How streamflow has changed across Australia since the 1950's: evidence from the network of Hydrologic Reference Stations

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Abstract

Streamflow variability and trends in Australia were investigated for 222 high quality stream gauging stations having 30 years or more continuous unregulated streamflow records. Trend analysis identified seasonal, inter-annual and decadal variability, long-term monotonic trends, and step changes in streamflow. Trends were determined for annual total flow, baseflow, seasonal flows, daily maximum flow, and three quantiles of daily flow. A distinct pattern of spatial and temporal variation in streamflow was evident across different hydroclimatic regions in Australia. Most of the stations in south-eastern Australia spread across New South Wales and Victoria showed a significant decreasing trend in annual streamflow, while increasing trends were retained within the northern part of the continent. No strong evidence of significant trend was observed for stations in the central region of Australia and northern Queensland. The findings from step change analysis demonstrated evidence of changes in hydrologic responses consistent with observed changes in climate over the past decades. For example, in the Murray-Darling Basin 51 out of 75 stations were identified with step changes of significant reduction in annual streamflow during the middle to late 1990s, when relatively dry years were recorded across the area. Overall, the Hydrologic Reference Stations (HRS) serve as critically important gauges for streamflow monitoring and changes in long-term water availability inferred from observed datasets. A wealth of freely downloadable hydrologic data is provided at the HRS web portal including annual, seasonal, monthly and daily streamflow data, as well as trend analysis products, and relevant site information.

Keywords: Hydrologic Reference Stations, streamflow variability, trends, step change, climate change, unregulated catchments, Australia

1 Introduction

Assessing changes and trends in streamflow observations can provide vital information for sustainable water resource management. The influence of diverse environmental factors and anthropogenic changes on hydrological behaviour makes the investigation into streamflow changes a challenging task. Trend detection is further complicated from intra-annual, inter-annual, decadal and inter-decadal variability in streamflow as well as from various influencing factors that can hardly been analysed separately (WWAP, 2012; Hennessy et al., 2007).

Extensive studies have been undertaken in different parts of the world to analyse long-term hydrologic trends, and to investigate the possible effect of long-term climate variability on hydrologic response (Stahl et al., 2010; Birsan et al., 2005; Lins and Slack, 2005; Milly et al., 2005; Burn and Elnur, 2002). Previous works on streamflow trends draw largely on national and continental analyses, especially for Europe and North America. Studies of streamflow variability include analysing trends across Europe (Stahl et al., 2010; Stahl et al., 2012), and at the national level. For example, Bormann et al. (2011) and Petrow and Merz (2009) analysed trends under flooding conditions on German rivers. Extensive literature on hydrological trends have been reported for the UK: Hannaford and Buys (2012) demonstrated variability in seasonal flow regimes; Hannaford and Marsh (2006, 2008) analysed flow indicators at an annual resolution, and other studies focused on particular regions (Biggs and Atkinson, 2011; MacDonald et al., 2010; Dixon et al., 2006; Jones et al., 2006). A wide range of research on streamflow trends has been published in the USA (Kumar et al., 2009; Novotny and Stefan, 2007; McCabe and Wolock, 2002) and Canada (Bawden et al., 2014; Monk et al., 2011; Burn and Hag Elnur, 2002).

Few studies have been published for Australia to-date partly due to limited information on data records, researches and documentation that could cover all flow regimes. Rivers in some regions have received close attention only recently. Australia is the driest inhabited continent with an average annual precipitation of 450 mm and the lowest river flow compared with other continents (Poff et al., 2006). Water is relatively scarce and is therefore a valuable resource across the country. Australian streams are characterized by low runoff, high inter-annual flow variability, and large magnitudes of variations between the maximum and minimum flows (Puckridge et al., 1998; Finlayson and McMahon, 1988). The wide variety of unique topographic features combined with variable climates and frequency in weather extremes result in diverse flow regimes. The recent rise in average temperature and the risk of future climate variability (BOM, 2015; IPCC, 2014; Cleugh et al., 2011) have added new dimensions to the challenges already facing communities. Climate variability and its impact on the hydrologic cycle have necessitated a growing need in Australia to seek evidence of any emerging trends in river flows.

Chiew and McMahon (1993) examined the annual streamflow series of 30 unregulated Australian rivers to detect trends or changes in the means. They found that identified changes in the tested dataset were directly related to the inter-annual variability rather than changes in climate. The analysis of trends in Australian flood data by Ishak (2010) indicated that about 30% of the selected 491 stations show trends in annual maximum flood series data, with a downward trend in the southern part of Australia and an upward trend in the northern part. Several other studies investigated trends of selected streamflow statistics in a particular region, e.g. southwest Australia (Petrone et al., 2010; Durrant and Byleveld, 2009), southeast Australia or Victoria (Tran and Ng, 2009; Stewardson and Chiew, 2009). All these studies addressed the trend analysis of Australian rivers with a limited spatial or temporal coverage of flow data. A gap in the research remains mainly due to constraints in the access to a dataset of catchments that can be large enough to represent the diversity of flow regimes across Australia. Such a dataset would enable a comprehensive and systematic appraisal of changes and trends in observed river flow records.

The Australian national network of Hydrologic Reference Stations (HRS) was developed by the Bureau of Meteorology to address this major gap and to provide comprehensive analysis of long-term trends in water availability across the country (Zhang et al., 2014; Turner et al., 2012). The HRS website is a one-stop portal to access high-quality streamflow information for 222 well-maintained river gauges in near-natural catchments. An intention is that the stations will serve as critically important gauges that record and detect changes in hydrologic responses to long-term climate variability and other factors.

This paper presents a statistical analysis to detect changes or emerging trends across a range of flow indicators, based on the daily flow data of 222 sites from the HRS network. The objective of this study is to provide a nationwide assessment of the long-term trends in observed streamflow data. Evaluation of past streamflow records and documenting recent trends will be of benefit in anticipating potential changes in water availability and flood risks. It is hoped that the findings from trend analysis presented in this paper will inform decision makers on long-term water availability across different hydroclimatic regions, and be used for water security planning within a risk assessment framework.

2 Site selection, data and methods

2.1 Hydrologic Reference Stations and data

The 222 Hydrologic Reference Stations (HRS) were selected from a preliminary list of potential streamflow stations across Australia according to the HRS selection guideline (SKM 2010). These guidelines specified four criteria for identifying the high quality reference stations, namely unregulated catchments with minimal land use change, a long period of record (greater than 30 years) of high quality streamflow observations, spatial representativeness of all hydro-climate regions, and the importance of site as assessed by stakeholders. Catchments with extensive basin water use or groundwater pumping were filtered and not included in HRS catchments, based on the local knowledge of the basin, stakeholder consultation and land use change analysis. The station selection guidelines were then applied in four phases to finalise the station list (www.bom.gov.au/water/hrs/guidelines.shtml). The HRS network will be reviewed and updated every two years to ensure that the high quality of the streamflow reference stations is maintained.

Two features were considered in order to define the hydroclimatic regions in HRS: climatic zones and Australia’s drainage divisions. The climatic zones were defined according to climate classification of Australia based on a modified Koeppen classification system (Stern et al., 2000). Australia has a wide range of climate zones, from the tropical regions of the north, through the arid expanses of the interior, to the temperate regions of the south (ABS, 2012). The Australian Hydrological Geospatial Fabric (Geofabric) Surface Catchments (BOM, 2012) were used to delineate 12 topographically defined drainage divisions approximating the drainage basins from the Geoscience Australia (2004) definition. The selection of HRS stations aimed to maximise the geographical extent of the available records. As shown in Figure 1, the final set of 222 hydrologic reference stations cover all climatic zones, jurisdictions and most drainage divisions. Since most Australian rivers are located near the coast, there is a high density of stations along the coast and sparsely distributed stations across inland areas. One third of the HRS sites are in temperate climate zone, and the majority of the rest are either in Tropical or Subtropical regions; only a few are located in other climate zones. The distribution of Hydrologic Reference Stations across multiple hydroclimatic regions provides data for a comprehensive investigation of long-term streamflow variability across Australia.

All data used in this study were daily streamflow series of 222 gauging stations from the HRS network. Table 1 lists the twelve drainage divisions and the number of stations in each division. The drainage division names are marked on Figure 1. One third of the HRS stations are located within the Murray-Darling basin, half of the rest are distributed along the east coast. This is the best compiled long-term quality controlled data for Australia and the trends derived from this dataset constitute the first such statement on long-term water availability across Australia.

The earliest record included in the data set is from 1950. Data prior to this has been excluded due to the common existence of large gaps in the pre-1950 period. All stations included in the HRS had a target of 5% or less missing data to meet the completeness criteria for high quality streamflow records. A few stations were included with more than 5% missing data where they excelled in other criteria such as stakeholder importance or spatial coverage. The periods of data gaps were filled using a lumped rainfall-runoff model GR4J (Perrin et al., 2003). The gap filling was found to perform well at most sites. The mean Nash-Sutcliffe coefficient of the gap-filled time series, when compared to the available original time series data, was 0.72 with standard deviation of 0.12. The model was calibrated and forced with catchment average rainfall and potential evapotranspiration from the Australian Water Availability Project (AWAP) (Raupach et al., 2009).

