregations was derived to obtain a 15 level nested catchment hierarchy overall. The finest level sub-division in the nested hierarchy delineates the sub-catchment areas draining to each of the segments in the DEM derived stream network or where there were no AusHydro watercourse features, the drainage basins that drain directly to the coast or an inland sink. The size of the catchment units varies greatly within each level of the hierarchy, depending on the extent of drainage basin sub-division, although the average area of the catchment units changes little after Level 9 (Table 2).

The hierarchical relationships of the catchments are coded into the catchment identifier that combines the Level 1 Drainage Division and Level 2 Basin Group together with the 13 level Pfafstetter code. Not all basins were sub-divided as far as the topology of the stream network allowed even after 15 levels of sub-division. For instance, small, internally draining basins are so numerous in some areas that many still needed to be merged with a lower neighbour for Pfafstetter code assignment as they were not yet the largest internal basin. To assist users wishing to utilise the Pfafstetter coding within a specific basin, the database also records the results of an independent, 15 level, within basin Pfafstetter sub-division applied to each drainage basin individually to code every tributary and main stem stream segment in the basin.

3.3 Stream and catchment environmental descriptors

An extensive suite of environmental descriptors (Table 3) characterize the natural and anthropogenic environment of each stream segment and its catchment at three, increasingly broader, spatial scales:

1. the local stream and its valley as defined by the grid cells that comprise the stream segment and where appropriate, the adjacent valley bottom flats;
2. the sub-catchment, being just the local area draining directly to a segment in the DEM derived stream network and the smallest spatial units of the catchment hierarchy and
3. the entire catchment upstream or for some attributes, the flow path downstream, of the sub-catchment outlet cell.

The stream valley was delineated by the valley bottom flats identified from the values of the multi-resolution Valley Bottom Flatness (mrVBF) and Ridge Top Flatness (mrRTF) indices calculated using the method of Gallant and Dowling (2003) for the 9 s DEM.

The selection of attributes for inclusion was informed by literature review (Stein, 2006) and the requirements of national and regional scale applications (Walsh et al., 2007; Stein et al., 2009; Kennard, 2010), constrained by the availability of data with consistent continent-wide coverage. The principal objective was to include attributes that described key drivers of stream ecological, hydrological and geomorphological processes.

Catchment mean values were calculated by averaging the values of all grid cells upstream of the stream segment outlet cell, dividing accumulated totals and cell counts at bifurcations in the stream network in the ratio of 8 rivers : 4 creeks : 1 unnamed streams: 0.1 floodplain wetlands, based on the ratios observed for gauged streams (Stein, 2006). Custom tools were developed to calculate the catchment attribute values as the multiple flow directions used to encode distributary points in the stream network were not recognized by the flow accumulation and routing functions in standard

GIS packages. These distributary drainage structures also required special treatment so that, for example, stream order did not increment and contributing areas were not counted twice when bifurcating streams rejoined downstream.

To ensure that small but potentially important features were included, categorical source data (geology, landuse and vegetation) were gridded and classified at a grid cell resolution finer than 9 s and then the proportion of each 9 s grid cell occupied by each category used to calculate the stream segment, sub-catchment or catchment summary values. Indicators of connectivity were derived by considering the length of stream that was unimpeded by built structures (dam walls, spillways or large reservoirs) that formed potential barriers to in-stream movement of aquatic biota. The location of a stream segment relative to a natural barrier (a waterfall or cliff) was also recorded in the database as was the name of the AWRC River Basin overlaying the majority of the segment sub-catchment to enable linkages with existing data organised according to the AWRC spatial framework.

The stream and catchment environmental descriptors are best explored within a GIS or in the context of particular applications. Nevertheless, it is possible to derive useful summaries that can demonstrate the continent-wide spatial variation in key drivers of riverine processes and the human activities that threaten the integrity of those processes (Table 4). Thus, while the variability in runoff in Australia is often highlighted (McMahon et al., 2007), and supported by our modelling, it is also clear that there are many regions that experience less variable runoff and thus more reliable stream flow (Fig. 7).

4 Discussion

4.1 A new national framework

The new national framework has been developed to support resource assessment and planning for Australia's rivers and streams. It overcomes many of the shortcomings of previously available national catchment data. It delineates streams and their catchments continent-wide, based consistently on surface topography irrespective of administrative arrangements.

The analysis of these catchments has identified previously unrecognised areas of inland drainage, including those within the Murray Darling Basin. It also highlights the prevalence (56 %) of endorheic drainage in Australia, in contrast to other continents where endorheic regions occupy less than 20 % of the landmass and as low as 5 % in North America (Hammer, 1986).

