Reply to the comments for revised manuscript "How streamflow has changed across Australia since the 1950's: evidence from the network of Hydrologic Reference Stations" by S. X. Zhang et al.

Authors' point-by-point response to all comments received

08 August 2016
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1. Authors' response and changes to review Referee #1,

(Received and published 8 March 2016; Editor's decision to compile all the changes and upload the revised manuscript, received 30 June 2016)

Many thanks for your time to review our manuscript. We highly appreciate your insightful and constructive comments which will help to improve the submitted manuscript. Please find our response below to your comments, questions and suggestions. The referee's comments are first recalled in *italics, blue colour font*, and then followed by our **response** and **changes** made in the revised manuscript.

General comments

This article is well written overall and provides important results relevant to historical changes in Australian streamflows. It appears to be the first comprehensive analysis of streamflow trends and variability for Australia. It utilizes a newly available data set of minimally disturbed streamflow basins, which is critical for looking at climate driven changes. I don't see any major technical problems, however, more information is needed as it appears that catchments with different time periods are analysed together, this limits the comparability of catchments which is important for this type of trend/variability analysis. The results and discussion in places could be clarified, and better match the article figures. It's important to add at least a first cut at relating streamflow variability to large scale atmosphere/ocean patterns, particularly with the large number of step changes that were found.

Answer

The authors would like to thank the referee for those positive evaluations of the manuscript and our work; and for the insightful comments on the data and method.

For the first question in general comments: catchments with different time periods are analysed together. Firstly, we checked the statistics of data availability of all 222 stations, with minimum 30 years data, average 48 years data, and 86% stations longer than 40 years data. Most of the stations have observations starting in 1970s. One intention of this study is to look at the long term changes in Australian streamflow, therefore the full length of observations of all stations are used in the analysis. If the data is truncated to have a consistent time periods over the continent, this means only 30 years data to be used, and for some stations half of data length will be cut which will limits an holistic examination of the historic records.

Secondly, 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 and observation time periods were more consistent. Additionally, data of stations (86%) has very similar time period which implies that the comparisons are mostly consistent.

Lastly, the primary purpose of the work is to provide long-term trends of streamflow data of Australian rivers with as much observation data as available. This helps to provide long-term high-quality daily flow observations data of Australian rivers for a broad range of users and researchers. In our next biennial upgrade of the Hydrologic Reference web portal, we will try and include the continental scale analysis within a common period as an important project activity.

For the second question in general comments: relating streamflow variability to large scale atmosphere/ocean patterns. We agree to this point. Though a thorough analysis of the relationship between streamflow and climate indices is out of scope of this study, we have added relevant literatures on climate, and include a discussion (see section 5.2 in the revised manuscript) to relate the flow changes with main climate indices. We illustrate the rainfall trend map for discussion. The figure below (Figure 1) gives an example showing an updated summary of long-term rainfall trends (1970-2015). Changes in precipitation or other climate variables impact on the rainfall-runoff process directly, and indirectly causing changes in flora, relief and soil erosion. The identified trend patterns in annual total streamflow are spatially consistent with trends in annual total rainfall as shown in this Figure, 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 intent of this paper is to quantify for the first time, trends in long-term streamflow data across pristine catchments using a consistent methodology. We examine the non-stationarity of the hydrologic response through a separate paper, currently under review (Ajami et al.; under review with HESS).

The figure below was not attached in the revised manuscript but the website link was provided.

Changes:

- Added references on climate change, non-stationarity, and text revised accordingly
- Added discussion in Section 5.2