The study examined all sites using the full length of observations after 1950. Prior to 1950 the gauge network is generally too sparse for reliable analysis, and analysis periods starting after mid-1970s are considered too short to calculate meaningful trend values. Although, the data length of every station was not exactly the same over the continent, but for the stations within the same region, the data lengths were in more consistent time periods. Data for most of stations (86%) have very similar time periods. These allow for comparisons on a fairly consistent basis.

The gap-filled daily flow data were aggregated into annual series based on a water year calculation. The start month of the water year was defined as the month with the lowest monthly flow across the available data period. The start month of water year for each region was recorded in Table 1. The data used in this study were up to end of 2014, so the last water year cycle ended in 2014. In order to ensure the statistical validity of the trend analysis, all stations had minimum 30 years of record, with mean time-series length of 48 years and median time-series length of 46.6 years. The longest record length was 64 years. 25% of the stations have 50 or more years of record, and 86% stations longer than 40 years data. Catchment sizes ranged from 4.5 to 232,846 km^2 with a median size of 328.6 km^2. The majority (80%) of the stations had an upstream drainage area less than 800 km^2, and only three stations had a drainage area larger than 50,000 km^2.

The primary water data has been collected across Australia by many organisations, utilities and regulators in different states and territories, often to meet the requirements of their own documented procedures and sometimes with reference to Australian or international standards or guidelines. The Bureau's role as the national water information provider, has been working collaboratively with the water industry to develop and promote water information standards and guidelines to collate, interpret and access nationally consistent data. All data included in the HRS database are compiled, quality-checked by the Bureau, and therefore are consistent nationally and over the time. Bureau has developed a set of standard data quality code and references guides on how it relates to different agencies quality code. The data and the long term series gathered in this study are the best compiled and quality assured data for HRS catchments. The analysis and trends derived from the HRS datasets constitute the first statement on long-term water availability across Australia.

2.2 Streamflow variables for trend analysis

Long-term climate variability can be reflected through trends in streamflow variables. To understand the importance of the components of the hydrologic regimes and their potential link to long-term climate variability, ten streamflow variables were chosen for statistical and trend analysis. Two variables related to fluctuation of annual flows were annual total flow (Q_T) and annual baseflow (Q_{BF}). Baseflow was separated from daily total streamflow using a digital filter based on theory developed by Lyne and Hollick (1979) and applied by Nathan and McMahon (1990).

Daily streamflow data were analysed to form a group of indicators of daily flow trends. They were daily maximum flow (Q_{Max}), the 90th percentile (non-exceedance probability) daily flow (Q_{90}), the 50th percentile daily flow (Q_{50}), and the 10th percentile daily flow of each year (Q_{10}). The median daily flow Q_{50} was used in the study instead of daily mean flow because the flow distribution is skewed and outliers are present.

Four seasonal flow indicators were analysed to examine the seasonal trend patterns. These variables included summer flow Q_{DJF} (December to February), autumn flow Q_{MAM} (March to May), winter flow Q_{JJA} (June to August), and spring flow Q_{SON} (September to November). The trend analysis was applied to the ten hydrologic indicators of streamflow data at each HRS station.

2.3 Trend and data statistical analysis

Changes in streamflow data can occur gradually or abruptly. Statistical significance testing is commonly used to assess the changes in hydrological datasets (Helsel and Hirsch, 2002; Monk et al., 2011; Hannaford and Buys, 2012). The Mann-Kendall (MK) trend test (Mann, 1945; Kendall, 1975) was adopted in this study to identify statistically significant monotonic increasing or decreasing trends (Petrone et al., 2010; Zhang et al., 2010; Miller and Piechota, 2008). In order to ensure the assumption of independence was met for the MK test, the non-parametric Median Crossing and Rank Difference tests (Kundzewicz and Robson, 2000) were applied to entire datasets. Both randomness tests consider the long-term persistence as well. When either of the randomness tests indicated that the time series was not from a random process, the site was excluded from the MK trend assessment. As this study attempted to examine patterns in raw historical streamflow records, no further adjustments were made to account for the non-random structure of data.

The non-parametric MK trend test was used to detect the direction and significance of the monotonic trend, and the trend line by the non-parametric Sen Slope (Sen, 1968; Theil, 1950) was used to approximately represent the magnitude of the trend. The trend magnitude was standardised using the ratio of Sen Slope coefficient to average annual flow in order to make the change comparable across stations for reporting purposes.

All data were subject to step change analysis to detect any abrupt changes during the record period. The distribution free CUSUM test (Chiew and Siriwardena, 2005) was applied to identify the year of change in streamflow series. The significant difference between the median of the streamflow series before and after the year of change was tested by Rank-Sum method (Zhang et al., 2010; Miller and Piechota, 2008; Chiew and Siriwardena, 2005). More information and equations of the statistical tests used in this study can be found in Appendix A.

In addition to the trend analysis for the ten flow indicators, other statistical data analyses were included in the HRS web portal to gain a broad understanding of hydrologic regimes. Aggregated monthly and seasonal flow data were investigated for changes in flow patterns in different basins or regions. Daily event frequency analyses were used to examine the variations in daily streamflow magnitude, and daily flow duration curves were presented to examine changes in daily flow among decades.

3 Development of the HRS web portal

A web portal has been developed to house the network of Hydrologic Reference Stations and provide access to streamflow data, results of analysis, and associated site information. Figure 2 summarises the development process of the HRS network and website. Through a data quality assurance process following the guidelines and stakeholder consultations, the final list of 222 streamflow gauging stations was established. A suite of software tools, "the HRS toolkit" was developed to undertake data aggregation, analysis, trend testing, visualisation and manipulation. The toolkit is capable of automatically converting the flow variables to monthly, seasonal and annual totals, and quantifying the step and/or linear changes in the selected streamflow variables. The toolkit also generated and processed graphical products, data, statistical summary tables and statistical metadata included in the web portal.

A snapshot of the HRS web portal is shown in Figure 3. The main page was designed with three parts. A series of links on the top provide the project information. Below this is the station selector, which facilitates searching for the site of interest by location. The third part is the product selector containing the core information sections of the website. Several tabs are offered for users to explore the web portal dependent on their needs and the level of information they require. The daily streamflow data, graphical products, statistics and trend analysis results are available for users to view and download. Information provided on the HRS web portal will assist in detecting long-term streamflow variability and changes at the 222 sites, and therefore supports water planning and decision-making. More information can be found at the website http://www.bom.gov.au/water/hrs.

This web portal provides public access to high quality data and information. It has more than 15,000 graphic products for display. It is carefully designed for the public to have synthesised and easily understandable information on water availability trends across Australia. In order to ensure currency of this web site, streamflow data are updated and reviewed every two years.

4 Results

The study to detect long-term streamflow trends was performed on the 222 gauging stations included in the HRS network. This section presents an overview bar-plot of the Mann-Kendall test results for the selected ten hydrologic variables. Maps showing trend detection results and step change analysis for the annual total flow are presented as well as a table listing the stations with significant trends in annual total flow at 1% significance level ($p < 0.01$). In addition, result statistics of trends and step changes were summarised for different regions. Finally, variations in trend among daily flow indicators and seasonal flows were examined.

4.1 Overview

A stacked bar-plot is shown in Figure 4 that stratifies the stations by the trend across each streamflow variable. Overall, a consistent pattern is seen across the 10 streamflow variables – the majority of stations have either no trend or a non-random time-series; of the stations with a trend detected, the majority are decreasing.

Patterns of trends were noted in the different flow regimes. Moving through the flow variables from low (Q_{10}), median (Q_{50}), to high (Q_{90}), and onto maximum (Q_{Max}), an increasing number of stations were found with no trends, combined with decreasing number for non-random series. The overall number of stations with statistically significant trends was around the same across the median, high, and maximum variables but much lower for the low flow variable. In the trends of seasonal flows, around one third of stations showed a decreasing trend in spring and a quarter of stations in summer and winter. A significant proportion of stations do show a decreasing trend across the four seasons. Summer flow at a large number of stations showed no trend and three stations with an increasing trend. At most stations the autumn flow time-series were non-random or had no trend, and only about one tenth stations presented a decreasing trend. Due to non-randomness of streamflow variables, a number of stations are not amenable to trend analysis.

4.2 Spatial distribution of trends in annual total streamflow

Many hydrological time series exhibit trending behaviour or non-stationarity (Wang, 2006). In fact, trend or step change is one type of non-stationarity (Bayazit, 2015; Rao et al., 2012; Kundzewicz and Robson, 2000). The purpose of trend test in the present study is to determine if the values of a series have a general increase or decrease in the observation time period. Detecting the trends in a hydrologic time series may help us to understand the possible links among hydrological processes, anthropogenic influences and global environment changes. Many of the streamflow time series in this dataset exhibit trends or step-changes in the mean or median. Abrupt changes and trends in the hydrologic time series could be indicators of hydrologic non-stationarity or long-term gradual changes in the rainfall-runoff transformation processes.