The Level 1 and 2 groupings of drainage basins reveal the broader scale drainage structure of the continent and indicate some significant departures from the AWRC boundaries, most notably for the Western Plateau Drainage Division and the rivers flowing into the Timor Sea. Consistent with the drainage analysis of Hutchinson and Dowling (1991), and the palaeodrainage analysis of van de Graaff and others (1977), our analysis recognizes a major drainage divide that splits the Western Plateau Division into a northern and southern section associated respectively, with drainage into the Indian Ocean and Great Australian Bight. Also consistent with Hutchinson and Dowling (1991), our analysis links the AWRC basins Mackay, Wiso and Barkly, that were included within the Western Plateau Division, to coastal basins in the AWRC Timor Sea Drainage Division and includes the AWRC Bulloo Bancannia Division within the Lake Eyre Level 1 division.

Unlike the AWRC second tier however, our Level 2 division encompasses entire drainage basins and so does not divide the Murray Darling and Swan River drainage basins. Similarly, by recognizing distributary drainage structures connected drainage areas have been delineated where the AWRC identified separate basins. Our analysis required that internally draining basins, such as the AWRC River Basins of Mackay and Warburton, were connected to either the coast or Lake Eyre. Accordingly, our Level 2 analysis delineates 54 fewer aggregated basin units than the 245 AWRC River Basins.

The stream network derived from the DEM complements the AHGF cartographic streams. The direct link to sub-catchments and the enhanced connectivity of the DEM

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derived product facilitates network tracing and other analytical tasks while the shared AusHydro identifier enables users to link the results of these analyses to the AHGF cartographic streams.

The Pfafstetter coding associated with each stream segment and its associated sub-catchment encodes complex streamline and nested catchment relationships in a readily accessible form. Users are thus able to infer information about topological relationships in a catchment using simple algebraic queries, for example, to identify all sections of a river network up or down stream of any feature of interest or to discriminate mainstem and tributary streams. The identifying codes also enable users to extract catchments at any level in the hierarchy, allowing the scale of analysis and reporting to be varied to match the scale of the available data and to optimise the derived spatial patterns for particular applications.

The Pfafstetter coding and unique catchment identifiers can be associated with other features of the hydrological system located within the sub-catchment, whether natural (e.g. wetlands and lakes) or anthropogenic (stream gauges, locks, weirs, dams). This catchment reference system establishes a standard and seamless scheme for consistent referencing of water features to assist co-ordinated approaches to cross-agency water resource data collection and collation, overcoming the difficulties associated with current systems based on stream names that are inconsistently applied (e.g. streams that change their name along their length or share the same name) or are simply unnamed (Wilson and Nason, 1991).

The database supplies attributes that describe the stream and catchment environment at multiple spatial scales. These attributes characterize important drivers of hydrological, geomorphological and ecological processes that in turn influence water resource availability and condition and ultimately, river ecosystem patterns and processes. For example, the size and shape of the catchment influence the water and sediment yield and its timing and distribution (Fryirs and Brierley, 2012) while measures of slope and relief provide an indicator of the energy available for sediment transport and the potential for erosion or deposition (Jerie et al., 2003).

4.2 Applications

The seamless national data offered by the new framework can support a wide range of modelling and analytical uses in addition to more traditional reporting and mapping applications. The data have already been used to:

1. assist the selection of monitoring sites for bioassessment programs (Gilligan, 2010; Davies et al., 2010),
2. develop models of reference condition for macroinvertebrate community composition and channel physical form for the Murray Darling Basin Sustainable Rivers Audit program (Walsh et al., 2007; Davies et al., 2010, 2012),
3. underpin an ecohydrological environment classification for Australia (Pusey et al., 2009),
4. explore the environmental factors that control genetic diversity and dispersal of riverine fish species (Faulks et al., 2010) and compositional turnover (Turak and Blakey, 2011).

The data have also facilitated the application of systematic conservation planning approaches to riverine systems in Australia (Linke et al., 2011; Turak et al., 2011). In particular, recent enhancements to conservation planning methods to account for catchment connectivity and condition (Linke et al., 2012) depend on the Pfafstetter coding and the broad scale indicators of disturbance provided by the new national framework. Catchment units extracted from this framework also provided planning units for the identification of priority areas for terrestrial biodiversity (Douglass et al., 2011; Klein et al., 2009a, b; Fuller et al., 2010).

A trial of the Australian Government's new high conservation value aquatic ecosystems framework across northern Australia (Kennard, 2010) relied on data supplied by the new stream and nested catchment framework and associated environmental attributes. The DEM derived stream network delineated riverine hydrosystems (Aquatic

Ecosystems Task Group, 2012b) for classification according to the draft Australian National Aquatic Ecosystem Classification Scheme (Aquatic Ecosystems Task Group, 2012a). The ecotopes level of this semi-hierarchical classification scheme was derived by clustering the stream segments according to the similarity of their environmental attributes. The environmental predictors were also used to develop predictive models of the distribution of a wide range of aquatic taxa using sampling units tailored to the ecological characteristics of the faunal group extracted from different levels in the catchment hierarchy – larger catchments (average area 72 km^2) for modelling the distribution of more mobile taxa such as waterbirds and finer resolution catchments (average area 3.5 km^2) for other aquatic taxa including macroinvertebrates, fish and turtles (Kennard, 2010). The modelled distribution of these aquatic taxa, together with the ecotope classification, provided spatially explicit biodiversity surrogates to assess relative conservation value across northern Australia.