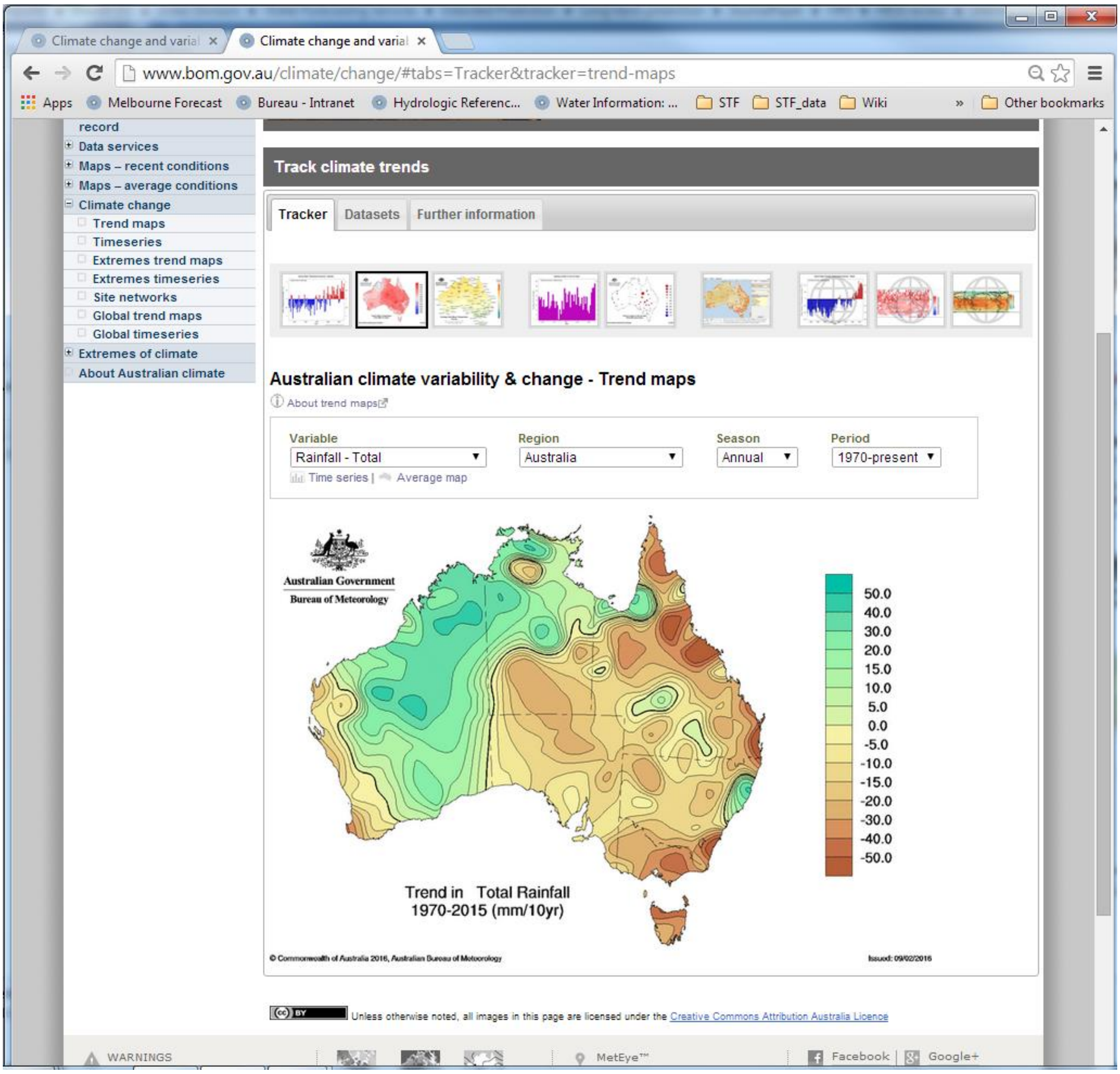

Figure 1: Trend in annual total rainfall in Australia 1970-2015.
(Source: http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=trend-maps)

Specific comments

Line 109, Was there a criteria for the Hydrologic Reference Stations for extensive basin water use or groundwater pumping? This could be hard to quantify, but is important, especially for low flows and in dry areas.

Answer

Yes, whether there is water use diversion or not, is important especially for low flow or dry areas. There was a criterion regarding this: line 109 "unregulated catchments with minimal land use change". 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. For more information on the station selection process and involvement of stakeholders in prioritising the stations list, users can refer to the HRS web site at http://www.bom.gov.au/water/hrs/guidelines.shtml .

Changes:

- Added explanation in section 2.1, line 113-115 (track-change version)

Line 109, Was any consideration given for catchments with substantial overlap in area (nested basins). Basins with substantial overlap would not offer independent information for an analysis.