4.2.1 Linear trend

Maps were generated showing the trend results for each variable across Australia. As mentioned before, the rank-based non-parametric Mann-Kendall test was used to assess the significance of monotonic trend in the selected flow variables. The magnitude of trend was calculated from Sen Slope. The Rank-Sum test was used to identify the presence of a step change in median of two periods, with the distribution free CUSUM method providing the year of change. Values are reported for sites with Mann-Kendall or Rank-Sum test at higher than 0.1 significant levels for statistically significant monotonic trend or step change. The trend analysis map of annual total streamflow (Q_T) displays the direction and significance of a trend (Figure 5) at different levels of significance: $p < 0.01$, $p < 0.05$ and $p < 0.1$. Although trends in Q_T vary across different hydro-climatic regions of the continent, a clear spatial pattern is evident from the map: all stations showing decreasing trends (35% of stations) are in the southern part of Australia and all stations showing increasing trends (4% of stations) in the northern part, while there is no significant trend visible in the central region of Australia. The general downward trends observed in southern Australia may have been affected by the dry period in the last decade in the south-eastern and south-western regions. Stations in the Murray-Darling Basin demonstrated the strongest decreasing trends with 30 stations exhibiting high levels of significance at $p < 0.05$.

A set of 22 gauging stations were identified with trends in annual total streamflow at 0.01 significance levels (Table 2). All sites showed consistent direction of change using MK test and Sen Slope. None of those 22 gauges showed increasing trend. Trends in annual baseflow were found to be similar to the results of annual totals when a significant trend was detected. Baseflow index was listed in Table 2 calculated by the ratio of baseflow to total flow, and the trend results of baseflow was indicated at the top right corner. The number of stations showing significant declining trends in baseflow conditions was less than it was for annual total flow. However, some time-series of annual baseflow were non-random and therefore not available for further trend testing.

4.2.2 Step change

Step change analysis was applied to all sites where the time series data was random to give comparable results of gradual and abrupt changes in annual total flows. The Rank-Sum test was used to identify the presence of a step change in the median of two periods, with the distribution free CUSUM method providing the year of change. Values were reported for sites with Rank-Sum test at 0.1 significance levels or higher. Figure 6 shows the results of step change analysis, where colours indicate the year of change appearing in each decade, and upward arrows represent increased median values after the year of change and vice versa.

The step change map reveals a definite spatial pattern in the location of stations that exhibited a significant step change. As expected, the direction and significance of step-changes is consistent with the Mann-Kendall results for most stations. The identified years of step changes appear to show spatial groupings at different divisions. Table 2 gives the Rank-Sum test (RS) results and lists the year of change for the 22 stations. The majority of stations in southeast Australia were characterised with step changes in mid-1990s, when the so-called "millennium drought" (BOM and CSIRO, 2014; SEACI, 2011) started to dominate the weather in this region. It has been reflected in Table 2: 13 of 22 stations presented the years of the step change in 1996, which was clearly the most dominating year. In Ummenhofer et al. (2009) where the most severe drought in Australia was discussed, the affected region referred to as south-eastern Australia is defined as the land region enclosed within 35° – 40°S and 140°– 148°E. Stations inside that defined region exhibited the major feature of a step change in the 1990s which can be seen by the purple downward arrows dominating Figure 6, stations outside the region exhibited step changes with mixed years of changes. This included a good number of 1970s changes at the northeast New South Wales, 1980s changes at the south east coast of Queensland, and 2000s changes in South Australia. Five stations in south-west West Australia had a key feature of 1975 step change, which might be partly due to the observed rainfall decline since the mid-1970s. It was also noted that most stations located in the Northern Territory and some in the northeast coast of Queensland showed a significant increasing step change.

Figure 7 summarizes the results of the trend test on the flow variable of annual total streamflow. It describes the percentage and number of stations with an upward or downward trend or step change in each region. The Australian states on the x axis were organised from left to right in the order of the increasing number of stations in each state. Across all the eight regions investigated in this study, the stations located in southern part of the country displayed a decreasing trend and step change persistently. These regions included Australian Capital Territory (ACT), South Australia (SA), Tasmania (TAS), southwest of Western Australia (WA), New South Wales (NSW), and Victoria (VIC). The number of stations with significant downward step changes was similar to, or slightly higher than the ones with detected trends. Upward changes were only observed at the north part of continent: most stations in Northern Territory (NT), one station with weak trend at north WA and one at north Queensland (QLD). Mixed patterns of upward and downward step changes were detected in Queensland, which has the most diverse climatic conditions.

4.3 Spatial distribution of trends in daily flows and seasonal flows

Trend analysis maps shown in Figure 8 decompose trends of daily flow for Q_{Max}, Q_{90}, Q_{50} and Q_{10}. In general, the identified trends were spatially consistent with the trend pattern in Q_T: with upward trends in the north-west and downward trends in the south-east, south-west and Tasmania. The Q_{50} and Q_{10} series were notable for the number stations with non-random time-series and therefore an invalid MK test result, this could be seen most dramatically in Figure 8d, and was due to the higher correlation of the time-series. This daily flow trend analysis indicated similar results to previous studies (Tran and Ng, 2009; Durrant and Byleveld, 2009) for the respective sites and flow statistics.

The analysis of maximum daily flow Q_{Max} could be considered as analysis of extreme flow as this series contains the maximum value for each year. The general pattern of trends in Q_{Max} was in accordance with the preliminary trend analysis results in Ishak (2010), which suggested that about 30% of selected stations showed trend in Q_{Max}, with downward trend in the southern part of Australia and upward trends in the northern part (Figure 8a).

The spatial distribution of trends in seasonal flows was investigated to disaggregate total flow series into seasons (Figure 9). The broad pattern from the analysis was a collection of few upward trends in the north and predominant downward trends generally in the south. Across the four seasonal variables, spring flow (Q_{SON}), winter flow (Q_{JJA}), summer flow (Q_{DJF}), and autumn flow (Q_{MAM}) were in the sequence of decreasing number of detected downward trends. All seasons presented significant downward trends mostly in the southern parts of Australia, with autumn having fewer than others.

5. Discussion

We have demonstrated a comprehensive statistical and trend analysis in long-term streamflow data for 222 unregulated river gauges from the HRS national network. Ten streamflow variables were examined to detect underlying changes or trend in streamflow and to identify spatial variations across Australia. Evidence from previous research and this current study raises an important question: what could be the key driver of the detected changes in Australian streamflow data? Though it is beyond scope of this study to examine underlying mechanisms linking flow, climate and other factors, some remarks may help to provide valuable information for understanding and interpreting Australian hydrology.

5.1 Evidence for trends in hydrological records Australia

Numerous studies have analysed Australian streamflow data to detect any existing trends in hydrologic records. Chiew and McMahon (1993) examined trends in annual streamflow of 30 sites across Australia and no clear evidence of changes were suggested with the data available at that time. Haddad et al. (2008) reported a decreasing trend in many Victorian stations of annual maximum floods particularly after 1990. Tran and Ng (2009) also showed a consistently decreasing trend among 9 streamflow statistics of 14 stations in a Victorian region, but indicated the result was not able to relate the effect of global climate change with the decreases in streamflow. Durrant and Byleveld (2009) analysed post-1975 flow record at 29 sites across south-west Western Australia; they indicated the majority of sites show a consistent regional reduction in streamflow. Silberstein et al. (2012) further computed simulations of runoff from 13 major river basins in south-western Australia. They found that the reduction in runoff for the study region is likely to continue under projected future climates. Pui et al. (2011) detected changes in annual maximum flood data of 128 stations in NSW according to multiple climate drivers. Ishak et al. (2010, 2013) presented trend analysis in annual maxima flood series data from 491 stations in Australia, and suggested much of the observed trend may be associated with the climate modes on annual or decadal timescales.

Commonality and differences were found from this study when compared with previous streamflow trend studies across Australia. This could be expected given the different selection of flow statistics, gauge location, data length, employed techniques and methodology. For example, to examine the trends in south-west Western Australia (SWWA), Durrant and Byleveld (2009) has investigated 29 sites in the area using post-1975 data, whilst this paper considered the full record of data since 1950 and the full water year was used. Owing to the different data record periods used in trend analysis, seven stations in Durrant and Byleveld (2009) showed a possible increase, while in this study a homogenous spatial pattern of downward trends was revealed across the SWWA. Three stations in common were examined in both studies. The streamflow data of Yarragil Brook at Yarragil Formation, AWRC ID 614044 (Australian Water Resources Council), in Murray River basin was a non-random series, which was strongly biased by the 1975 step change. When only looking at the runoff of post-1975 period at this site, it revealed a very weak decreasing trend, which was similar to the result of Durrant and Byleveld (2009). Carey Brook at Staircase Road (608002) in Donnelly River basin had similar time series data starting from the mid-1970s in both studies. A slight decreasing linear trend and a 1997 step change at 0.05 significance level was identified in this study. No statistically significant trend was detected in Durrant and Byleveld (2009), which could be attributed to the limited record until 2008 and not considering the recent years of 2010, 2011 and 2012 that were relatively dry. The results were in agreement in both studies showing no strong decreasing trend for the Kent River at Styx Junction (604053). At this site the 1975 change was not predominant.

The results of this study have demonstrated the main characterisation of hydrological change of river flows across Australia since the 1950's. Overall, most of the downward trends in Q_T

appeared within or very close to the temperate climate zone, while upward trends were in the tropical region. And a large number of step changes occurred in 1996 across southeast Australia.

