CAMELS-AUS v2: updated hydrometeorological timeseries and landscape attributes for an enlarged set of catchments in Australia

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Abstract. This paper presents Version 2 (v2) of the Australian edition of the Catchment Attributes and Meteorology for Large-sample Studies (CAMELS) series of datasets. Since publication in 2021, CAMELS-AUS (Australia) has served as a resource for the study of hydrological change, arid-zone hydrology, and hydrological model improvement. In this update, the dataset has been significantly enhanced both temporally and spatially. The new dataset comprises information for ~~over~~ more than twice as many catchments (561 compared to 222). The streamflow and climatic information have been ~~are~~ updated a further eight years (2022 compared to 2014). Lastly, the catchment attribute information has been~~is~~ improved, particularly with respect to hydrological statistics (signatures) and uncertainty in streamflow. Together, these updates make CAMELS-AUS v2 a more comprehensive and current resource for hydrological research and applications. CAMELS-AUS v2 is freely downloadable from https://zenodo.org/doi/10.5281/zenodo.12575680 (Fowler et al., 2024).

1 Introduction

Large-sample hydrology plays a crucial role in understanding hydrological processes across diverse catchments, and is essential for developing generalisable insights in hydrology (Gupta et al., 2014). The large sample approach enhances the robustness and generalizability of hydrological models, contributes to schemes for prediction in ungauged or poorly gauged regions, and contributes to the development of machine learning methods in hydrology (Addor et al., 2019; Kratzert et al., 2023). Among many large sample hydrology datasets and projects, the CAMELS initiative (Catchment Attributes and Meteorology for Large-sample Studies) is a prominent example, offering comprehensive data for various regions including the United States (Newman et al., 2015; Addor et al., 2017), Great Britain (Coxon et al., 2020), Chile (Alvarez-Garreton et al., 2018), Brazil (Chagas et al., 2020), France (Delaigue et al., 2022), Switzerland (Höge et al., 2023), ~~and~~ Sweden (Teutschbein, 2024) and India (Mangukiya et al., 2024). These datasets provide streamflow data, climatic information suitable as forcing data for hydrological modelling, and catchment attributes such as catchment properties and hydroclimatic statistics.

This paper presents the second version of CAMELS-AUS, the CAMELS dataset for Australia. Since publication in 2021 (Fowler et al., 2021a), CAMELS-AUS has supported a wide variety of hydrological studies, including development and testing of machine learning techniques (Kapoor et al., 2023), exploring properties and causes of hydrological drought (Fowler et al., 2022; Brunner and Stahl, 2023) and road-testing methods for rainfall-runoff and river system modelling (Fowler et al., 2021b; John et al., 2021; McInerney et al., 2024). A particular focus has been the study of evapotranspiration, as CAMELS-AUS is one of few large sample hydrology datasets providing several potential evapotranspiration formulations (Abbas et al., 2022; Kim et al., 2022; Niu et al., 2024). Many studies have combined CAMELS-AUS with other datasets to create near-global samples of catchments (e.g. McMillan et al., 2022; Althoff and Destouni, 2023; Chen and Ruan, 2023; Wang et al., 2023; Lei et al., 2024; Rasiya Koya and Roy, 2024; Van Oorschot et al., 2024). Responding to ~~this need~~the same imperative to create combined datasets, the CAMELS datasets have recently been merged into a global freely available dataset, termed CARAVAN, with a particular focus on consistency and inter-continental comparability (Kratzert et al., 2023).

2 Rationale for updating the dataset

Given the wide spectrum of research activity supported by CAMELS-AUS, it is highly desirable to update and expand the dataset where possible. The current expansion has been~~is~~ facilitated by recent updates to the CAMELS-AUS source datasets, which have made streamflow information easily available for a wider set of catchments. Specifically, the Hydrological Reference Stations (HRS) dataset, maintained by Australia's Bureau of Meteorology (BOM), which provided the streamflow ~~data~~ component of CAMELS-AUS v1, has been updated with a significant increase in the number of catchments. ~~Streamflow data from CAMELS-AUS v1 were from the 2015 version of HRS (HRS-2015; 222 catchments) while the 2020 update (HRS-2020) saw the number of catchments increase to 467. A further update in 2022 (HRS-2022) extended the streamflow timeseries without altering catchment selection, and this latest update is adopted for CAMELS-AUS v2.~~ Note that the contribution of the HRS to CAMELS-AUS is limited to streamflow data, while non-streamflow data (hydroclimatic timeseries and catchment attributes) are sourced from elsewhere.

An additional factor is the opportunity to augment the catchment set via a separate dataset which has become available since publication of CAMELS-AUS v1. This second dataset (Saft et al., 2023) has been used by several hydrological studies in Australia (see list in Section 3.2.2). Although most Saft et al. (2023) catchments are also in HRS, including all such catchments gives users the option to adopt the same selection of catchments as these earlier studies, improving comparability between different research efforts (see Section 3.2.2. for more details).

The remainder of this paper is concerned with describing the changes between v1 and v2 in more detail (Section 3), in addition to providing guidance and advice for users of the new dataset (Section 4). The appendix provides tables with information on each hydrometeorological timeseries and each catchment attribute, highlighting new or altered information for this update.

3 Dataset changes

3.1 Overview of changes

The following table summarises the changes made to CAMELS-AUS for v2. Aside from the additional catchments, several minor changes have been made, some opportunistically as better information has become available, while others are responding to changes in source datasets.

Table 1: Summary of changes to CAMELS-AUS dataset for version 2

Change	Description	Reason and/or motivation	Section
Increased number of catchments	The number of catchments has increased from 222 to 561	The source dataset for the streamflow data has itself been expanded and updated; in addition, a second streamflow database has been incorporated.	2; 3.2; Fig. 1
Updated timeseries data	The data timeseries have been extended so their end date is now March 2022 (previously December 2014)		3.3; Fig. 2
Different hydrological signatures	The set of hydrological statistics (signatures) has been expanded from 13 to 39.	A freely available toolbox for signature calculation has been published, which is easily adopted for CAMELS-AUS.	3.4.1
Different metrics regarding streamflow uncertainty	The metrics characterising streamflow uncertainty have been improved.	The study providing the original characterisation has been updated and improved with better rating curve information.	3.4.2
Single, not multiple, solar radiation product	Omission of one of two solar radiation timeseries products that was provided with CAMELS-AUS v1	One of the source datasets for climate information, namely the Australian Gridded Climate Dataset, has stopped producing their solar radiation product.	3.5.1
Inclusion of additional vapour pressure timeseries product	One of the vapour pressure timeseries productes has split into two products: one quantifying vapour pressure in the morning and the other in the afternoon.	This responds to changes to the Australian Gridded Climate Dataset.	3.5.1

3.2 Enlarging the selection of catchments

As mentioned, the primary change to the dataset is an increase in the number of catchments from 222 to 561. All the original catchments have been retained, with additional catchments originating from:

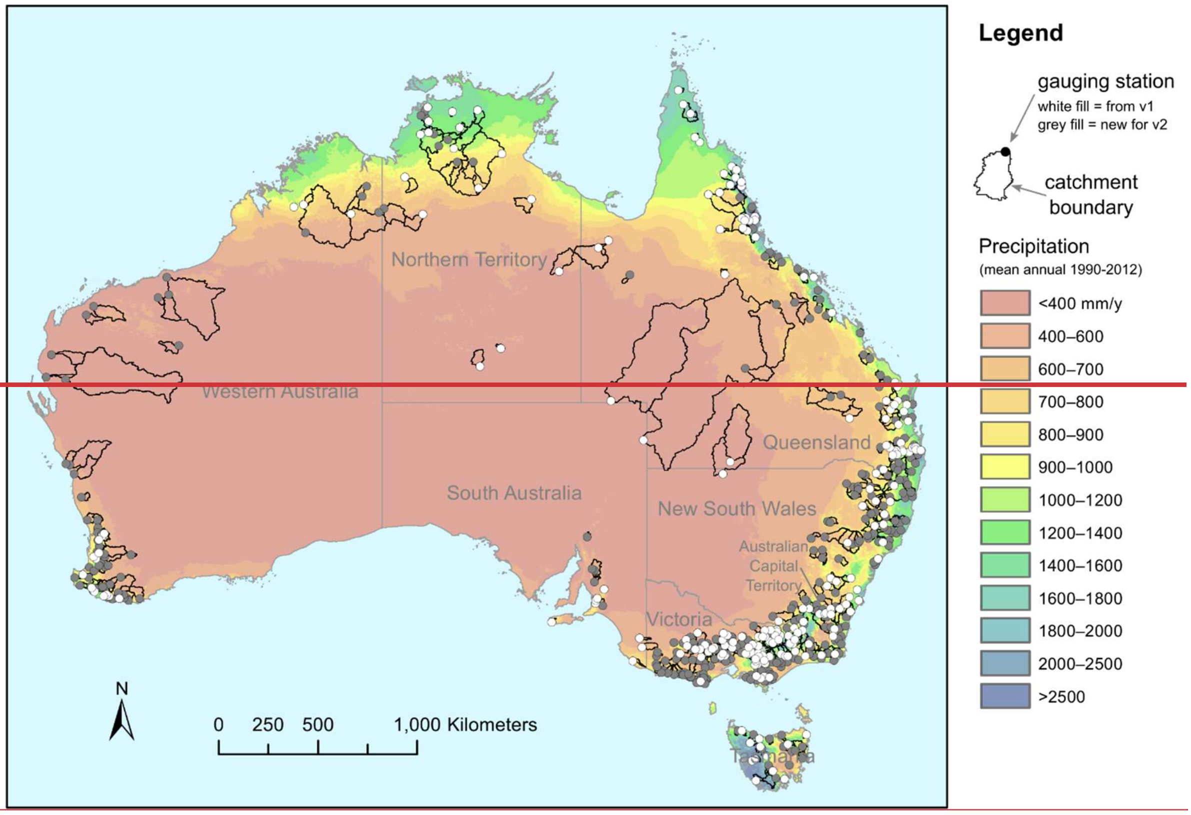
- An update to the source dataset of CAMELS-AUS v1, namely the Hydrological Reference Stations compiled by Australia's Bureau of Meteorology;
- Inclusion of additional catchments from the dataset of Saft et al. (2021), which has supported several hydrological studies, as outlined below.

These data sources are each discussed in more detail in the following subsections.

Figure 1 shows the spatial distribution of the updated set. This figure demonstrates that the updated set provides denser coverage overall, in addition to new-found coverage for some areas of Australia, notably in the west.

3.2.1 Hydrologic reference stations (HRS) update

The HRS, first published in 2013, was updated in 2015 (HRS-2015—the basis for CAMELS-AUS v1) and subsequently in 2020 and 2022. HRS-2020 was notable for considering a wider range of catchments than before while also tightening the rules