Answer

Overlapping in area has been considered. We have checked all HRS stations thoroughly, only at a few locations there are nested sub-basins: 3 in Queensland, 2 in North Territory and 1 in New South Wales. 5 of them have less than 10% area overlapping (which can be considered as independent) and only 1 has 50%. The influence on overall analysis is negligible.

Line 133, It's stated that "the primary data used in this study" are from the HRS network. Does this mean that stations outside the HRS network were used? This is problematic, if this is the case for this analysis.

Answer

All data used are from the HRS network. We have edited this sentence by removing "primary", and have "all data used" instead.

Changes:

- Text changed in section 2.1, line 137 (track-change version)

Line 145, Could use more specifics on how well the model did for filling in data gaps; "perform well" is quite vague.

Answer

We agree and have specified the model performance in this part, with the statistics of NSE results: Median = 0.74; mean 0.72; STDEV =0.12

Changes:

- model performance specified in section 2.1, line 150-152 (track-change version)

Line 159, I don't recall any discussion of the data collection agency/agencies. Were they collected by the same agency? If not, do they meet the same standards for inclusion in the HRS? If not, how do you assure consistency across regions when analysing trends or variability? Have collection methods remained constant over time? This should be addressed. If not consistent over time, monotonic trends or step changes could be biased.

Answer

Water data is 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. This has now been addressed in the manuscript.

Changes:

- text added in section 2.1, line 173-181 (track-change version)

Line 173, Why isn't Qmin (for 1-day, 7-day or similar) analyzed? These low flows are typically important for water managers and ecological flows.

Answer

Thanks for suggesting that. Qmin was not included in the current work, but it's a good idea and will include it in our future work.

Line 186, Does the Median Crossing and Rank Difference test consider the possibility of long-term persistence? If not, an important type of autocorrelation is being ignored.

Answer

Yes these 2 tests (Median crossing & Rank difference) consider the long-term persistence as well (Kundzewicz and Robson, 2000). Autocorrelation checking was part of the randomness test, and therefore it was not missed in this analysis.

Changes:

- text added in section 2.3, line 212 (track-change version)

Line 192, it doesn't appear that consistent periods of record were used for the various trend/step change tests in the article. This limits the comparability of results between catchments. Please provide more information. Authors should consider doing tests for selected periods and only including sites with mostly complete data for those periods. Multiple periods could be used, such as a 30 year period up to the present and a 50 year period up to the present. I don't recall a mention of what the last water year in this analysis is. This is important.

Answer

The first part of this comment is addressed above in general comments. For the second question, the data used in this study are up to end of 2014, so the last water year is 2014. We have added this in the text accordingly.

Changes:

- text added in section 2.1, line 165 (track-change version)

Line 194, Why not use the non-parametric Sen slope instead of least squares regression. Regression is sensitive to non-normality and outliers. Skewed distributions and outliers were noted previously in the article.

Answer

Many thanks for this suggestion. We have followed the advice to apply the non-parametric Sen Slope instead of LSR, and update the results in Table 2. The results show not much different from the LSR method. The following are the references for non-parametric slope estimator: Sen, Pranab Kumar (1968, Journal of the American Statistical Association 63: 1379–1389), Theil, H. (1950), which was added to the paper.

Changes:

- Updated Table 2 using Sen Slope
- text revised accordingly in Section 2.3

Line 251, The first sentence that summarizes trends seems inconsistent with the second sentence. Please reword.

Answer

The two sentences of this paragraph are rephrased for clarity.

Changes:

- sentences rephrased in Section 4.1, line 280-283: "Patterns of trends were noted in different flow regimes. Moving through the flow variables from low (Q10), to median (Q50), to high (Q90), and onto maximum (Qmax), an increasing number of stations were found with no trends, combined with decreasing number for non-random series. "

Line 261, I think of trends as being one type of non-stationarity.

Answer

We agree that trend or step change is one type of non-stationarity. Text is reworded in such a way that trend and step-change come under 'non-stationarity'.

Changes:

- text revised accordingly in Section 4.2, line 296-300 (track-change version)
- references on non-stationarity added

Line 261, Not clear what this paragraph is getting at, suggest expanding or contracting it.