5.2 Further remarks on detected trends

Many factors could contribute to changes in runoff characteristics, ignoring climate change as well as low-frequency climate variability and human intervention in river basins compromise the assumption of stationarity (Ajami et al., 2016; Bayazit, 2015; Smetterm et al., 2013; Ummenhofer et al., 2009). Higher temperature and changes in precipitation or other climate variables impact on the rainfall-runoff process directly, and indirectly causing changes in flora, relief and soil erosion. Changes in catchment characteristics, either naturally or under human influence such as farm dams, can also have an important influence on water flow.

Moreover, high climate variability and recent climate trends has been observed in Australia, as the continent is effected by many different weather systems and is driven by many significant climate features (CSIRO and BOM, 2015; BOM, 2015). Accordingly, hydrologic data of Australian rivers generally have strong natural variability, subject to data availability and quality. All these factors make it challenging to detect changes or trends in streamflow data. Even if a trend is identified, it is difficult to attribute changes to any specific cause, as global warming and other regional or local changes are contributing to the hydrologic process.

The long-term rainfall trends (1970-2015) in annual total rainfall Australia has been analysed and published (http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=trend-maps). The identified trend patterns in annual total streamflow are spatially consistent with trends in annual total rainfall, where most of eastern and south-western Australia has experienced substantial rainfall declines since 1970; while north-western Australia has become wetter over this period. This similarity implies that hydrological variability is closely related with changes in rainfall patterns.

The spatial pattern of trends matched the rainfall records maps that indicated rainfall deficiency in the south in the last decade comparing the historical records (Cleugh et al., 2011). Similar rainfall changes were also observed as shown in the recent CSIRO sustainable yield study projects (CSIRO, 2015). Drought conditions, the most persistent rainfall deficit since the start of the 20th century, persisted in the south-east and south-west of the continent from around 1996 to 2010, which might be attributed to the detected change in streamflow. This could be the reason that most of the gauging stations in southern Australia and southeast of Queensland showed a significant decreasing trend in annual streamflow. It was also found that positive trends observed at many locations in northern Australia could be related to increased rainfall in this part of Australia during the last decade (SEACI, 2011). Other changes such as within-year rainfall variation and increase in temperature may have played a role in affecting the hydrologic cycle.

Whilst it is a possible explanation, it is not explicit that climate change is the only cause of significant trends in streamflow. There are many other factors that may affect streamflow, for example, natural catchment changes, climate variability, data artefacts and other influences. Site specific comparison of rainfall, PE, and temperature may help to improve the understanding of the underlying causes of trends in hydrological variables. Further investigation would be required to discover the potential causes of detected trends, which was beyond the scope of this study.

Under the Water Act (2007), the Australian Bureau of Meteorology has responsibility for compiling and disseminating comprehensive water information nation-wide. Hydrologic Reference Stations (HRS) is an initial step to build up the national river data network. The network of HRS, which the present study was based on, is the first operational website in Australia as a national river flow data repository. It provides an excellent foundation for water planning and research – particularly in trend detection and the possibility to link to large scale atmospheric and climate variables. The information on the HRS website can be used as a test bed for model development, hydrological non-stationarity assessments and many other research interests.

6. Conclusions

This study investigated the streamflow variability and inferred trends in water availability for 222 gauging stations in Australia with long term and high quality streamflow records. The results present a systematic analysis of recent hydrological changes in greater spatial and temporal details than previously published for Australian rivers. Implications of the findings should aid decision making for water resources management, especially when considering the results in the context of climate variability.

The main findings of the study are:

- The spatial and temporal trends in observed streamflow varied across different hydro-climatic regions in Australia (Figure 1 and Figure 5). As a short summary of the trend test results in annual streamflow (Q_T) over the continent, most of the increasing trends were observed in northern part of Northern Territory, while there was only one weak trend visible in the northern region of Western Australia and Queensland. However, in south-eastern Queensland there was a significant decreasing trend. Most of the gauging stations in New South Wales, Victoria, south-east South Australia, south-west Western Australia, and north-west Tasmania showed a significant decreasing trend in annual streamflow. In central Australia, north Queensland and South Tasmania, most of the stations showed no significant trend in annual streamflow.

- The temporal trends also varied between different components of streamflow – annual total, daily maximum (Q_{Max}), high, median and low flows (Q_{90}, Q_{50}, Q_{10}), baseflow (Q_{BF}) and seasonal flows (Q_{JJA}, Q_{SON}, Q_{DJF}, Q_{MAM}). Out of 222 stations, only 7 showed an increasing trend, 90 decreasing and 98 no trend in total annual streamflow. The annual daily maximum streamflow showed decreasing trends at 67 stations while the low flow and baseflow components showed decreasing trends at 18 and 73 stations respectively. Trends also varied between different seasonal flows and also across different hydro-climatic regions. Seasonal flow maps were dominated with decreasing trends. A few stations in northern Australia presented increasing trend for spring, summer and winter flow, while no stations were found with increasing trend for autumn flow (Q_{MAM}) anywhere in Australia.

- The analysis of step changes revealed definite regional patterns: The majority of stations in the southern parts of Australia were characterised with downward step changes, while stations with significant upward step changes were seen in the Northern Territory and some of the northeast coast of Queensland.

- The web portal (http://www.bom.gov.au/water/hrs) displays all the graphical products, tables, and statistical test results of all 222 stations. It contains a comprehensive unique set of graphical products for linear trends and step change.

The streamflow trends evident from the statistical data analysis showed some parallels with climate variability patterns that the country experienced through recent decades. Long-term trends in water availability across different hydroclimatic regions of Australia reported in this study are derived purely from observations, not derived from models which can invariably be influenced by biases. The high quality streamflow data of HRS and the results from this analysis on streamflow variability provide critical information for water security planning and for prioritising water infrastructure investments across Australia.

Appendix A: Statistical tests

A1. Median Crossing Test

This method tests for randomness of a time series data. It is a non-parametric test. The n time series values (X_1, X_2, X_3... X_n) are replaced by ‘0’ if $X_i < X_{median}$ and by ‘1’ if $X_i > X_{median}$. If the time series data come from a random process, then the count ‘m’, which is the number of times 0 is followed by 1 or 1 is followed by 0, is approximately normally distributed with:

Mean: $\mu = \frac{(n-1)}{2}$

Standard deviation: $\sigma = \frac{(n-1)}{4}$

The z-statistic is therefore defined as:

$$z = \frac{|(m-\mu)|}{\sigma^{0.5}}.$$

A2. Rank Difference Test

This method also tests for randomness of a time series data. It is a non-parametric test. The n time series values (X_1, X_2, X_3… X_n) are replaced by their relative ranks starting from the lowest to the highest (R_1, R_2, R_3… R_n). The statistic ‘U’ is the sum of the absolute rank differences between successive ranks:

$$U = \sum_{i=2}^{n} | R_i - R_{i-1} |$$

For large n, U is normally distributed with:

Mean: $\mu = \frac{(n+1)(n-1)}{3}$

Standard deviation: $\sigma = \frac{(n-2)(n+1)(4n-7)}{90}$

The z-statistic* is therefore defined as:

$$z = \frac{|(U-\mu)|}{\sigma^{0.5}}.$$

A3. Mann-Kendall Test

This method tests whether there is a trend in the time series. It is a non-parametric rank-based test. The n time series values (X_1, X_2, X_3… X_n) are replaced by their relative ranks starting from the lowest to the highest (R_1, R_2, R_3… R_n).

The test statistic S is defined as:

$$S = \sum_{i=1}^{n-1}[\sum_{j=i+1}^{n}\operatorname{sgn}(R_i - R_j)]$$

where sgn(y) = 1 for y > 0
sgn(y) = 0 for y = 0
sgn(y) = -1 for y < 0
sgn() is the signum function.

If there is a trend in the time series (i-e the null hypothesis H_o is true), then S is approximately normally distributed with:

Mean: $\mu = 0$

Standard deviation: $\sigma = \frac{n(n-1)(2n+5)}{18}$

The z-statistic* is therefore:

$$z = \frac{|S|}{\sigma^{0.5}}$$

A positive value of S indicates that there is an increasing trend and vice versa.

A4. Distribution Free CUSUM Test

This method tests whether the means in two parts of a record are different for an unknown time of change. It is a non-parametric test. Given a time series data (X_1, X_2, X_3… X_n), the test statistic V_k is defined as:

$$V_k = \sum_{i=1}^{k}\operatorname{sgn}(X_i - X_{median})]$$

where sgn(y) = 1 for y > 0
sgn(y) = 0 for y = 0
sgn(y) = -1 for y < 0
X_{median} is the median value of the X_i data set.

The time at which 'max|V_k|' occurs is considered as the time of change. The distribution of V_k follows the Kolmogorov-Smirnov two-sample statistic (KS = (2/n) max|V_k|). A negative value of V_k indicates that the latter part of the record has a higher mean than the earlier part and vice versa.