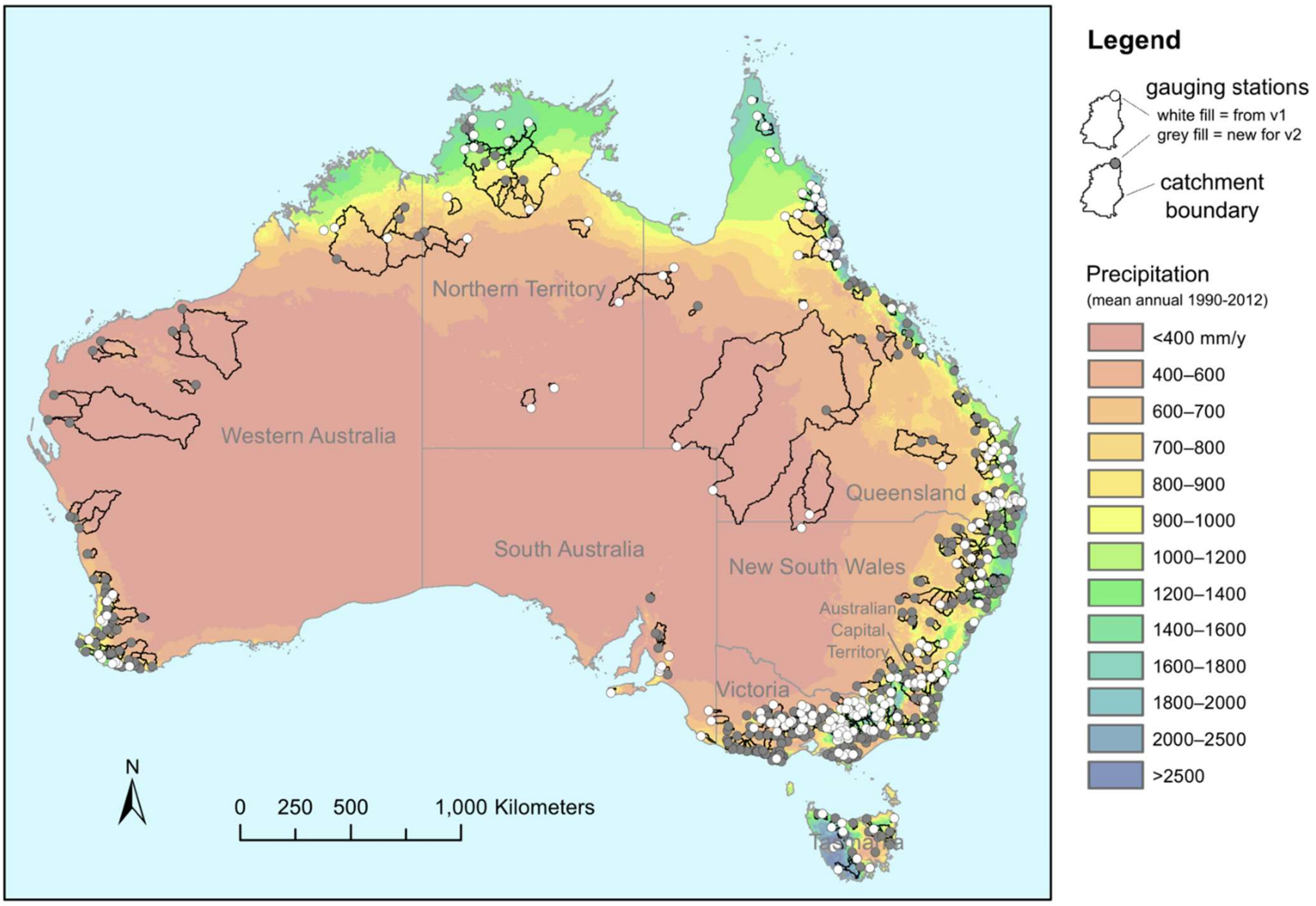


Figure 1: Map after Fowler et al. (2021a) showing location of the CAMELS-AUS flow gauging stations and catchments, distinguishing v1 catchments from those added for v2. Shown along with mean annual precipitation (from Jones et al., 2009) and Australian states and territories.

for station selection, as discussed below. HRS-2015 had ~~Streamflow data from CAMELS-AUS v1 were from the 2015 version of HRS (HRS-2015;~~ 222 catchments~~)~~ while ~~the 2020 update (~~HRS-2020~~)~~ saw the number of catchments increase to 467. A further update in 2022 (HRS-2022) extended the streamflow timeseries without altering catchment selection, and this latest update is adopted for CAMELS-AUS v2.

Note that all actions described in this subsection (3.2.1) were taken by Australia's Bureau of Meteorology, not the authors. Further information on these actions can be found at http://www.bom.gov.au/water/hrs/update_2020.shtml (last access 3rd December, 2024).

When station selection was undertaken for HRS-2013, data quality information such as quality codes and rating curves were not available for some catchments. For affected catchments, the issue was not that this information did not exist, but rather that it was not provided by the data owners (the states and territories of Australia) in time for the selection process. This led to a relatively smaller sample of catchments being initially considered for HRS-2013. Later, during the selection process for HRS-2020, this information was available for a much wider set of catchments. In addition, the selection requirements—namely the requirements of 30 years' record with less than 5% missing data—were more easily met due to the passage of time between the two updates.

However, two rules were more restrictive than before, namely:

- no more than 25% of measured flow volume could be extrapolated above the highest available rating; and
- missing data could constitute a maximum of 10% by volume (where volumes on missing days were estimated via a rainfall runoff model).

The first of these rules was new, whereas the second one was a redefinition of an existing missing data rule.

Of the 222 HRS-2015 stations, 179 were included in HRS-2020, while 43 failed the new selection guidelines. In addition to the 179 catchments from the previous version, HRS-2020 included 288 new catchments that were not previously included, for a total of 467.

Despite the omission of these 43 failed catchments from HRS-2020, they are included in CAMELS-AUS v2. Partly, this is to allow for users of CAMELS-AUS v1 who may wish to continue to use the same set of catchments as before~~, but with updated timeseries data~~. More broadly, while we do not intend to trivialise the issues of missing data or flow extrapolation, we prefer to provide information relevant to these issues directly to CAMELS-AUS users (eg. uncertainty information, Section 3.4.2) and then let users decide upon the inclusion or otherwise of such catchments, depending on study context. However, we do provide some guidance on this issue in Section 4.2.

Given the above, the net effect of the 2020 HRS update on the CAMELS-AUS dataset is the addition of 288 catchments to CAMELS-AUS v2 compared to v1, while no catchments are removed. Note that the adopted basis for CAMELS-AUS v2 is the most recent HRS version (HRS-2022), which updated timeseries data without altering HRS-2020 catchment selection.

3.2.2 Saft et al. (2023) dataset

The Saft et al. (2023) dataset was compiled with the support of the State Government of Victoria and covers only that state. It is a significant dataset in the sense that it has been used by several hydrological studies, including Peterson et al. (2021), Trotter et al. (2021, 2023, 2024), Trotter (2023), Gardiya Weligamage et al. (2021, 2023, 2024) and Fowler et al. (2022). Given the importance of those studies in examining recent unusual hydrological behaviour in response to multi-year drought, we wish to give users the option to adopt the same selection of catchments as the earlier studies, and thus we include any catchment in the Saft dataset not otherwise present in CAMELS-AUS v1 or HRS-2020—a total of 51 catchments. This is done using the streamflow data provided by Saft et al. (2023) for those 51 catchments.

The rules used for catchment selection are listed in Peterson et al. (2021). In summary, the criteria include consideration of upstream reservoirs and diversions, which can sum to a maximum of 5% of mean annual streamflow. Separate criteria were framed around availability of high-quality data associated with the multi-year drought that formed the focus of all the above studies, called the "Millennium" Drought (1997-2010). Catchments were eliminated with less than 15 years, 7 years or 5 years of streamflow data prior to, during or after this drought, respectively.

~~In line with the above, 51 catchments are added to CAMELS-AUS v2 to ensure inclusion of all Saft et al. (2023) catchments.~~

3.2.3 Summary of changes to catchment selection

In summary, CAMELS-AUS v1 had 222 catchments, to which 288 catchments have been~~are~~ added from the 2020 HRS update, and a further 51 ~~are~~ have been added from Saft et al. (2023). Thus, the total number of catchments in CAMELS-AUS v2 is 561.

3.3 Updating timeseries to 2022

Relative to the temporal coverage of CAMELS-AUS v1 (to 2014), the new source datasets both have more recent data. Timeseries data in CAMELS-AUS v2 are now provided up to 31st March 2022. Figure 2 shows the range of record length across the updated catchment sample, along with missing data proportions for different periods.

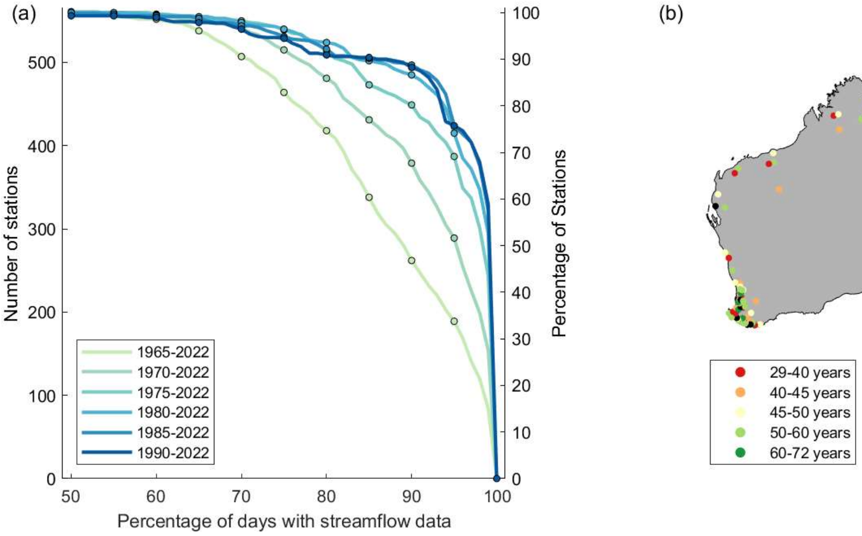


Figure 2: Figure after Fowler et al. (2021a) and Coxon et al. (2020) showing (a) number of stations with percentage of available streamflow data for different periods and (b) length of the flow time series for each gauge.