The DEM-derived stream network and nested catchments are the foundation data for the Australian Hydrological Geospatial Fabric (the "Geofabric") network streams and catchment products that support the Bureau of Meteorology's water information and accounting needs (http://www.bom.gov.au/water/geofabric/index.shtml). The reporting units for the 2010 Australian Water Resources Assessment (AWRA) (http://www.bom.gov.au/water/about/publications/document/InfoSheet_10.pdf), the first in a series of annual reports on the availability, quality and use of water to be produced by the Bureau, were based on the Level 1 Drainage Divisions, while the Geofabric hydrology reporting regions that will provide finer level catchment delineations for future AWRA assessments are largely delineated by the Level 2 Drainage Basin Groups, except In the Murray Darling Basin where the reporting regions are delineated by lower level Pfafstetter aggregations that represent the AWRC River Basins (Australian Government Bureau of Meteorology, 2012). This tailored delineation of the hydrology reporting regions demonstrates the flexibility of the new nested catchment framework and its capacity to be adapted to individual user's needs, in this case, the requirement that the reporting regions resemble the AWRC River Basins.

4.3 Limitations and uncertainty

The new framework consistently represents streams and their catchments at a map scale of about 1 : 250 000 and is thus appropriate for applications at regional to continental scale. The environmental attributes are derived from best available, but relatively coarse scale, national data sources so are also best suited for applications at regional and national scales. A primary source of spatial data uncertainty is that associated with the 9 s DEM representation of height and surface drainage flow paths (Hutchinson et al., 2008). In particular, in areas of dune fields the DEM depicts the land surface underlying the sand ridges and so might more accurately delineate palaeo-catchment boundaries (Craddock et al., 2010). The variable representation of smaller peaks by the DEM (Hutchinson et al., 2008) may also have produced occasional errors in the location of drainage divides and derived terrain attributes. On the other hand, the remarkable consistency of the 9 s drainage division analysis with that obtained from the earlier 90 s DEM, derived by Hutchinson and Dowling (1991) from completely different source data, indicates broad scale robustness in the delineation of catchment boundaries from drainage-enforced DEMs.

Floodplains and floodplain flow paths are inadequately represented at the 9 s DEM resolution. There is no modelling of overbank flow and other floodplain processes and hence the environmental characteristics attributed to isolated floodplain channels (e.g. oxbows, flood runners etc.) describe the local environment only, not the broader catchment upstream of the associated main river channel.

4.4 International comparisons

The new national streamline and nested catchment database for Australia, based on the 9 s DEM, may be compared with catchment frameworks and associated suites of environmental attributes that have been developed to underpin national water information needs elsewhere (Table 5). The Australian 9 s framework differs in a number of key aspects.

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The Australian catchments are based on a coarser resolution DEM and streamline mapping than the comparable international examples. However, unlike the US and European DEMs, no "stream burning" or other additional hydro-enforcement processes were required to impose stream positions into the DEM. Instead the drainage enforcement applied by the ANUDEM program (Hutchinson, 2011) incorporated the streamlines directly into the elevation gridding (Hutchinson et al., 2008; Hutchinson, 1989). Thus stream positions are accurately located within the DEM without distorting DEM heights. Accordingly, topographic descriptors such as catchment relief can be derived directly from the DEM. This includes the large areas of the continent with low topographic relief, effectively overcoming what is commonly seen as a key limitation of DEMs.

We have applied novel methods of drainage analysis (Stein, 2006; Stein and Hutchinson, 2014) to accommodate the natural variation in drainage density and the diversity of drainage patterns that are evident at continental scale. Although distributary drainage patterns are common among large rivers globally (Jansen and Nanson, 2004), the national framework presented here appears to be the first to derive a stream network from a DEM that explicitly includes complex distributary and anabranching drainage patterns. As noted above, these systems occur extensively across the low relief areas of the Australian continent. The new framework also provides a solution to the problem of apportioning accumulated runoff and other attributes between a stream and its anabranch that is appropriate for continental scale applications.

The coding of the hierarchical relationships between catchments presented here is compatible with that used in the European Catchment Characterization and Modelling data set (CCM). The highest levels in the European catchment hierarchy were formed by grouping basins according to the sea into which they drain and their connectivity to the open ocean (de Jager and Vogt, 2010). This is analogous to our levels 1 and 2. The CCM similarly applies the Pfafstetter coding scheme to individually code and then internally sub-divide drainage basins. Our application of the Pfafstetter scheme differs however, in our use of a surrogate for river flow instead of contributing area to distinguish the tributary and mainstem, and the necessary inclusion of a method to systematically sub-divide and code the very large number of internally draining basins and distributary stream networks.