A5. Rank-Sum Test

This method tests whether the medians in two different periods are different. It is a non-parametric test. The time series data is ranked to compute the test statistic. In the case of ties the average of ranks are used. The statistic S is the sum of ranks of the observations in the smaller group. The theoretical mean and standard deviation of S under H_o for the entire sample is given as:

Mean: $$\mu = \frac{n(N+1)}{2}$$

Standard deviation: $$\sigma = \left[\frac{nm(N+1)}{12}\right]^{0.5}$$

where n and m are the number of observations in the smaller and larger groups respectively. The standardised form of the test statistic, Z* is computed as:

$Z = (S - 0.5 - \mu) / \sigma$ if $S > \mu$
$Z = 0$ if $S = \mu$
$Z = |S + 0.5 - \mu| / \sigma$ if $S < \mu$

Z is approximately normally distributed.

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Table 1: Metadata of the drainage divisions and Hydrologic Reference Stations

Division map code	**Drainage division names**	**Mean annual rainfall (mm) (1976-2005)***	**Mean elevation (m)**	**Number of HRS stations**	**Water year start month**	**Smallest catchment area (km^2)**	**Largest catchment area (km^2)**
I	Northeast Coast	764	173	42	October	6.6	7486.7
II	Southeast Coast	599	323	44	March	4.5	4660.0
III	Tasmanian	1519	199	12	February	18.3	775.3
IV	Murray-Darling	479	260	75	March	26.3	35238.9
V	South Australia Gulf	344	269	5	February	5.3	187.4
VI	Southwest Coast	329	365	13	March	14.1	1786.0
VII	Indian Ocean	369	162	0	(No data)	(No data)	(No data)
VIII	Timor Sea	520	339	13	September	65.4	47651.5
IX	Gulf of Carpentaria	674	293	13	October	170.0	43476.2
X	Lake Eyre	429	312	5	October	434.9	232846.3
XI	North Western Plateau	456	359	0	(No data)	(No data)	(No data)
XII	South Western Plateau	321	297	0	(No data)	(No data)	(No data)

* Calculation was based on rainfall data from BOM climate website http://www.bom.gov.au/

Table 2: Results of trend analysis for stations showing MK trend test at 0.01 significance level in annual total streamflow

Div	State	Basin	Station ID	Site name	Area (km²)	Data series time		Ave. annual flow (GL/yr)	BF index	Trend		Step change	
						Start year	End year			MK	Sen Slp	RS	year
II	VIC	Snowy River	222206	Buchan River at Buchan	850	1951	2014	140.0	0.45--	**,↓	-1.2%	**	1976
	VIC	Mitchell-Thomson Rivers	223202	Tambo River at Swifts Creek	899	1951	2014	77.1	0.46--	**,↓	-1.3%	**	1978
	VIC	Werribee River	231213	Lerderderg River at Sardine Creek O'brien Crossing	152	1959	2014	25.9	0.34--	**,↓	-1.7%	**	1996
	VIC	Hopkins River	236213	Mount Emu Creek at Mena Park	448	1974	2014	13.6	0.18--	**,↓	-3.3%	**	1996
	VIC	Glenelg River	238208	Jimmy Creek at Jimmy Creek	23	1951	2014	3.4	0.47**,↓	**,↓	-1.5%	**	1996
	SA	Millicent Coast	A2390519	Mosquito Creek at Struan	1550	1971	2014	21.7	0.25--	**,↓	-2.6%	**	1992
	SA	Millicent Coast	A2390523	Stony Creek at Woakwine Range	485	1973	2014	4.8	0.55**,↓	**,↓	-2.6%	**	1990
III	TAS	Smithton-Burnie Coast	314213	Black River at South Forest	318	1968	2014	194.1	0.38--	**,↓	-1.0%	**	1992
IV	NSW	Upper Murray	401009	Maragle Creek at Maragle	217	1951	2014	35.9	0.47**,↓	**,↓	-1.2%	**	1996
	VIC	Kiewa River	402217	Flaggy Creek at Myrtleford Road	26	1970	2010	4.0	0.42**,↓	**,↓	-2.6%	**	1996
	VIC	Goulburn	405238	Mollison Creek at Pyalong	164	1972	2014	19.5	0.29--	**,↓	-3.8%	**	1996
	VIC	Goulburn	405248	Major Creek at Graytown	288	1971	2014	13.2	0.10**,↓	**,↓	-2.9%	**	1996
	VIC	Goulburn	405251	Brankeet Creek at Ancona	122	1973	2014	14.8	0.45--	**,↓	-2.4%	**	1996
	VIC	Campaspe River	406214	Axe Creek at Longlea	237	1972	2014	13.4	0.18--	**,↓	-4.0%	**	1996
	VIC	Loddon River	407214	Creswick Creek at Clunes	300	1951	2014	24.0	0.32**,↓	**,↓	-1.9%	**	1996
	VIC	Loddon River	407230	Joyces Creek at Strathlea	156	1973	2014	9.2	0.17--	**,↓	-3.3%	**	1996
	NSW	Lachlan	412028	Abercrombie River at Abercrombie	2631	1951	2014	277.0	0.30--	**,↓	-1.6%	**	1978
	NSW	Lachlan	412066	Abercrombie River at Hadley	1630	1960	2014	169.8	0.29--	**,↓	-1.7%	**	1978
	VIC	Avon	415226	Richarson River at Carrs Plains	125	1971	2014	3.7	0.04**,↓	**,↓	-2.7%	**	1996
	VIC	Wimmera	415237	Concongella Creek at Stawell	244	1976	2014	9.1	0.12**,↓	**,↓	-3.8%	**	1996
VI	WA	Murray River (WA)	613002	Harvey River at Dingo Road	148	1970	2014	29.7	0.58--	**,↓	-1.6%	**	1993
	WA	Swan Coast	616065	Canning River at Glen Eagle	537	1953	2014	18.9	0.36**,↓	**,↓	-1.7%	**	1975

* Significant at $p < 0.05$ ** Significant at $p < 0.01$
⁻ baseflow series non-random ° baseflow no trend
↓ decrease trend ↑ increase trend

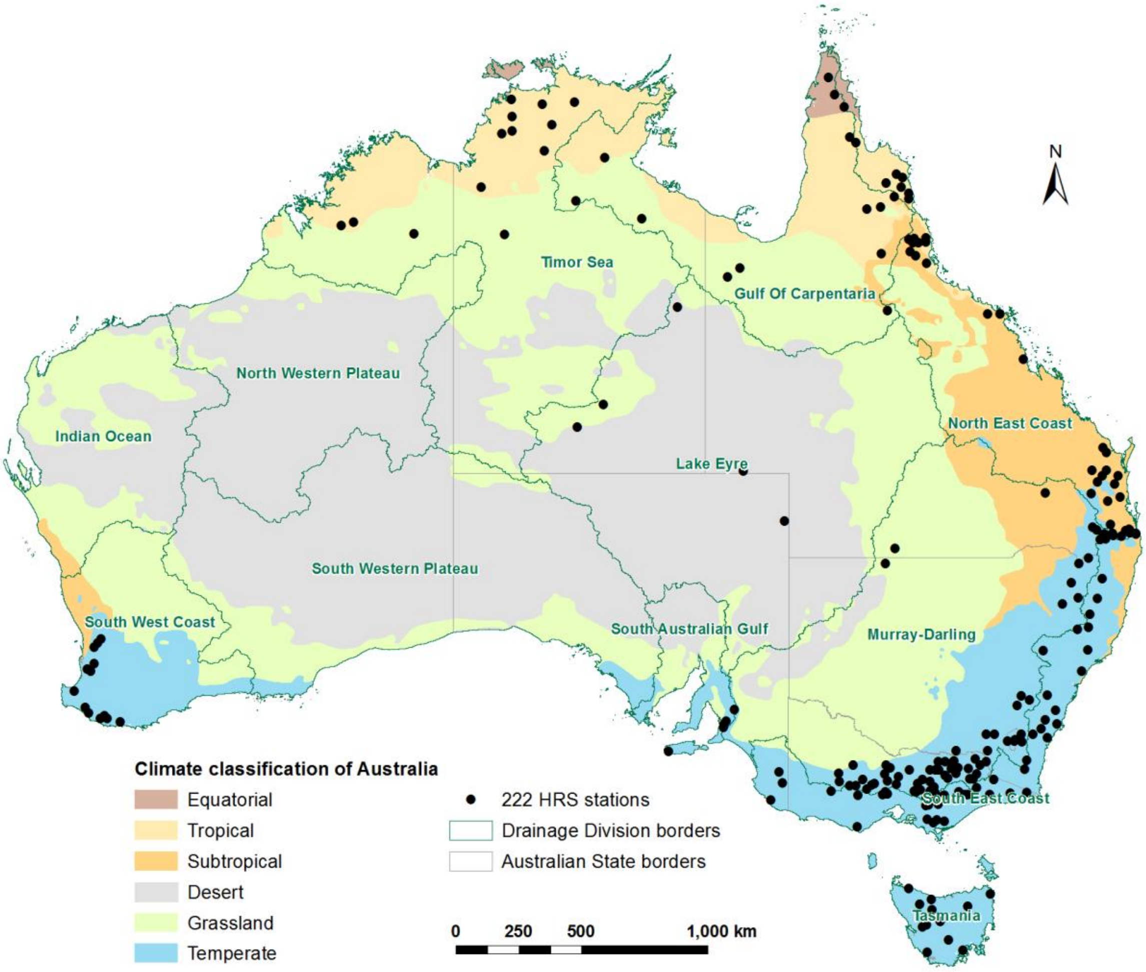


Figure 1: Location of the 222 high quality streamflow reference stations, the climatic regions and Australia drainage divisions (Geofabric Surface Hydrology Catchments, Geofabric V2.1, BOM 2012)