Answer

We tried to address the question broadly, what could be the reasons behind the observed flow changes, as an introducing paragraph for the following sections of trend and step changes. This paragraph has been rephrased accordingly.

Changes:

- text revised in Section 4.2, line 300-308 (track-change version)

Line 267, Need quick summary of trend methods.

Answer

A quick summary of trend methods was added here, to support the results statement.

Changes:

- summary of trend methods was added in Section 4.2.1, line 311-317 (track-change version)

Line 271, Suggest rewording, this statement seems incorrect. All stations showing significant trends are in the south (depending on how you define south) and all increasing trends are in the north.

Answer

We have reworded the sentence.

Changes:

- statement reworded in Section 4.2.1, line 320-323 (track-change version)

Line 274. Why not test the importance of the last decade on trends? This could be done by repeating analyses but removing the last decade. This would be easy or hard, depending on how automated the trend testing is.

Answer

This will be interesting to look at, but it is not within the scope of the present paper. We would prefer to keep the current trend testing results, and put the suggestion as future research work.

Line 275, Need Murray-Darling labeled on the figures and also the major regions of Australia (boundaries already in place for the major regions) for readers not from Australia.

Answer

Figures have been modified.

Changes:

- Figure 1 was modified with drainage division basin names (green colour font matching the colour of drainage division borders) labelled on the map
- Figure 5 was modified with Australian state names (grey colour font matching the colour of Australian state borders) labelled on the map

Line 280, Did you do trends in baseflow or baseflow index? The former is described in the methods and the latter is labeled in Table 2. The interpretation of these is obviously different.

Answer

Thank you for pointing out this. The trend test was applied to baseflow, not baseflow index. In Table 2, baseflow index was listed there (calculated by the ratio of baseflow to total flow), and the trend results of baseflow was indicated at the top right corner.

Changes:

- Clarification added in Section 4.2.1, line 332-333 (track-change version)

Line 302, Why aren't the numerous step change decreases from the 1970s in southeastern Australia (Figure 6) mentioned?

Answer

Discussion is added, in section 4, sub-section about "step change", to address the step change decreases from the 1970s in south-eastern Australia.

Changes:

- Text added in Section 4.2.2, line 360-362 (track-change version)

Line 306, Rainfall changes, whether they are monotonic trends or step changes would force streamflow changes. Please clarify.

Answer

More discussions were added here for relating rainfall changes with flow trends, as addressed above in general comments.

Changes:

- Discussion added in Section 5.2

Line 307, Please state what percentage of sites in different regions had significant Mann-Kendall trends, step changes, or both, and comment on whether, for the latter, this implies that Mann-Kendall significant trends were due to step changes.

Answer

We have added a quick summary of result statistics for trends and step changes for different regions.

Changes:

- result statistics for different regions added in Section 4.2.2, line 371-383 (track-change version)
- A new figure was added for this statistics summary, as Figure 7. Numbering of other figures was changed accordingly.

Line 329, Why mention only winter trends for southern Australia, all seasons seem to have significant downward trends, with autumn having fewer than the others. Please clarify.

Answer

Clarification was added here to cover more aspects of seasonal changes.

Changes:

- Sentence reworded in Section 4.2.2, line 402-406 (track-change version)

Line 358, Specify what parts of Australia these are here for non-Australians (to avoid people having to look for this earlier in the article).

Answer

Texts were revised to specify what parts of Australia. Also Figure 1 and 5 were modified with the basin code, to make it more clear where the discussion is about (it's addressed above in Line 275 question).

Changes:

- Text revised in Section 5.1 (track-change version)
- Figure 1 and 5 labelled with drainage basin name and Australian state name

Line 361, Rainfall deficiency "observed all over the continent" is not consistent with streamflow increases in the north.

Answer

This sentence was rephrased accordingly.

Changes:

- Text revised in Section 5.2, line 485-486 (track-change version)

Line 362, The accuracy of the statement on drought conditions depends on what type of drought you're referring to (meteorological, hydrological, soil moisture, etc.).

Answer

Accuracy of statement on drought was added, with referring to literature on the severe drought in southeast Australia 1997-2009 (SEACI, 2011, The Millennium Drought and 2010/11 Floods; Ummenhofer et.al, 2009).