3.4 Improved attributes

Most of the attributes remain~~ed~~ unchanged, but the following subsections outline the exceptions, where the formulation or calculation of the attribute did change relative to Version 1. Figure 3 shows the spatial distribution of selected attributes, using the updated methods and catchment set.

3.4.1 Hydrological signatures

In the new version of CAMELS-AUS, we have transitioned to using TOSSH (Toolbox for Streamflow Signatures in Hydrology; Gnann et al., 2021) for calculating streamflow statistics (signatures). TOSSH offers a comprehensive and standardized approach to signature calculations, incorporating both the 13 signatures used in CAMELS-AUS version 1 by Addor et al. (2018) and additional signatures from related research (e.g. Sawicz et al., 2011; Euser et al., 2013; McMillan, 2020).

We ran all the calculation functions in TOSSH and obtained a unique set of 49 streamflow signatures (note the number of signatures in ~~the Sebastian~~ Gnann et al.~~,~~ (2021) appears greater, but some functions produce overlapping results). Among these, 10 signatures have multiple outputs, so we stored only the 39 single-output signatures in the dataset attribute table. For users who need the complete set, we also provided a .mat file that includes all outputs of TOSSH including the 49 signatures and associated information such as run-time messages. For easy use, we categorized the 39 single-output signatures into six categories based on Poff et al. (1997): magnitude, frequency, duration, timing, rate of change, and other. Within each category, the signatures are ordered alphabetically (see Table A3 for details).

3.4.2 Metrics of streamflow uncertainty

We have adopted the new method proposed by McMahon et al. (2024~~under review~~) for streamflow uncertainty assessment. This method offers a straightforward and practical approach for estimating uncertainty in daily streamflow data. ~~It involves calculating two key metrics: the root mean square error (RMSE) of gauged versus rating curve discharges for both low and high flows, and the percentage volume of flow extrapolated beyond the maximum rated discharge.~~ For CAMELS-AUS v1, the uncertainty information was from an earlier study (McMahon and Peel, 2019) which was not provided with the rating curves used for flow estimation (only the raw data), and thus was forced to use a method (Chebyshev polynomials) to estimate its own rating curves. Since then, the Bureau of Meteorology organised for the same authors to be supplied with the actual rating curves, leading to a new study (McMahon et al., 2024) using this updated information. McMahon et al. (~~under review~~2024) post-processed their data for 459 stations in CAMELS-AUS v2 to derive the following statistics (Table A3): (i) number of unique rating curves; (ii) root mean square error (RMSE) of the gauged versus rating curve discharges as a percentage of the mean discharge for all non-zero gauged values, for the lower half of non-zero gauged values, and for the upper half of non-zero gauged values; (iii) the percentage of days for which the published discharge values exceed the maximum gauged discharge; and (iv) the percentage of the total discharge volume that is above the maximum gauged discharge.

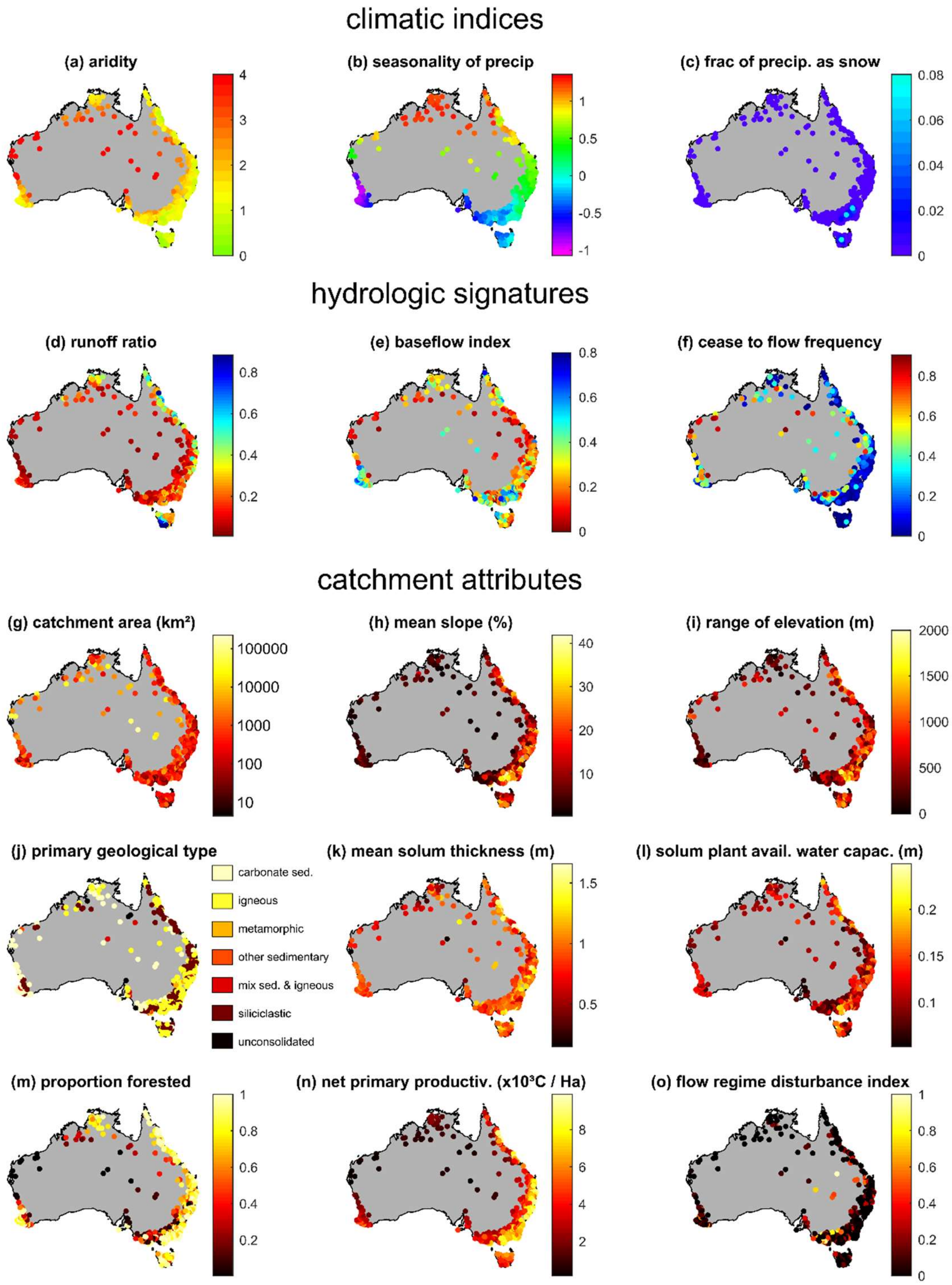


Figure 3: Maps of selected climatic indices (a–c), hydrologic signatures (d–f) and other catchment attributes (g–o). For definitions, see Tables A3 and A4—for easy identification, attributes shown here are highlighted in purple in those tables.