4.5 Data availability and future developments

The stream and nested catchment database is freely available under a Creative Commons licence – the AHGF version in vector format from http://www.bom.gov.au/water/geofabric/about.shtml and the original foundation layers in raster format, together with the lookup tables of environmental attributes, from http://ga.gov.au/surfacewater. Future developments include an upgrade of the AHGF foundation layers by Geoscience Australia based on the higher resolution Shuttle Radar Topography Mission (SRTM) 1 s DEM-S (Gallant et al., 2011) drainage enforced with a compilation of the best available streamline mapping (map scales ranging from 1 : 25 000 to 1 : 250 000). The AHGF upgrade will include tables to link the new stream segments and their catchments to the equivalent features in the 9 s DEM derived version so that attribution and other associated data can be easily transferred. There will be fine scale differences in catchment delineations due to the finer resolution of the SRTM DEM and the streamline mapping but also due to the nature of the surface topography depicted by the DEM. Thus the 1 s SRTM DEM models the land surface in the year 2000 when the radar observations were collected and so may include anthropogenic features such as large buildings, open cut mines, road cuttings and artificial drainage channels. In contrast, the 9 s DEM was interpolated from elevation spot heights principally sampled from contour mapping and essentially represents a pre-European landscape.

5 Conclusion

The new stream and nested catchment database supplies a comprehensive spatial framework for regional and national scale planning and assessment across Australia.

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The structure of this framework reflects the natural hierarchical organization of the river system and its boundaries respect the surface drainage characteristics of the Australian continent, largely irrespective of administrative or jurisdictional borders. The broad applicability of this framework and its associated environmental database has already been amply demonstrated, suggesting it could provide a useful template to serve the water information needs of other continents.

The successful implementation of the spatial framework across the large areas of low topographic relief and endorheic drainage that make up the majority of the continent has been jointly facilitated by the underpinning drainage enforced 9 s DEM and associated drainage analysis methods and a systematic extension of the Pfafstetter system.

Future higher resolution versions of the catchment framework for Australia will extend its application to management tasks requiring finer scale information. Nevertheless, the robustness of catchment delineations from drainage enforced DEMs is likely to generate a high degree of concordance between the 9 s catchment framework presented here and future finer scale national catchment frameworks. For many broader scale planning and assessment tasks the 9 s framework will still be a suitable choice.

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Table 1. Australia's largest drainage basins with area > 25 000 km^2.

Basin Name	Area (km^2)
Lake Eyre (North)	826 161
Murray Darling Basin	792 600
Flinders-Norman Rivers	231 314
Fitzroy River (Qld)	141 283
Burdekin River	129 868
Gascoyne River	103 688
Fitzroy River (WA)	91 190
Victoria River	89 416
Ord River	83 800
Nicholson-Leichhardt Rivers	82 947
Mitchell River (Qld)	82 743
Swan River	81 790
Ashburton River	74 975
Bulloo River	70 915
Roper River	66 445
Murchison River	65 368
De Grey River	59 431
Lake Moore	55 538
Lake Frome	51 366
Lake Gregory	49 496
Daly River	49 443
Fortescue River	48 671
Hanson River	48 580
Lake Mackay	38 164
Burnett River	33 272
Lake Torrens	32 020
Hay River	30 621
Lake Disappointment	30 382
Newcastle Waters/Lake Woods	28 844

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Table 2. Number and average area of catchment units at each level in the nested hierarchy.

Level	Number of catchment units	Average area (km^2)
1	12	641 977
2	191	40 334
3	1740	4427
4	12 614	611
5	56 782	136
6	161 198	47.8
7	336 753	22.9
8	559 250	13.8
9	748 118	10.3
10	881 719	8.7
11	978 391	7.9
12	1 036 084	7.4
13	1 066 063	7.2
14	1 082 029	7.1
15	1 090 035	7.1

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Table 3. Stream environment descriptors. Data are organized into lookup tables that can be related to both the DEM derived streams and catchment spatial layers using a shared segment number identifier.

Table	Description	Primary source data
Climate	Parameters describing annual and seasonal climate and rainfall erosivity	ANUCLIM (Xu and Hutchinson, 2013) National Land and Water Resources Audit (2000) 9 s DEM version 3.1 (Hutchinson et al., 2008)
Terrain	Elevation, relief, slope, aspect, catchment area and shape, stream order, confinement, distance from source/outlet	9 s DEM version 3.1 (Hutchinson et al., 2008)
Substrate	Soil hydrological characteristics and lithological composition	Surface geology of Australia 1 : 1M (Liu et al., 2006; Raymond et al., 2007a, b, c; Stewart et al., 2008; Whitaker et al., 2007, 2008)
Veg; Veg-MVSG	Catchment and valley natural and extant vegetation cover (forests, woodlands, shrubs, grasses, bare), Valley natural and extant vegetation cover (NVIS major vegetation sub-groups)	NVIS 100 m (Australian Government Department of the Environment and Water Resources, 2006a, b)
Runoff	Monthly time series of accumulated runoff volume 1970 to 2008, summary statistics describing annual and seasonal mean and extreme conditions, inter and intra-annual variability	Monthly climate surfaces 1970 to 2008 (Kesteven et al., 2004; Hutchinson, 2004) Growest water balance module (Hutchinson et al., 2004)
NPP	Catchment average annual and monthly mean Net Primary Productivity	Raupach et al. (2001)
Landuse	Stream and valley and catchment average and maximum population density, proportion of stream and valley, sub-catchment or catchment on which particular landuse activities take place	Catchment scale land use mapping for Australia (Bureau of Rural Sciences, 2009), population density 2006 (Australian Bureau of Statistics, 2006)
River Disturbance	Indicators of pressure on stream ecosystems due to human activities (Stein et al., 2002)	Data sources in Stein et al. (1998) updated with catchment scale land use mapping for Australia update Apr 2009 (Bureau of Rural Sciences, 2009), Geodata TOPO 250K series 2 (Geoscience Australia, 2003b), integrated vegetation cover (Bureau of Rural Sciences, 2003)
Network	Stream network parameters/indicators of habitat availability	AusHydro (Bureau of Meteorology, 2010)
Connectivity	Presence of major in-stream barriers including dams and waterfalls	AusHydro (Bureau of Meteorology, 2010), 9 s DEM version 3.1 (Hutchinson et al., 2008)
Identifiers	AWRC and topographically defined basin identifier, up and downstream segment identifiers, outlet geographic location	Australia's River Basins (AUSLIG, 1997)