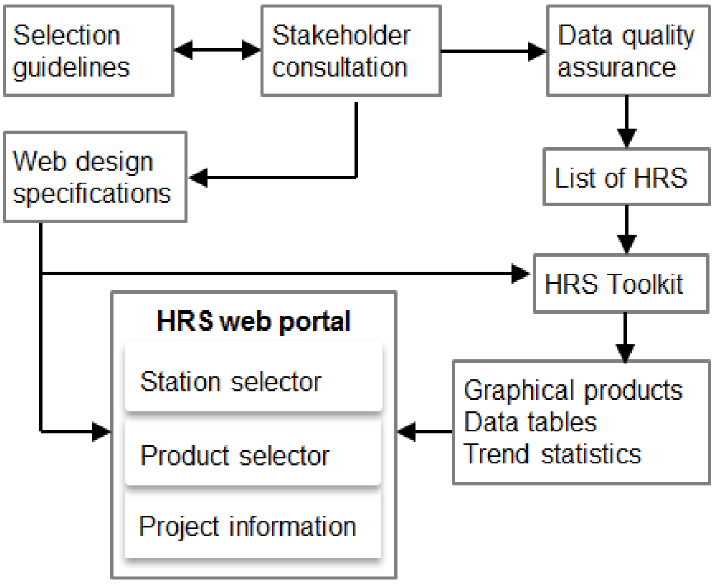
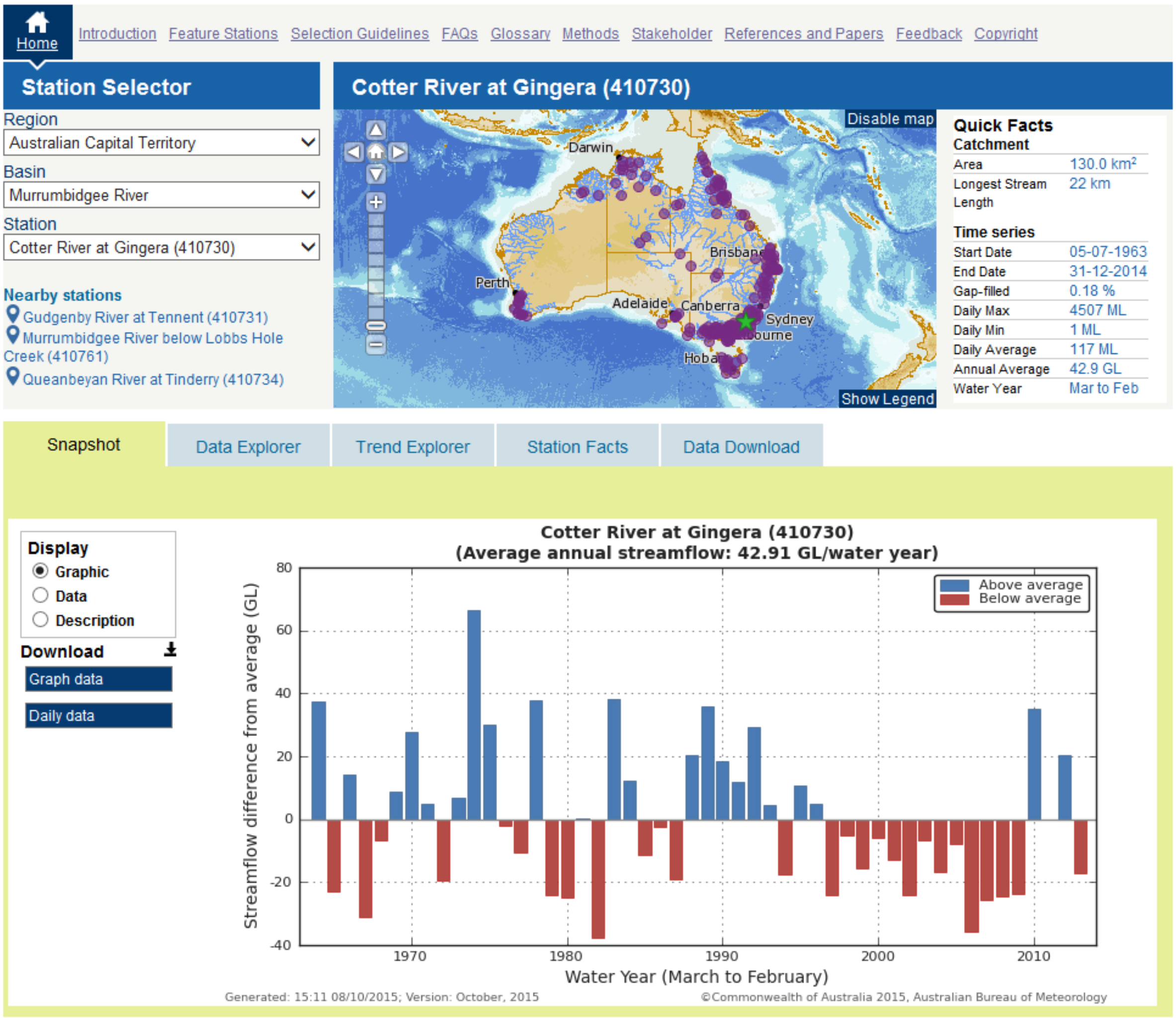


Figure 2: Framework of developing Hydrologic Reference Stations



Region: Australian Capital Territory
Basin: Murrumbidgee River
Station: Cotter River at Gingera (410730)

Quick Facts

Catchment

Area	130.0 km²
Longest Stream Length	22 km

Time series

Start Date	05-07-1963
End Date	31-12-2014
Gap-filled	0.18 %
Daily Max	4507 ML
Daily Min	1 ML
Daily Average	117 ML
Annual Average	42.9 GL
Water Year	Mar to Feb

Figure 3: Snapshot of the HRS web portal

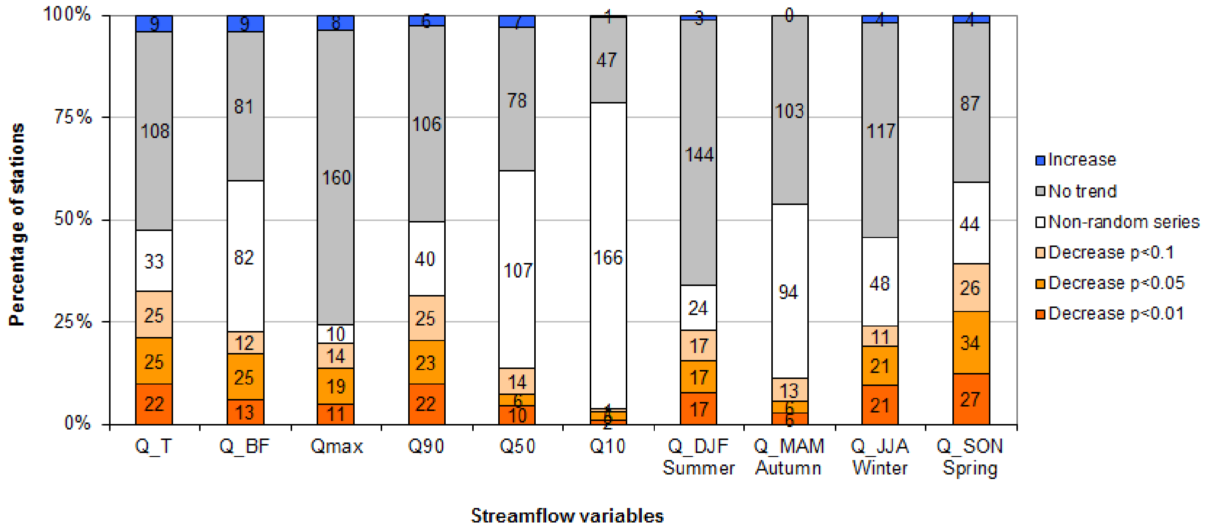


Figure 4: Stacked bar-plot summarizing the MK trend test results for the 222 HRS stations, with data labels showing the number of stations in each category (Q_T: annual total flow, Q_BF: annual baseflow, Qmax: daily maximum flow, Q90: 90th percentile daily flow, Q50: 50th percentile daily flow,Q10: 10th percentile daily flow, Q_DJF: summer flow, Q_MAM: autumn flow, Q_JJA: winter flow, Q_SON: spring flow)