3.5 Other changes

3.5.1 Changes to hydrometeorological data

A significant source of gridded climate information is the Bureau of Meteorology's Australian Gridded Climate Dataset (AGCD). This superseded an earlier program called the Australian Water Availability Project (AWAP). Thus, whereas v1 of CAMELS-AUS referred to AWAP, v2 refers to AGCD instead. Regarding changes to the underlying methods:

- Our understanding is that no changes have been made to the underlying method in the case of temperature and precipitation data.
    - Significant investment was made to improve the monthly gridded precipitation dataset, as described in Evans et al. (2020). However, the monthly data is not included with CAMELS-AUS, and the improvement efforts have not affected the daily gridded precipitation dataset, the derivation of which is described by Jones et al. (2008).
- Regarding solar radiation, whereas AWAP provided solar radiation, the~~The~~ most recent update of AGCD (v1.0.1) no longer includes solar radiation data, but solar radiation data are still provided within CAMELS-AUS v2 from an alternate source (namely the Scientific Information for Land Owners (SILO) dataset, as it was in v1).
- Regarding vapour pressure, ~~T~~the AGCD now provides two variants of vapor pressure data collected at either 9:00 AM or 3:00 PM (Jones et al., 2009; https://doi.org/10.25914/hjqj-0x55, last accessed on 10 April 2024), and each are incorporated into CAMELS-AUS, as shown in Table A2.

4 User guidance and recommendations

Here we provide guidance for users on various issues and decisions to be made when using the updated dataset.

4.1 Karst topography

Karst topography, characterised by drainage systems such as sinkholes and caves, can significantly affect surface runoff. Thus, it is important to note any catchments that are affected. Karst topography is relatively rare in Australia, and as such, the relevant Geoscience Australia dataset (Geoscience Australia, 2008) reveals only twenty catchments contain any "carbonate sedimentary rock". Of these, the only five that have more than 10% covered are 912105A (approximately 60% covered by this rock type), 912101A (50%), G8110004 (50%), 304040 (30%) and G9070142 (15%). This coverage should be considered when users are analysing hydrological information or modelling results from these catchments.

4.2 Decisions regarding catchment choice

Although the extra catchments are welcome in this dataset, the different quality standards applied among the source datasets does raise questions for users. For example, since many of the original catchments (from version 1) were subsequently excluded from HRS2022 based on data quality rules, should users now avoid such catchments even though they are included in CAMELS-AUS v2? A key focus for the data quality rules is the degree of extrapolation of the rating curve, since this affects uncertainty. However, some studies can account for variable levels of uncertainty because they explicitly consider it in the study design (this could be done with reference to the CAMELS-AUS v2 attributes regarding uncertainty – see Section 3.4.2). For such studies, it is recommended that all 561 catchments are used. Furthermore, for studies that combine across several datasets, vetting the catchments may have limited value unless such vetting is done consistently across the other datasets, which might be difficult given that uncertainty information is different for different datasets (or omitted entirely). Ultimately, it is a question of whether the information content added by the catchments in question outweighs the increased uncertainty in their data. The answer to this question is context specific because it depends on how the data are being used. We recommend that researchers give due consideration to these matters, including the option of using the smaller subset of 467 catchments from HRS2022.

Furthermore, some users of the dataset may seek a set of catchments that are "almost" natural (ie. mostly free of human impact). To identify such rivers, Stein et al. (2002) defined various indices of disturbance (see the “anthropogenic influences” section of Table A4). They suggested that the aggregate index (River Disturbance Index, or “river_di” in Table A4) should ideally be below 0.01 for truly “wild” rivers, but this may be untenable for a large sample study since only 20 out of 561 CAMELS-AUS v2 catchments are under this threshold. Stein et al. (2002) also tested a threshold of 0.05, and this threshold provides a sample of 81 catchments which are relatively well spread over Australia’s climatic zones (not shown). Thus, a threshold of 0.05 is recommended for users seeking a set of catchments that are “almost” natural. Lastly, note that a key factor that disqualifies many catchments is altered landuse relative to pre-European settlement; thus, studies seeking a larger sample size of “almost” natural catchments might consider relaxing this criterion first.

4.3 Decisions regarding selection of forcing data for modelling

The next decision is the selection of forcing data—namely, which precipitation and which potential evapotranspiration product should be used for hydrological modelling? Whereas many large sample datasets have only one option, CAMELS-AUS has several, and in the interests of consistency between studies, it is useful to nominate which dataset is the preferred option. For potential evapotranspiration, the AGDC provides no estimates and thus a SILO product must be adopted, but the question remains which formulation to adopt. Some formulations contain rather specific assumptions (regarding crops being grown) which may not be appropriate in broader contexts including natural catchments—this disqualifies the FAO56 short crop and the ASCE tall crop formulations. Other formulations are disqualified because they give no consideration to land-atmosphere feedbacks whereby evaporated water can change the properties of the overlying air mass. Such considerations are important when modelling at catchment scale and greater, so this disqualifies the pan evaporation and Morton point potential estimates. The Morton Wet Environment Evaporation is recommended, as it avoids both these criticisms.

For precipitation, we feel either product is suitable for modelling purposes, but we recommend the AGCD gridded precipitation product over SILO. The SILO interpolation "is set to accurately reproduce the observed data" (Tozer et al., 2012), meaning that SILO matches its calibration gauges much more closely than AGCD. For example, Tozer et al. (2012) reported that the Nash Sutcliffe Efficiency scores exceed 0.99 in approximately half of the stations tested. Given each 0.05 degree grid cell covers an area of approximately 25 km² or 10 square miles, in our opinion it is unreasonable to expect that the gauged precipitation at a point will exactly match the areal average (particularly in areas with a high runoff ratio, which tend to be steeper). Thus, we recommend the method that does not require this exact matching in the interpolation, namely the AGCD. Nonetheless, it is noted that Tozer et al. (2012) reported that the SILO and AGDC datasets had similar accuracy when tested on gauges not included in the calibration, which is why either dataset is considered suitable for modelling. It is noted that SILO has recently increased in popularity in academic studies due to a period during which AGDC data was temporarily placed behind a paywall, but pleasingly this has now been retracted and both datasets are once again freely available.

Regardless of which gridded dataset is adopted, it is noted that the quality of the precipitation data changes over time, due to the sensitivity of interpolated precipitation to gauge network density, among other things. A comparison conducted by Lucas Pamminger (Monash University), which examined the degree of agreement between AGCD and SILO precipitation estimates, indicates greater agreement post-1960 for many catchments. This may reflect that the gauging network density approached its zenith around this time. It is recommended that studies use post-1960 precipitation data if possible, and employ caution if earlier data are required. Note that the Pamminger analysis is included in the repository, in the folder entitled *"Comparison of AGCD and SILO precipitation"*.