Table 4. Characteristics of Australian streams and catchments: examples derived from the environmental descriptors.

Longest flow path length (Source to outlet along main channel)	3515 km (Murray Darling Basin)
Wettest named stream (Named stream with highest catchment average annual rainfall)	East Mulgrave River, Queensland Catchment average annual rainfall: 3845 mm
Driest named stream (Named stream with lowest catchment average annual rainfall)	Manuwalkaninna Creek (Lake Eyre Basin) Catchment average annual rainfall: 110 mm
Hottest named stream (Named stream with highest catchment average maximum temperature of the hottest month)	Dead Horse Creek (Ashburton River Basin) Catchment average hottest month mean maximum temperature: 41.4 °C
Coldest named stream (Named stream with lowest average minimum temperature of the coldest month)	Swampy Plain River (Murray Darling Basin) Catchment average coldest month mean minimum temperature: −5.7 °C
Greatest relief (Drainage basin of a named stream with highest relief ratio value)	Ketchem Creek, southern Tasmania Maximum catchment relief 594 m, basin length 4.8 km
Least relief (Drainage basin of a named stream with the lowest relief ratio value)	Station Creek, Gulf of Carpentaria, Queensland Maximum catchment relief 6 m, basin length 25.7 km
Most variable flow (Basin of named stream with highest CV annual mean accumulated runoff, 1970–2008)	Manunda Creek, South Australia (largest of 108 basins with CV annual totals of accumulated runoff = 6.245)
Basin of named stream with greatest proportion of annual mean runoff (1970–2008) generated above the snow line	Mersey River, Tasmania (32 %)
Most urbanized basin of a named stream	Cherry Creek, Melbourne, Victoria (78.9 % of the 19 km^2 catchment is urban landuse)
Largest undisturbed or minimally disturbed named stream (RDI ≤ 0.01) (Stein et al., 2002)	South Alligator River, Northern Territory
Undisturbed or minimally disturbed stream length (RDI ≤ 0.01) (Stein et al., 2002)	11.7 % length of all streams 5.95 % length of named streams
Stream length fragmented by large dams (up or downstream)	28.4 % length of all streams 45.6 % length of named streams

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Table 5. A comparison of the new Australian stream and catchment framework with comparable international examples.

	DEM resolution	Streamline mapping scale	Hierarchical coding system
Australia	9 s (∼ 270 m)	1 : 250 000	Pfafstetter
USA (McKay et al., 2013; Wang et al., 2011)	1/9 to 1 s (∼ 3 to 30 m)	1 : 100 000	Hydrological Units Code (HUC)
Europe (Vogt et al., 2007)	100 m	1 : 100 000	Pfafstetter
New Zealand (Snelder and Biggs, 2002; Wild et al., 2005)	30 m	1 : 50 000	River Environment Classification[1]

[1] Supplies a hierarchical context for each stream segment based on its environmental characteristics but not a unique identifier.