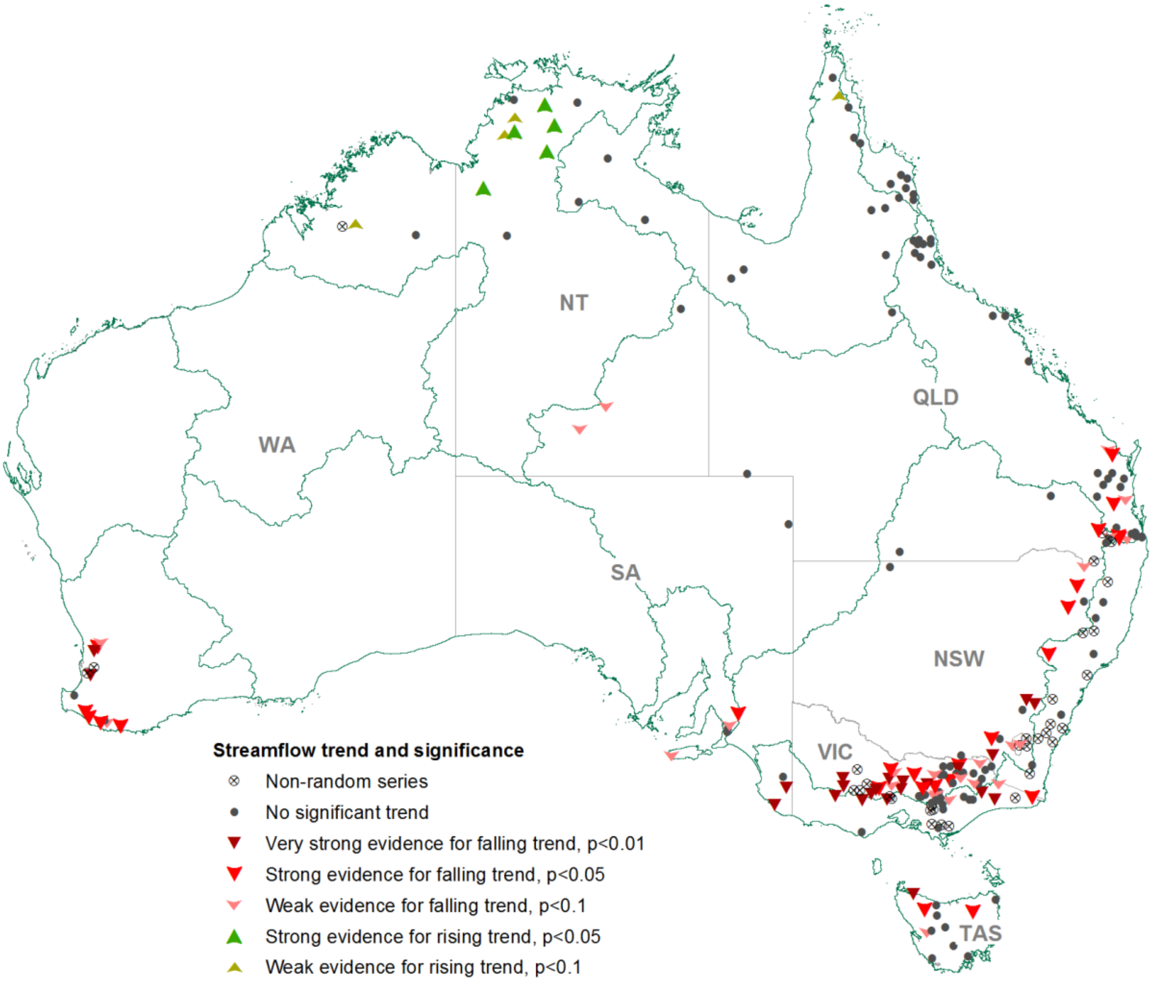


Figure 5: Spatial variation in trend results of annual total flow (Q_T), trends were shown in significance levels at 0.01, 0.05, and 0.1

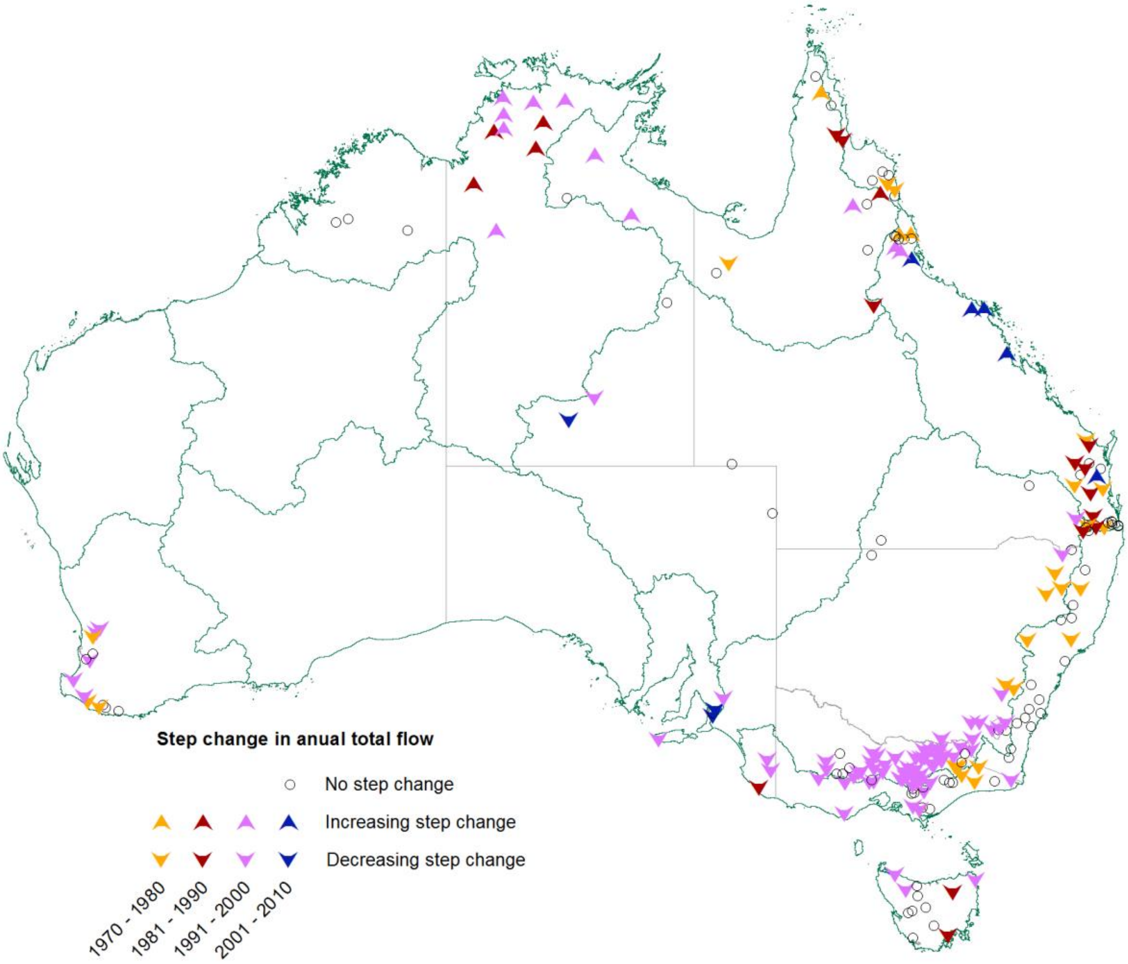


Figure 6: Variations of step change in annual total flow (Q_T), with the year of change indicated in each decade

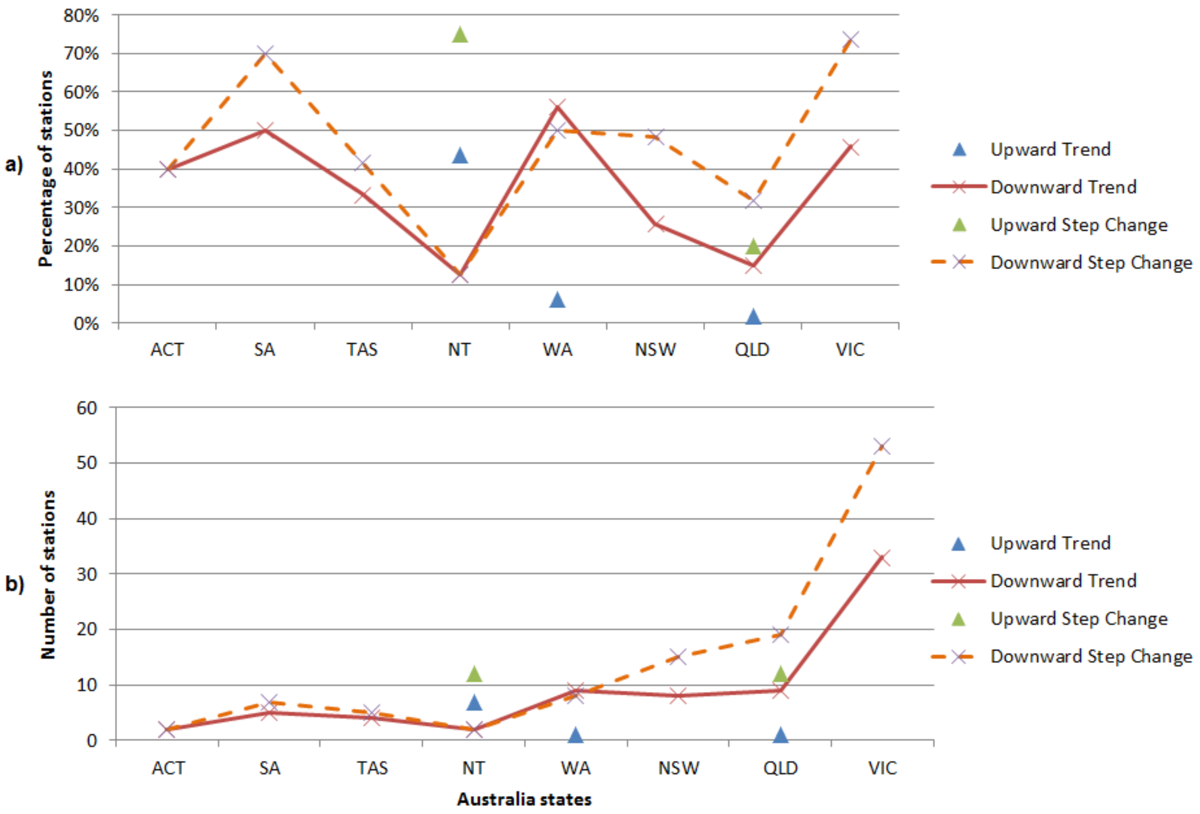


Figure 7: a) Percentage and b) number of stations showing significant upward and downward trends or step changes in Australia states and territories