~~4~~5 Data availability

The CAMELS-AUS dataset is freely available for download from the Zenodo online repository at https://zenodo.org/doi/10.5281/zenodo.12575680 (Fowler et al., 2024). The dataset (along with datasets on which it is based) is subject to a Creative Commons BY (attribution) licence agreement (https://creativecommons.org/licenses/, last access: 28 June 2024).

~~5~~6 Conclusion

This paper presents an updated version of the CAMELS-AUS dataset, in which ~~. This version significantly extends~~ the temporal coverage has been extended to 2022 and ~~expands~~ the spatial coverage has been expanded to 561 catchments. Changes in hydrometeorological data and catchment attributes make this dataset more comprehensive, current, and valuable for research. These updates provide critical support for hydrological research and water resource management, facilitating the study of Australia's unique and variable hydroclimate for researchers globally.

~~6~~7 Appendices

Table A1: Basic catchment information provided in the attribute table of CAMELS-AUS v2. Changes compared to CAMELS-AUS v1 are highlighted in red. Variables that are mapped in Figure 3 are written in purple.

Short name	Description	Data source / notes
station_id	Station ID used by the Australian Water Resources Council.	Source dataset (HRS-2022; HRS-2015; or Saft et al., (2023))
station_name	River name and station name	
drainage_division	Drainage division, of the 13 defined by the BOM.	Bureau of Meteorology (BOM) website www.bom.gov.au and also provided in "bonus data" folder.
river_region	River region, of the 218 defined by the BOM.	
notes	General notes about data issues and/or catchment area calculations	This study For daystart_Q, see Jian et al., (2017)
lat_outlet	Latitude and longitude at outlet. Note, in most cases this will be slightly different to the BoM published value because most outlets needed to be moved onto a digital streamline in order to facilitate flow path analysis.	
long_outlet		
lat_centroid	Latitude and longitude at centroid of the catchment.	
long_centroid		
map_zone	Map zone used to calculate catchment area (function of longitude)	
catchment_area	Area of upstream catchment in km²	
state_outlet	Indicates which state or territory of Australia the outlet is within	
state-alt	If the catchment crosses a state or territory boundary, the alternative state or territory is listed here, otherwise "n/a"	
daystart	Time (UTC) for midnight local standard time (for *state_outlet*). This is the day start time for T_{max} and T_{min} (see Fowler et al., 2021a).	
daystart_P	Time (UTC) for 9am local standard time (for *state_outlet*). 9am is when once-per-day precipitation measurements are reported (see Fowler et al., 2021a).	
daystart_Q	Time (UTC) for streamflow day start time, assuming local standard time for *state_outlet.* This varies by state/territory (Fowler et al., 2021a).	
nested_status	"Not nested" indicates the catchment is not contained within any other. "Level1" means it is contained within another, except in cases where it is contained in another "Level1" catchment in which case it is marked "Level2". Same for "Level 3" and "Level 4".	
next_station_ds	For nested catchments, *NextStationDS* ('DS' meaning downstream) indicates the catchment they are contained within.	
num_nested_within	Indicates how many catchments are nested within this catchment.	
start_date	Streamflow gauging start date (yyyymmdd)	Source dataset (HRS-2022; HRS-2015; or Saft et al., (2023))
end_date	Streamflow gauging end date (yyyymmdd)	
prop_missing_data	Proportion of data missing between startdate and enddate	

Table A2: Hydrometeorological time series data supplied with CAMELS-AUS v2. All timesteps are daily. All non-streamflow data were processed as part of the CAMELS-AUS version 2 to extract catchment averages from Australia-wide AGCD/SILO grids. Changes compared to CAMELS-AUS v1 are highlighted in red. Variables that are mapped in Figure 3 are written in purple.

Category	File name	Source data	Description / comments	Unit
streamflow	*streamflow_MLd.csv*	HRS-2022; HRS-2015; or Saft et al., (2023)	Streamflow (not gap filled)	ML d^{-1}
	streamflow_ MLd_infilled.csv		Streamflow gap filled by the BOM using GR4J (Perrin et al, 2003)	ML d^{-1}
	streamflow_ mmd.csv		Streamflow (not gap filled) expressed as depths relative to CAMELS-AUS version 2 adopted catchment areas	mm d^{-1}
	streamflow_QualityCodes.csv		Quality codes/flags as supplied by the HRS website, with meanings listed at www.bom.gov.au/water/hrs/qc_doc.shtml	-
precipitation	*precipitation_agcd.csv*	BOM's Australian Gridded Climate Data (AGCD) v1.0.1, (Evans et al., 2020) www.bom.gov.au/climate/maps/ AGCD provides 0.05° grids.	catchment average precipitation (Note, AGDC supersedes earlier AWAP data used in v1)	mm d^{-1}
	precipitation_var_agcd.csv		Spatial internal variance in precipitation	mm^2 d^{-2}
	precipitation_silo.csv	Scientific Information for Land Owners (SILO) project, Government of Queensland (Jeffrey et al., 2001) www.longpaddock.qld.gov.au SILO provides 0.05° grids.	catchment average precipitation	mm d^{-1}
Actual and potential evapo-traspiration (AET and PET)	*et_short_crop_silo.csv*		FAO56 short crop PET (see FAO, 1998)	
	et_tall_crop_silo.csv		ASCE tall crop PET (see ASCE, 2000)	
	et_morton_wet_silo.csv		Morton (1983) wet-environment areal PET over land	
	et_morton_potential_silo.csv		Morton (1983) point PET	
	et_morton_actual_silo.csv		Morton (1983) areal AET	
evaporation	*evap_morton_lake_silo.csv*		Morton (1983) shallow lake evaporation	
	evap_pan_silo.csv		Interpolated Class A pan evaporation	
	evap_syn_silo.csv		Interpolated synthetic extended Class A pan evaporation (Rayner, 2005)	
temperature	*tmax_agcd.csv*	AGCD (see above)	Daily maximum temperature	°C
	tmax_silo.csv	SILO (see above)		
	tmin_agcd.csv	AGCD (see above)	Daily minimum temperature	
	tmin_silo.csv	SILO (see above)		
Other variables	*vapourpres_h09_agcd.csv*	AGCD (see above)	Vapour pressure	hPa
	vapourpres_h15_agcd.csv			
	vp_silo.csv	SILO (see above)		
	radiation_silo.csv		Solar radiation	MJ m^{-2}
	vp_deficit_silo.csv		Vapour pressure deficit	hPa
	rh_tmax_silo.csv		Relative humidity at the time of maximum temperature	%
	rh_tmin_silo.csv		Relative humidity at the time of minimum temperature	%

	mslp_silo.csv		Mean sea level pressure	hPa

Table A3: Flow uncertainty information, climatic indices and streamflow signatures provided in the attribute table of CAMELS-AUS v2. Changes compared to CAMELS-AUS v1 are highlighted in red.