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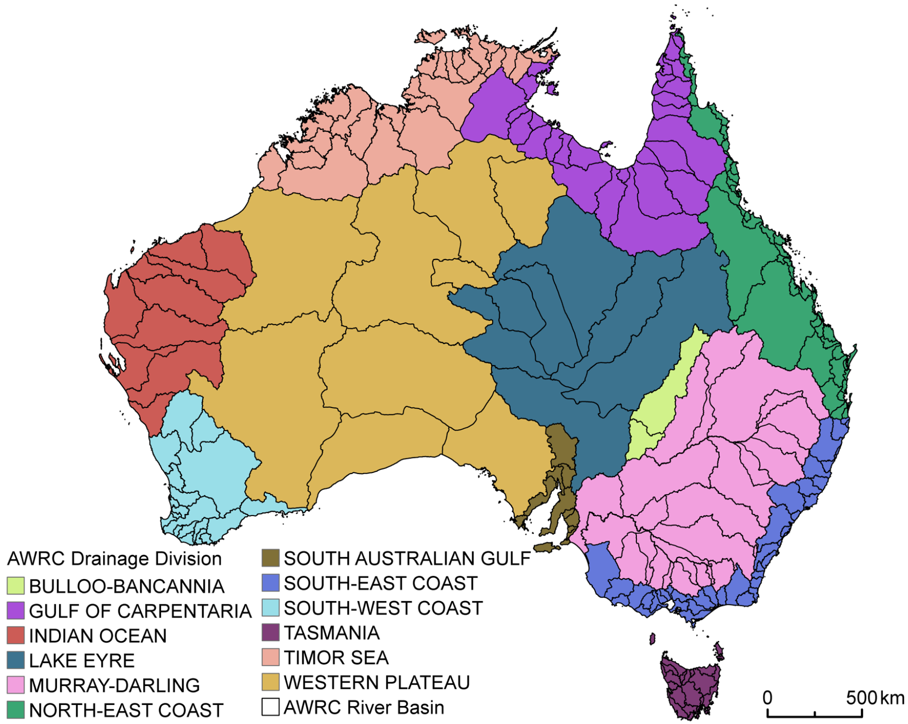

Fig. 1. Australian Water Resource Council (AWRC) Drainage Divisions and River Basins.

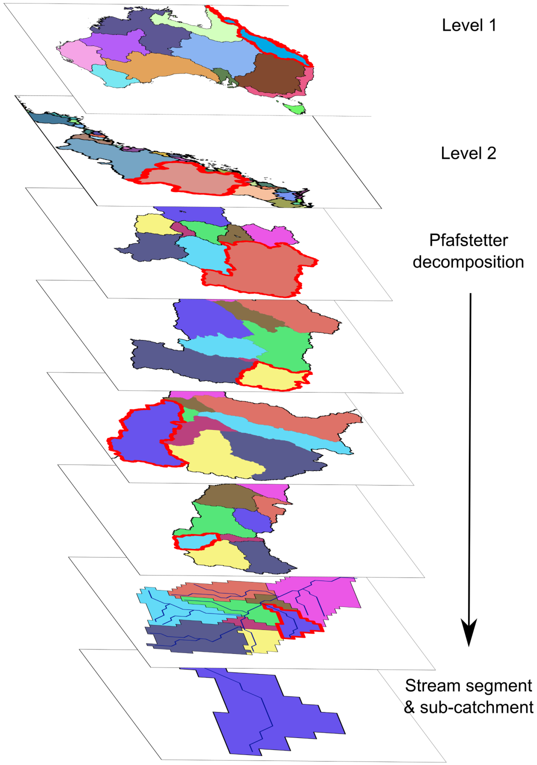

Fig. 2. Components of the nested stream and catchment database. The nested hierarchy of catchments aggregates drainage basins at its highest levels and at its lower levels, sub-divides basins into successively smaller catchment units based on the Pfafstetter system. The smallest units in the catchment framework are the catchment areas draining to individual stream segments in the associated DEM derived stream network. Attributes describing the natural and anthropogenic environment of the stream and its catchment are contained in the related lookup tables. The area shown at each level is highlighted with a red boundary at the next higher level.

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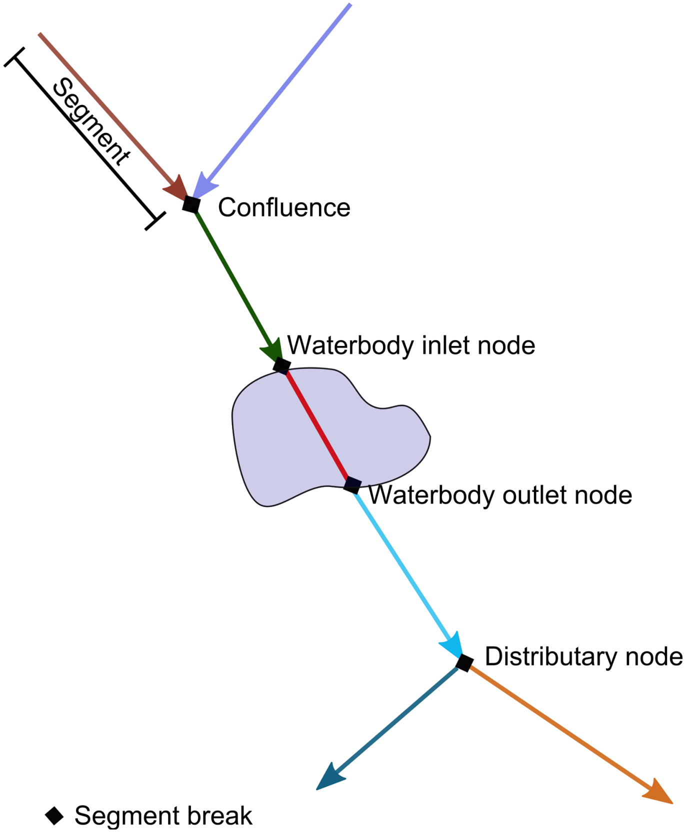

Fig. 3. Breaks inserted into the DEM derived stream network at confluences, distributary nodes and waterbodies. The breaks delineate uniquely identified stream segments.