Changes:

- Text revised in Section 5.2, line 486-489 (track-change version)

Line 368, need reference after "decade."

Answer

Reference was added: decade means for the years 1997–2009 inclusive. SEACI, 2011, The Millennium Drought and 2010/11 Floods, http://www.seaci.org/publications/documents/SEACI-2Reports/SEACI2_Factsheet2of4_WEB_110714.pdf.

Changes:

- Literature added in References

Line 370. It would be very useful, in helping to interpret trends (especially with the large number of step changes) to look at the relation between streamflow statistics and major atmosphere/ocean patterns. A thorough analysis I can understand being beyond the scope of the article, but a first cut I think is reasonable and important. For example, you could correlate the interannual variability of streamflow statistics to major atmosphere/ocean indices. I'm not familiar with which ones are important for Australia, but ones that are known or suspected to be important to rainfall or streamflows could be tested. These could be relatively easy and may provide valuable information for interpreting the step changes. The discussion could also focus on the timing of known changes (what year) for indices that are important to Australian hydrology and compare those to the years that catchments showed step changes.

Answer

This is already addressed above in general comments, more discussion were added for this point.

Changes:

- Literatures on climate indices/changes added in References and discussion added in Section 5.2

Line 396, It seems like the text describing trends for different regions doesn't match Figure 5. Rather than "Northern Territory and north-west of Western Australia, shouldn't it be "northern part of Northern Territory"? There's only one weak trend in northern Western Australia.

Answer

We have modified the text to be more specifically describing the locations.

Changes:

- Text revised in Section 6, line 521-531 (track-change version)

Line 401, Catchments in the southeast of S. Australia have significant downward trends in Figure 5.

Answer

We have included it in the text.

Changes:

- Text revised in Section 6, line 521-531 (track-change version)

Line 413, Both areas have a mix of step changes in the 1990s and 1970s in Figure 6.
General comment on figures: the trend symbols are too small in Figures 5-8.
Technical corrections and typos

Answer

We have added this comment in the paragraph, and improve the figure quality (enlarge the symbol, size of graph, and improve the resolution).

Changes:

- Text revised in Section 6, line 543-548 (track-change version)
- Figure 5-9, picture quality improved, with larger size of symbols

Line 396, incorrect figure reference.

Answer

It's been corrected as "Figure 1". Thanks for pointing it out.

Changes:

- corrected in Section 6, line 521 (track-change version)

Figure 5 caption, change "decrease" to "decreasing"

Answer

We have changed the caption accordingly.

Changes:

- Corrected in Figure 5 caption

Thank you again for your valuable comments!

2. Authors' response and changes to Referee #2

(Anonymous Referee #2, Received and published: 29 April 2016; Editor's decision to compile all the changes and upload the revised manuscript, received 30 June 2016)

General comments

The overall impression of this paper is that it is very clear, well-structured and interesting. The topic of temporal hydrologic change is highly relevant, and the quantitative data analysis of 222 stream gauges is comprehensive and previously unprecedented.
The paper presents a neat compilation of a large quantity of data and addresses relevant scientific questions within the scope of HESS – both regarding the issues of temporal hydrologic change, but also the central question regarding aggregation, compilation and presentation of large data quantities (daily discharge values for 222 stations for 45 years).
The presentation of the HRS web portal great! This is a valuable resource, which will be of great use for the international hydrological community. A paper such as "How streamflow has changed across Australia::" will (apart from its research significance in other ways) have an additional value of helping more researches find the publicly available Australian discharge data.
The paper is written in a clear, concise and straightforward manner, answering most questions that arise. The title clearly reflects the contents of the paper. The language is (as far as I can judge) fluent and correct, the paper is generally very readable. The mathematical formulae, symbols, abbreviations, and units correctly are correctly defined and used. The length of the paper is exemplary short, but still comprehensive enough.
The abstract provides a concise and complete summary, although I'm slightly confused about the expression 'living gauges'.

The scientific methods and assumptions are valid and clearly outlined, allowing reproduction (and traceability of results, as all data and used equations are publicly accessible).
The statistical methods are thoroughly explained, and the decision to have these equations in an appendix is wise. The amount and quality of supplementary material is considered appropriate, and the figures and tables are generally in good shape, and are referred to accordingly.
In general, the number and quality of references seems appropriate for the topic, even though I think that a few more references regarding climate change could have been provided. Especially, I miss a reference to the most recent IPCC which would be of value here.
The scientific approach and the applied methods are valid and the results are to be sufficient to support the interpretations, and the substantial conclusions that are reached.