Short Name	Description	Units	Data source / notes
q_uncert_unique_curves	Number of unique rating curves considered in analysis by McMahon et al. (2024~~under review~~)	-	McMahon et al. (2024~~under review~~)
q_uncert_rmse_all	Root mean square error (RMSE) of the gauged versus rating curve discharges as a percentage of the mean discharge for all non-zero gauged values	%	
q_uncert_rmse_lower	As above but for the lower half of non-zero gauged values (daily discharges less than the published non-zero median value)	%	
q_uncert_rmse_upper	As above but for the upper half of non-zero gauged values (daily discharges greater than the published non-zero median value)	%	
q_uncert_days_above	The percentage of days for which the published discharge values exceed the maximum gauged discharge	%	
q_uncert_Q_above	The percentage of the total discharge volume that is above the maximum gauged discharge	%	
p_mean	mean daily precipitation	mm d^{-1}	Climatic signatures are calculated using code from Addor et al. (2017), using the following datasets (cf. Table 1) - Precipitation is based on ~~AWAP~~ AGCD rainfall. - PET is based on SILO Morton Wet Env. PET - temperature data is based on ~~AWAP~~ AGCD temperature For *p_seasonality* see Eq. 14 in Woods (2009)
pet_mean	mean daily potential evapotranspiration (PET) (Morton's Wet Environment)	mm d^{-1}	
aridity	aridity (pet_mean / p_mean)	-	
p_seasonality	precipitation seasonality (0: uniform; +'ve: Dec/Jan peak; -'ve: Jun/Jul peak)	-	
frac_snow	fraction of precipitation on days colder than 0° C	-	
high_prec_freq	frequency of high precipitation days, ≥5 times p_mean	d y^{-1}	
high_prec_dur	average duration of high precipitation events	days	
high_prec_timing	season during which most high precip. days occur (djf, mam, jja, or son)	season	
low_prec_freq	frequency of dry days (≤ 1 mm/d)	d y^{-1}	
low_prec_dur	average duration of low precipitation periods (days ≤ 1 mm/d)	days	
low_prec_timing	season during which most dry days occur (djf, mam, jja, or son)	season	
sig_mag_BaseMag	Difference between maximum and minimum of annual baseflow regime	mm	Calculated using TOSSH by Gnann et al. (2021); the signature description is from tosshtoolbox.github.io/TOSSH/p2_signatures.html#list-of-signature-sets
sig_mag_BFI	Baseflow index	-	
sig_mag_Q_7_day_max	7-day maximum streamflow	mm/timestep	
sig_mag_Q_7_day_min	7-day min streamflow	mm/timestep	
sig_mag_Q_CoV	Coefficient of variation	-	
sig_mag_Q_mean	Mean streamflow	mm/timestep	
sig_mag_Q_skew	Skewness of streamflow	mm^3/timestep^3	
sig_mag_Q_var	Variance of streamflow	mm^2/timestep^2	

sig_mag_Q5	5-th streamflow percentile	mm/timestep	
sig_mag_Q95	95-th streamflow percentile	mm/timestep	
sig_mag_VarIdx	Variability index of flow, calculated from flow duration curve	-	
sig_freq_high_Q_freq	High flow frequency	-	
sig_freq_low_Q_freq	Low flow frequency	-	
sig_freq_zero_Q_freq	Zero flow frequency	-	
sig_dur_RespTime	Catchment response time	timestep	
sig_dur_high_Q_dur	High flow duration	timestep	
sig_dur_low_Q_dur	Low flow duration	timestep	
sig_dur_zero_Q_dur	Zero flow duration	timestep	
sig_timing_HFD_mean	Half flow date	day of year	
sig_timing_HFI_mean	Half flow interval	days	
sig_roc_AC1	Lag-1 autocorrelation	-	
sig_roc_AC1_low	Lag-1 autocorrelation for low flow period (the four months with the lowest average flows)	-	
sig_roc_BaseRecesK	Exponential recession constant	1/d	
sig_roc_FDC_slope	Slope of the flow duration curve	-	
sig_roc_FlashIdx	Richards-Baker flashiness index	-	
sig_roc_RecesK_early	Recession constant of early (exponential) recessions	1/timestep	
sig_roc_RecesVarSeasonality	Seasonal variations in recession parameters	-	
sig_roc_RLD	Rising limb density	1/timestep	
sig_other_EventRR	Event runoff ratio	-	
sig_other_PeakDistribution	Slope of distribution of peaks	-	
sig_other_PeakDistribution_low	Slope of distribution of peaks for low flow period (the four months with the lowest average flows)	-	
sig_other_QP_elasticity	Streamflow-precipitation elasticity	-	
sig_other_RR_seasonality	Runoff ratio seasonality	-	
sig_other_SnowDayRatio	Snow day ratio (T_threshold = 2 degC)	-	
sig_other_SnowStorage	Snow storage derived from cumulative P-Q regime curve	mm	
sig_other_Spearmans_rho	Non-uniqueness in the storage-discharge relationship	-	
sig_other_StorageFromBase	Average storage from average baseflow and storage-discharge relationship	-	
sig_other_TotalRR	Total runoff ratio	-	
sig_other_ratio_Event_TotalRR	Ratio between event and total runoff ratio	-	

Table A4: Catchment attributes included in the attributes table of CAMELS-AUS v2 (apart from climatic and hydrologic indices)

	Short name	Description	Unit	Data source	Notes/references
Geology and	*geol_prim*	Two most common geologies (see list in cell below) with corresponding proportions.	-	Geoscience Australia (2008)	Preprocessed by Stein et al. (2011)
	geol_prim_prop				
	geol_sec				
	geol_sec_prop				