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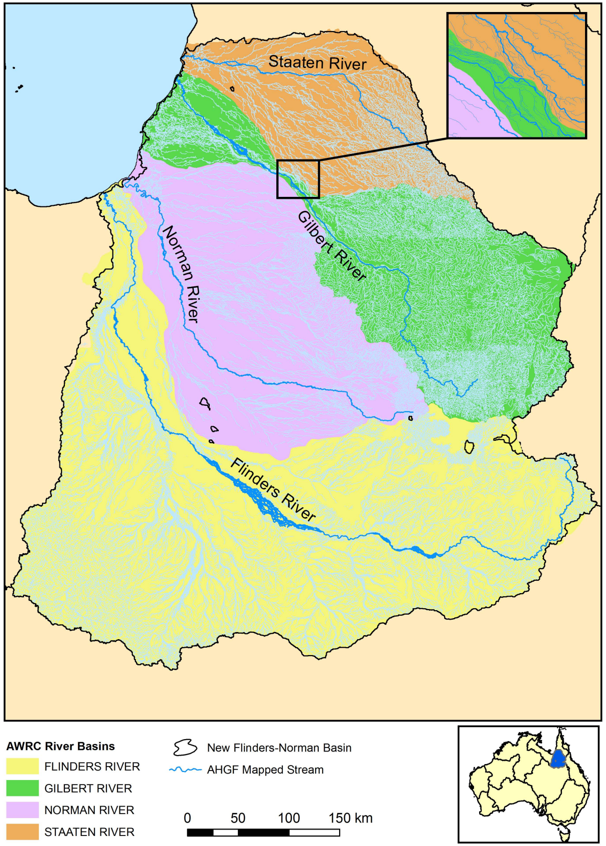

Fig. 4. The Flinders – Norman Drainage Basin combining the catchment areas of the Norman, Flinders, Staaten and Gilbert Rivers that are linked by floodplain distributaries. In contrast, the AWRC River Basins delineate four separate River Basins with boundaries drawn through the floodplain distributary channels. Note also the small areas of internal drainage.

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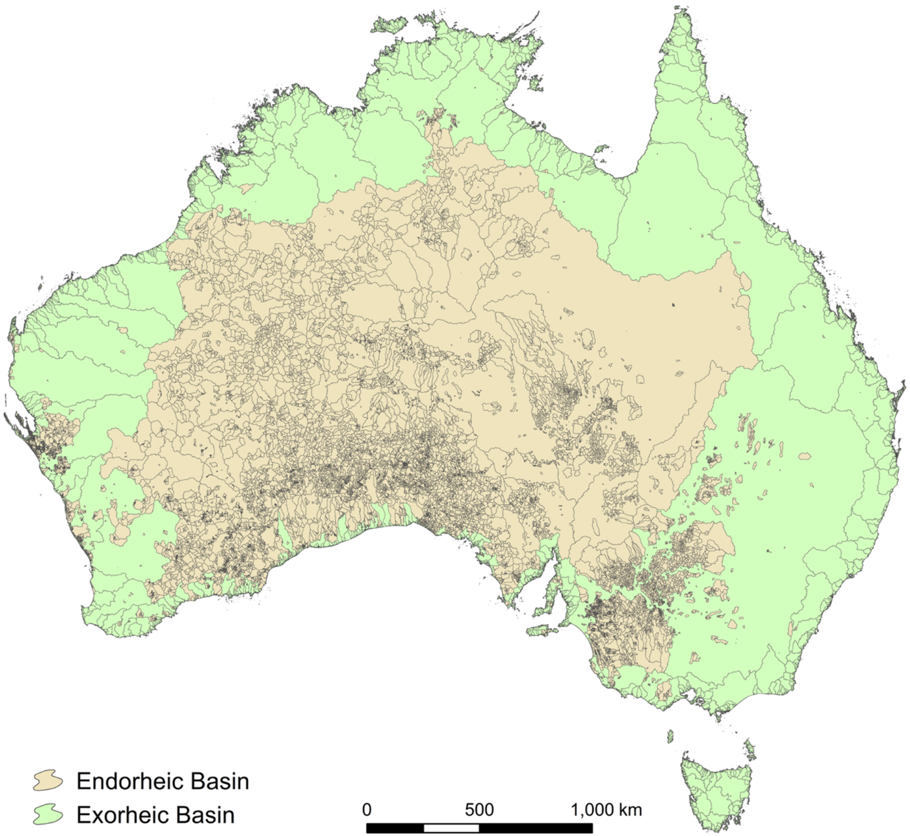

Fig. 5. Drainage basins delineated from the 9 s DEM.