Answer
The authors would like to thank the referee for those positive evaluations of the manuscript and our work; and for the insightful comments on the data and method.
For the first question in general comments about 'living gauges': we have avoided using the expression 'living gauges', and specify its meaning more clearly to avoid confusion (it was changed to "critically important gauges", at line 29 and line 93).
For the second question in general comments, we have added a few more references regarding climate change, including:
(1) CSIRO and Bureau of Meteorology (2015) *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report.* CSIRO and Bureau of Meteorology, Australia 222pp. http://www.climatechangeinaustralia.gov.au/
(2) Bureau of Meteorology (2016) Annual Climate Report 2015
http://www.bom.gov.au/climate/annual_sum/2015/Annual-Climate-Report-2015-LR.pdf

Changes:

- expression ‘living gauges’ was removed, text revised in Abstract, line 30; and in Section 1, line 96 (track-change version)
- a recent IPCC report added in References and in text

Specific comments

My primary concern regards the limited reasoning regarding how the temporal change in streamflow is interrelated to a temporal change in precipitation.
The authors mention clearly that this is not within the scope of the study – which of course is fine. However, the dry period in the last decade in the south-eastern and south-western region is mentioned as a cause of some of the general downward trend.
Although a thorough analysis is of course not viable within the scope of this paper, it would be nice to (if possible) have some discussion regarding the likeliness of this downward trend only being a consequence of the rainfall during a few dry years, or if the trend is likely to be consistent in the longer time perspective. Looking at table 2, at the years of the step change – 1996 is clearly the most dominating year (13 of 22!): an added reflection regarding the impacts of this (probably very non-normal) hydrological year would be interesting. How much impact does this “outlier year” have on the temporal trend? Would the same general pattern be seen even if it was to be omitted from the analysis? I do not request you to do the complete analysis of this issue, but some kind of (further) discussion on the topic could be useful.

Answer

Many thanks for the suggestion. We agree that this ought to be discussed. Though a thorough analysis is out of scope of this paper, we have added relevant literatures on climate (as mentioned above), and included discussion on relating the flow changes with rainfall, and more discussion on the finding of large numbers of 1996 step changes in southeast Australia linking to the millennium drought (SEACI, 2011, The Millennium Drought and 2010/11 Floods, http://www.seaci.org/publications/documents/SEACI-2Reports/SEACI2_Factsheet2of4_WEB_110714.pdf).

Changes:

- discussion added on linking flow and rain trend, see Section 5.2
- more literature on climate added

Also, I believe that most data is available from the 1950’s and onwards. However, I guess that longer time series should be available at least for some gauges. A comparison regarding an even more long-term time series would give additional weight to the results – although, this may be the subject of another study.

Answer

Yes, there are some stations which have longer time series but not many. More long-term time series will certainly give additional weight to the results, as you said, it will be an interesting point to be added for future study.

Line 152 – please also add the median time-series length.

Answer

The median time-series length (46.6 years) was added in this part.

Changes:

- median time-series length added in Section 2.1, line 168

Lines 206-208 – is any of this presented here? Or mainly as background info to the tables/figures?

Answer
These statistical data analyses in lines 204-208 were only mentioned here as background information for all types of graphic products in HRS web portal. For more details of other statistical data analyses that's not presented in this study, please check the information at the HRS website: http://www.bom.gov.au/water/hrs/

Line 262 – shouldn't also land-use changes be mentioned in this context?
Answer
Thanks for pointing it out. We have added discussion on land use changes in this context.
Changes:
- text added in Section 4.2, line 300-301

One last comment: the fact that different hydrologic years are used for different stations (if I understand it correct) – will this have an impact on the results (lines 149-151)?
Answer
A quick answer to this is "No, not much impact on the results".
Water year or hydrologic year was used in this study, but it's not different for every station. Table 1 has listed the water year start month for each division, and they are in a more consistent way: for regions in the south part of Australia, water year starts at March or February; for regions in the north and central Australia, it starts at September or October. In this way, the analyses were more following the natural hydrologic pattern, and representing the results in a better way.