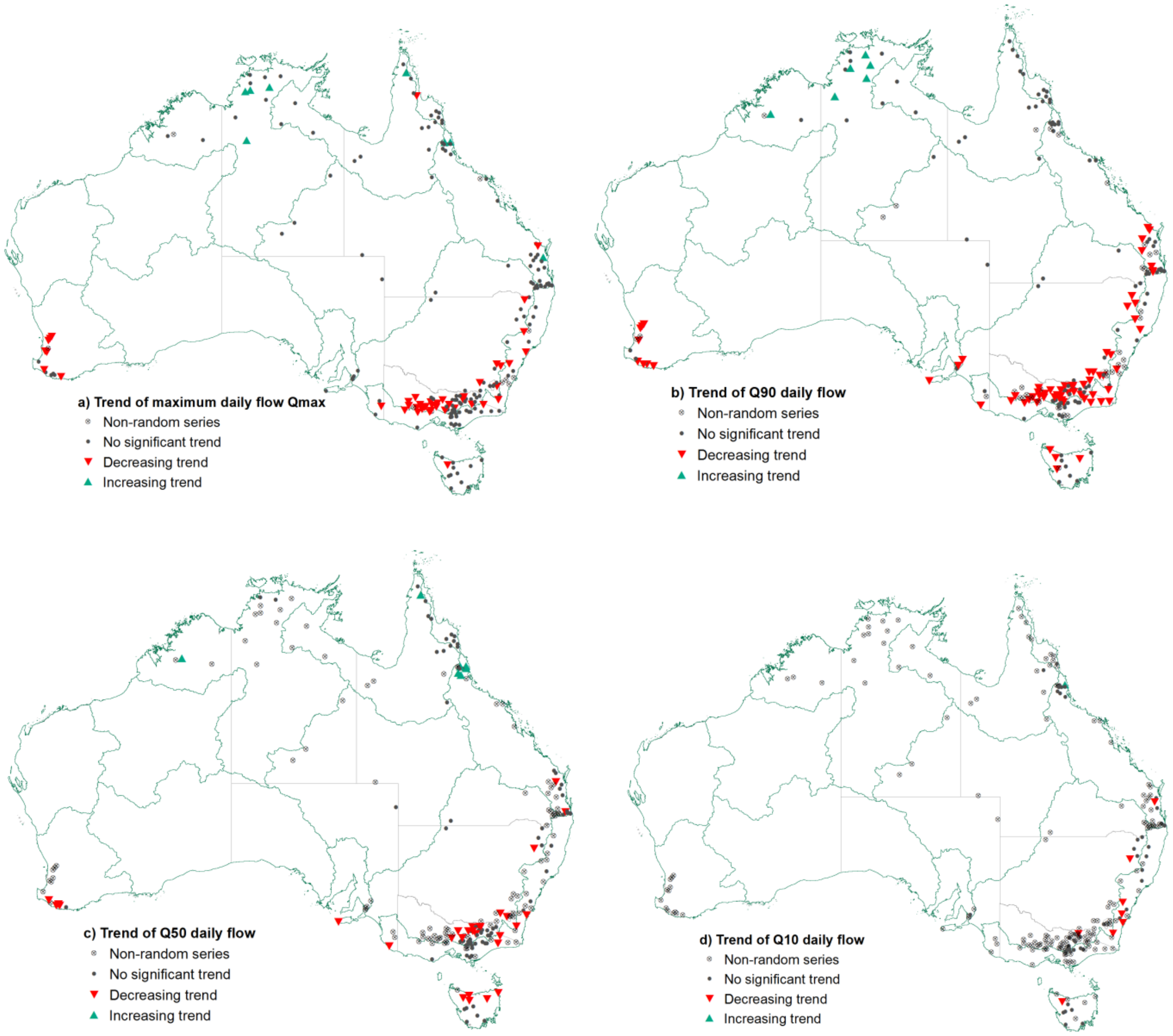


Figure 8: Maps showing trends of daily flow in various magnitude categories a) maximum daily flow Q_{Max}; b) Q_{90} daily flow; c) Q_{50} daily flow; d) Q_{10} daily flow at 10% significant level ($p<0.1$)

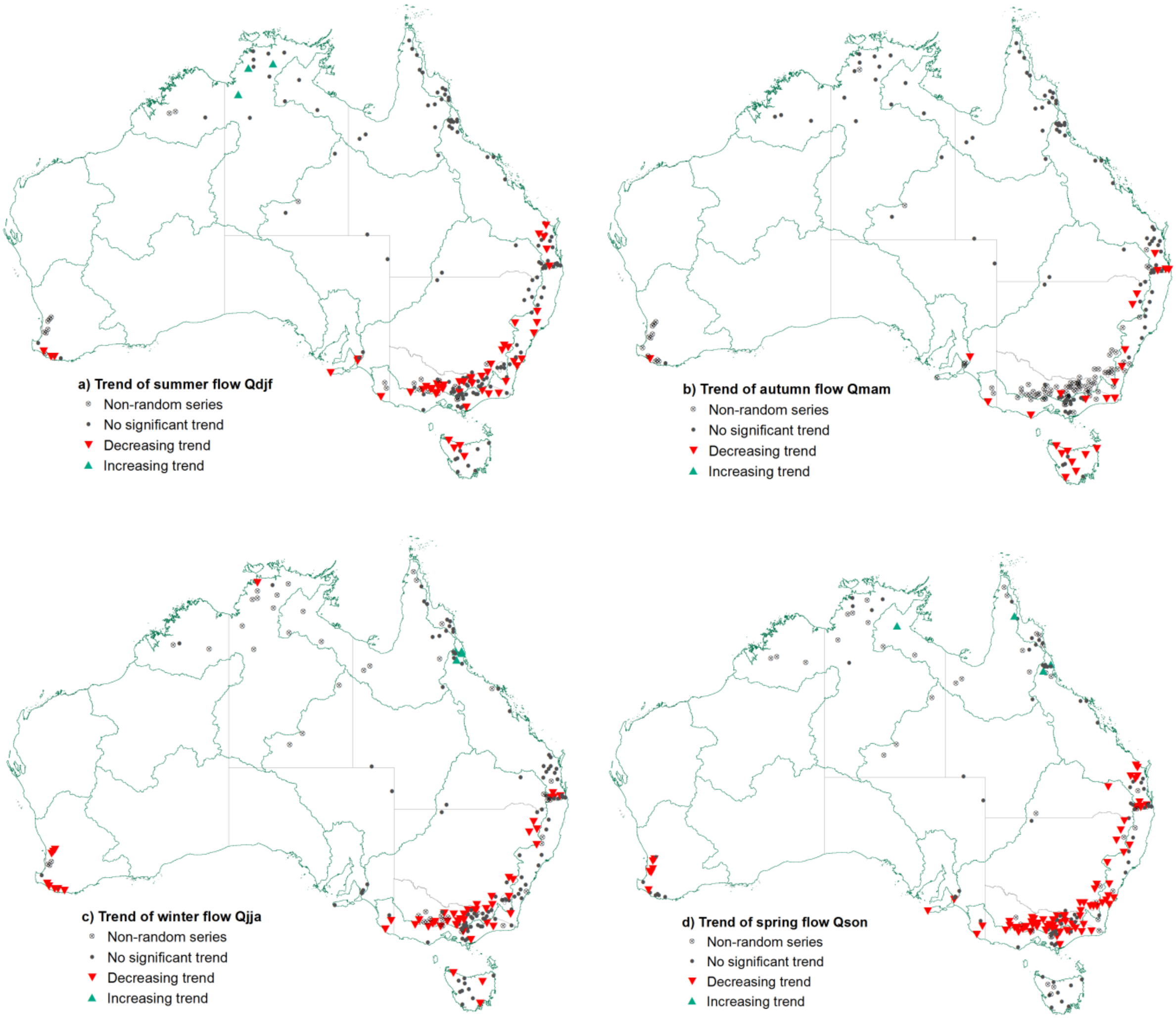


Figure 9: Maps showing trends of seasonal flow in a) Q_{DJF} Summer flow; b) Q_{MAM} Autumn flow; c) Q_{JJA} Winter flow; d) Q_{SON} Spring flow