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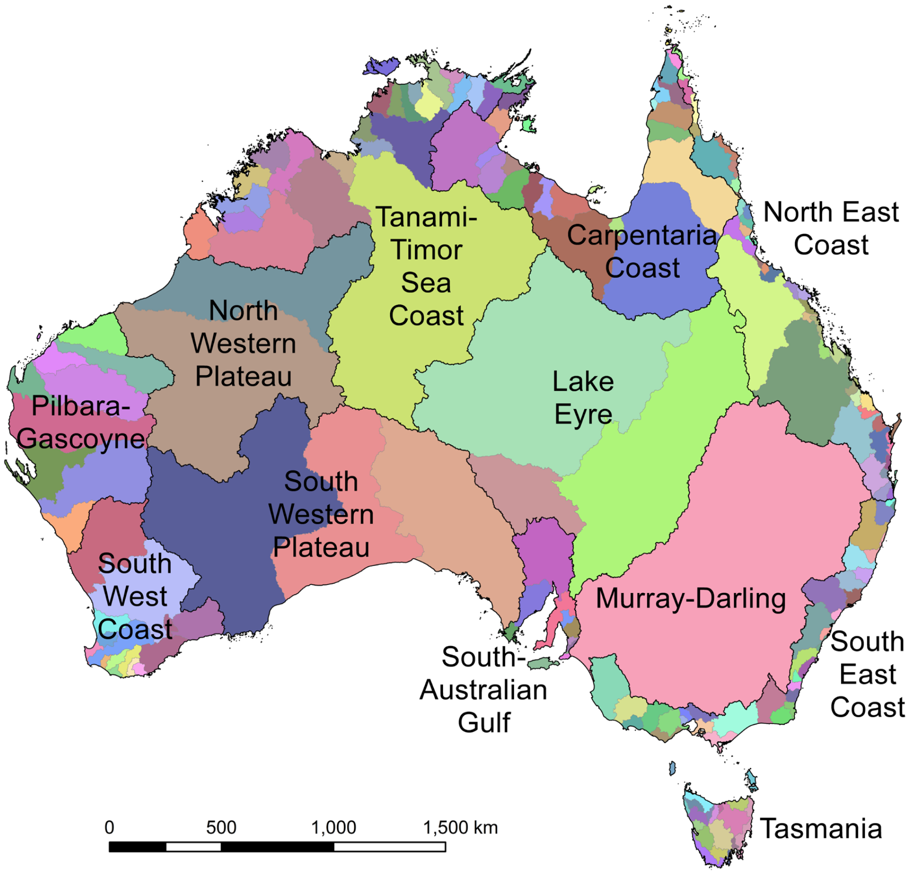

Fig. 6. Levels 1 and 2 of the new hierarchically nested catchment framework. Shown are the Level 1 Topographic Drainage Division names.

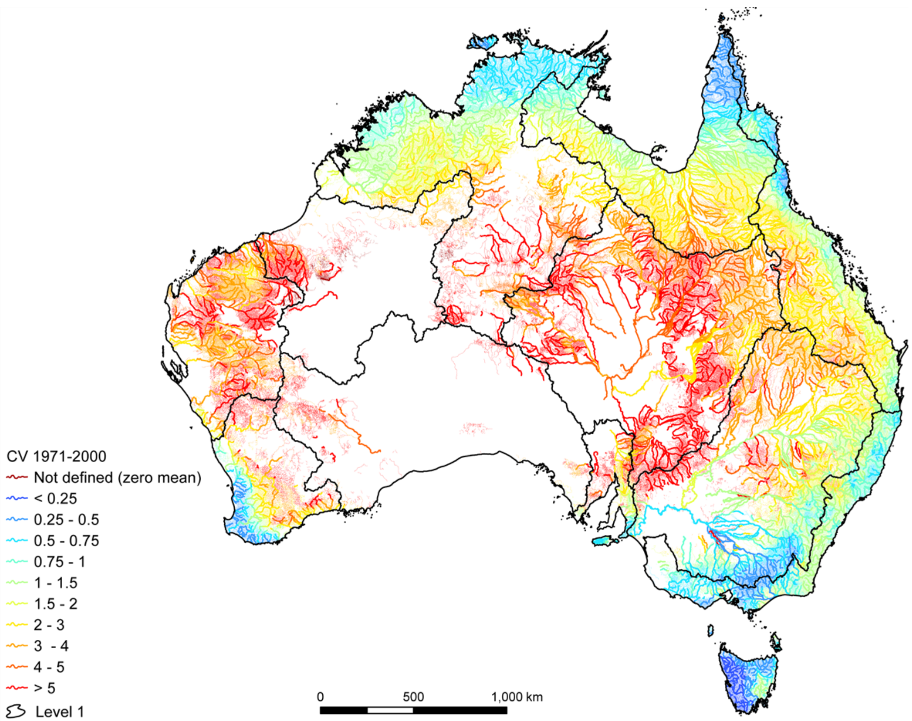

Fig. 7. Interannual runoff variability: coefficient of variation of the annual totals of accumulated runoff volume for the period 1971 to 2000.

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A new stream and nested catchment framework for Australia

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