Technical corrections
There are hardly any technical corrections that need to be addressed in the paper. The authors have made a robust study, and compiled the data in a presentable and concise manner.
I am however not clear about what the authors mean by the concept of 'living gauges', neither in the abstract nor in the text (lines 29 and 93) – don't just normal gauges record and detect changes in hydrologic responses?
Answer
This has been addressed in the general comments above.

As not being very familiar with Australian geography, I would have appreciated (if possible to do in an aesthetic manner) information regarding the names of the basins in figure 1 – perhaps by inserting the roman numerals from table 1 on the map?
Answer
We have modified Figure 1 in this way, by inserting the basin code for each region, and readers can refer the basin names to Table1.
Changes:
- Figure 1 was modified with drainage division basin names (green colour font matching the colour of drainage division borders) labelled on the map
- Figure 5 was modified with Australian state names (grey colour font matching the colour of Australian state borders) labelled on the map

Also, table 2 seems to be of somewhat low resolution (the letters are blurry) – if possible, please improve this.
Answer
We have improved the quality of Table 2. Table 2 in the submitted manuscript was actually a graph (that's why the letters look blurry), as we had difficulties to inset the text table in a landscape layout. We have updated it in the revised version.
Changes:

- Table 2, content updated and quality improved. We will upload the original Word file of Table 2 as a separate file

Figure 5 (and 6 and 8), please add Q_(appropriate index) in the text for clarity.
Thanks for a good read, and congratulations on your thorough study! I’m looking forward to seeing more of this paper in the future!

Answer

We have added Q_(appropriate index) in the figures, for readers could easily refer to.

Changes:

- Figure 5,6,8,9, Q_(appropriate index) was specified in figures and figure captions

3. Authors' response and changes to Short comments from M. Hipsey

(Short comments from M. Hipsey, matt.hipsey@uwa.edu.au; Received and published: 16 March 2016; Editor's decision to compile all the changes and upload the revised manuscript, received 30 June 2016)

Thank you for your time to review our manuscript. You have mentioned valuable points, which we really appreciate. Please find our response below to your comments, questions and suggestions. The referee's comments are first recalled in *italics, blue colour font*, and then followed by our **answer** and **changes**.

As an Australian, I have read the submission with great interest and was pleased to see the analysis undertaken. I highlight the substantial amount of work that has gone into curating and making sense of such a large dataset at this scale. This is important progress and important not only for scientific purposes but for shaping policy in Australia.
I would like to make a few short suggestions that could be considered during the discussion/revision process.
I think there are some problems with the section headings. Aside from the fact the sub-sub-heading is larger font than the sub-heading; I also note that section 4 is "Results and Discussion" and section 5 is "Discussion" ... There is also a Section 6 with "Conclusions". I suggest these 3 sections and their sub-headings could be carefully looked at, and would suggest splitting results and discussion into separate sections, with sub-headings used in the discussion to help navigate the reader to the significant findings.

Answer

Thank you for noticing this and helpful suggestions to improve the structure of manuscript. We will adjust all the headings at different levels in a systematic way to reflect the hierarchy structure clearly. Also the section or sub-section titles will be modified.

Changes:

- All headings format adjusted
- Sections and sub-sections re-arranged, with Section 4 – Results, Section 5 – Discussion, Section 6 – Conclusion, and sub-sections to help navigate the reader to different discussion points

Further from the above, the aim as stated at the end of the introduction is to provide a nationwide assessment of trends in streamflow which is achieved well. Of course one of the powers of compiling the dataset is to the try tease out the science of why trends are occurring and it would be nice to see this as an aim. I notice a brief paragraph on this point (Page 13) highlighting general drying trend in the climate etc, but I felt the study would become much more powerful if there was a more significant attempt to explain the non-stationary behaviour. This could range from a quantitative assessment of changes in the rainfall-runoff coefficient (is the streamflow change amplifying or dampening the broad rainfall trends in each region?) or at a minimum could consist of a more detailed and focused discussion on Page 13 introducing and citing previous studies explaining mechanisms for the trends. For example, Smettem et al 2013 undertook an analysis on the forest response to drying trend impacts streamflow; Ummenhofer et al., 2009 on mechanisms for increasing drought; there are obviously many more papers relevant to different regions that could help readers understand the mechanism and significance of the trend. It is stated as being beyond the scope (in ln376), however, I would suspect it would be of key interest to the HESS readership and I would suggest that space could be made by moving section 3 and Figure 3 to an Appendix; in fact I would encourage the authors to refocus the aims on the hydrological trends AND their explanations, rather than the focus on the web portal itself.