	Short name	Description	Unit	Data source	Notes/references
	unconsoldted	Proportion of catchment taken up by individual geological types, specifically: unconsolidated rocks; igneous rocks, siliciclastic/undifferentiated sedimentary rocks; carbonate sedimentary rocks; other sedimentary rocks; metamorphic rocks; and mixed sedimentary/igneous rocks.	-		
	igneous				
	silicsed				
	carbnatesed				
	othersed				
	metamorph				
	sedvolc				
	oldrock	Catchment proportion old bedrock	-		
	claya	Percent clay in the soil A & B horizons, for the stream valley in the reach containing gauging station.	%	National Land and Water Resources Audit (2001)	Preprocessed by Stein et al. (2011)
	clayb				
	sanda	As above, but % sand in the soil A horizon	%		
	solum_thickness	Mean soil depth considering all principle profile forms	m	McKenzie et al. (2000)	-
	ksat	Saturated hydraulic conductivity (areal mean)	mm h^{-1}	Western and McKenzie (2004)	Preprocessed by Stein et al. (2011)
	solpawhc	Solum plant available water holding capacity (areal mean)	mm		
Topography and geometry	*elev_min*	Elevation above sea level at gauging station	m	Gallant et al. (2009)	-
	elev_max	Catchment maximum and mean elevation above sea level	m	Hutchinson et al. (2008)	Preprocessed by Stein et al. (2011)
	elev_mean				
	elev_range	Range of elevation within catchment: elev_max-elev_min	m		-
	mean_slope_pct	Mean slope, calculated on a grid-cell-by-grid-cell basis	%	Gallant et al. (2012)	-
	upsdist	Maximum flow path length upstream	km	Hutchinson et al. (2008)	Preprocessed by Stein et al. (2011). For *strahler*, see Strahler (1957) For *elongratio*, see Gordon et al. (1992).
	strdensity	Ratio: (total length of streams) / (catchment area)	km^{-1}		
	strahler	Strahler stream order at gauging station	-		
	elongratio	Factor of elongation as defined in Gordon et al. (1992)	-		
	relief	Ratio: (mean elev. above outlet)/(max elev. above outlet)	-		
	reliefratio	Ratio: (elevation range)/(flow path distance)	-		
	mrvbf_prop_0 through to *mrvbf_prop_9*	Proportion of catchment occupied by classes of Multi-Resolution Valley Bottom Flatness (MRVBF). These indicate areas subject to deposition. Broad interpretations are: 0 – erosional; 1 – small hillside deposit; 2-3 – narrow valley floor; 4 – valley floor; 5-6 –extensive valley floor; 7-8 – depositional basin; 9 – extensive depositional basin	-	CSIRO (2016)	Gallant and Dowling (2003)
	confinement	Proportion of stream segment cells & neighbouring cells that are not valley bottoms (as defined by MRVBF)	-	Hutchinson et al. (2008)	Preprocessed by Stein et al. (2011)
Land Cover and Vegetation	*lc01_extracti*	Proportion of catchment occupied by land cover categories within the *Dynamic Land Cover Dataset* (DLCD):	-	Lymburner et al. (2015)	Note, the source dataset has 13 timeslices; these attributes indicate the temporal average. The timeslices are separately supplied with CAMELS-AUS
	lc 03_waterbo	*mines and quarries (*ISO name: *extraction sites*)			
	lc 04_saltlak	*lakes and dams (inland water bodies)*			
	lc 05_irrcrop	*salt lakes (salt lakes)*			
	lc06_irrpast	*irrigated cropping (irrigated cropping)*			
	lc07_irrsuga	*irrigated pasture (irrigated pasture)*			
	lc08_rfcropp	*irrigated sugar (irrigated sugar)*			
	lc09_rfpastu	*rain fed cropping (rainfed cropping)*			
	lc10_rfsugar	*rain fed pasture (rainfed pasture)*			
	lc11_wetlands	*rain fed sugar (rainfed sugar)*			
	lc14_tussclo	*wetlands (wetlands)*			
	lc15_alpineg	*closed tussock grassland (tussock grasses - closed)*			
	lc16_openhum	*alpine meadows (alpine grasses - open)*			
	lc18_opentus	*open hummock grassland (hummock grasses - open)*			
	lc19_shrbsca	*open tussock grasslands (tussock grasses - open)*			
	lc24_shrbden	*scattered shrubs and grasses (shrubs and grasses - sparse - scattered)*			
	lc25_shrbope				
	lc31_forclos				

	Short name	Description	Unit	Data source	Notes/references
	lc32_foropen	*dense shrubland (shrubs - closed)*			
	lc33_woodope	*open shrubland (shrubs - open)*			
	lc34_woodspa	*closed forest (trees - closed)*			
	lc35_urbanar	*open forest (trees - open)* *open woodland (trees - scattered)* *woodland (trees - sparse)* *urban areas (urban areas)*			
	prop_forested	sum(LC_31, LC_32, LC_33, LC_34)			
	nv_grasses_n *nv_grasses_e* *nv_forests_n* *nv_forests_e* *nv_shrubs_n* *nv_shrubs_e* *nv_woodl_n* *nv_woodl_e* *nv_bare_n* *nv_bare_e* *nv_nodata_n* *nv_nodata_e*	Major vegetation sub-groups within the *National Vegetation Information System* (NVIS). Despite redundancy with the DLCD attributes (see above), these are included because NVIS quantifies alteration from 'natural' by differentiating between 'pre-1750' ('_n') and 'extant' ('_e'). Subgroups: *grasses* *forests* *shrubs* *woodlands* *bare* *no data*	-	DEWR (2008)	Preprocessed by Stein et al. (2011)
Anthropogenic Influences	*distupdamw*	maximum distance upstream before encountering a dam or water storage	km	Geoscience Australia (2004)	Preprocessed by Stein et al. (2011)
	impound_fac *flow_div_fac* *leveebank_fac* *infrastruc_fac* *settlement_fac* *extract_inf_fac* *landuse_fac* *catchment_di* *flow_regime_di* *river_di*	Dimensionless factors quantifying human impacts on catchment hydrology, in two broad categories: - Flow regime factors: impoundments (*ImpoundmF*), flow diversions (*FlowDivF*), and levee banks (*LeveebankF*). The combined effect is disturbance index *FlowRegimeDI*; - Catchment factors: infrastructure (*InfrastrucF*), settlements (*SettlementF*), extractive industries (*ExtractiveIndF*) and landuse (*LanduseF*). The combined effect is captured in *CatchmentDI.* *FlowRegimeDI* and *CatchmentDI* are combined in *RiverDI*	-	Stein et al. (2002), updated by Stein et al. (2011)	
Other	*pop_mean* *pop_max*	Average and maximum human population density in catchment across 3" grid squares.	km^{-2}	ABS (2006)	Preprocessed by Stein et al. (2011)
	pop_gt_1 *pop_gt_10*	Proportion of catchment with population density exceeding 1 person / km² and 10 people / km²	-		
	erosivity	Rainfall erosivity (spatial average across catchment)	MJ mm ha^{-1} h^{-1}	NLWRA (2001)	
	anngro_mega *anngro_meso* *anngro_micro*	Average annual growth index value for megatherm, mesotherm and microtherm plants, respectively	-	Xu and Hutchinson (2011)	
	gromega_seas *gromeso_seas* *gromicro_seas*	Seasonality of growth index value for megatherm, mesotherem and microtherm plants, respectively	-		
	npp_ann *npp_1* *through to* *npp_12*	Net Primary Productivity estimated by Raupach et al. (2002) for pre-European settlement conditions: - annually; and - for the twelve calendar months of the year	tC Ha^{-1}	Raupach et al. (2002)	Preprocessed by Stein et al. (2011)

~~7~~8 Author contributions

Keirnan Fowler conceived the project, supervised all data processing, liaised with supporting organisations (notably the Bureau of Meteorology), and led the drafting of the manuscript. Ziqi Zhang did the majority of the data processing and contributed to the manuscript. Xue Hou contributed to data processing with a particular focus on derivation of catchment boundaries.

~~8~~9 Competing interests

The authors declare that they have no conflict of interest.

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