Answer

We agree to this point. Though a thorough investigation of reasons behind the hydrological trends is beyond scope of this article, we added relevant literatures on past climate changes, non-stationarity in streamflow Australia (including the papers you mentioned - Smettem et al 2013; Ummenhofer et al., 2009), and extend the discussion accordingly, also to relate the flow changes with rainfall.

About section 3 on web portal development, it provides important information for key users of this study. It will be kept in the main text however we will make it concise.

Changes:

- discussion added on linking flow and rain trend, see Section 5.2
- literatures added in References, including the above mentioned ones

Lastly, whilst it is related to the above, it would be ideal for the discussion to cover the projections of climate change for the different regions to address the question of whether the past changes are likely to continue, and as justification for the ongoing monitoring and assessment at the nation-wide scale. This need not be an extensive addition, just some targeted references cited for interested readers, potentially within a dedicated sub-section in the discussion.

Thank you very much for the opportunity to comment on this great study, and I do hope these comments will be seen as constructive criticisms to help improve the overall paper and usefulness of the analysis.

Answer

This study is focused on the flow changes that we observed from the historical data records, and not trying to refer it to the future. From the sustainable yield study done by CSIRO (http://www.csiro.au/en/Research/LWF/Areas/Water-resources/Assessing-water-resources/Sustainable-yields), It is likely that rainfall/streamflow trends in the Murray-Darling Basin, southern Australia and south-west Western Australia is likely to continue.

The suggestion you raised here will be an interesting point to look at, but unfortunately it's out of scope of this paper. We added relevant literatures on past climate changes (as mentioned above), and included discussion on relating the flow changes with rainfall trend, which we hope will provide some useful information for readers to understand and interpret the trends and step changes presented.

Thanks again for your valuable comments!

Here below attached a marked-up manuscript with track changes.

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 ~~observed in~~retained within the northern part of ~~Northern Territory and the north-west of Western Australia~~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 ~~'living~~ 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 literatures on hydrological trend studies 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~~ing~~ 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 ~~(Cleugh et al., 2011)~~ 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 (~~Turner et al., 2012;~~ 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 ~~'living~~ 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~~hydroclimatic regions provides data for a comprehensive investigation of long-term streamflow variability across Australia.

All ~~The primary~~ 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 eastern coasts. 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. ~~Some~~ 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)~~,~~. ~~Which~~ 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~~ with varying lengths of record depending on~~ using the full length of ~~the data availability~~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 ~~an average~~mean time-series length of ~~45~~ 48 years and median time-series length of 46.6 years. The longest record length was ~~62~~ 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 ~~mean~~ median size of ~~3108~~ 328.6 km^2. The majority (~~82~~80%) of the stations had an upstream drainage area less than ~~1000~~ 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 ~~of each year~~ (Q_{Max}), the 90th percentile (non-exceedance probability) daily flow ~~of each year~~ (Q_{90}), the 50th percentile daily flow ~~of each year~~ (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 total 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 ~~from~~by the ~~a least squares regression (LSR)~~ 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 ~~[trend (mm/yr) /~~Sen Slope coefficient to average annual flow ~~(mm)]~~ in order to make the change comparable across stations for reporting purposes ~~by dividing the regression slope coefficient by the average annual flow over the data period~~.

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 ~~on~~ 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 ~~and discussion~~

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 ~~are~~ were examined. ~~Finally, regional patterns in long term trends, inter-annual and decadal variability are further investigated for two feature stations.~~

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. ~~A distinction was noted between patterns of trends in the different flow regimes. Moving through the flow variables from low, to median, to high, and onto maximum, an increasing number of stations were found with no trends.~~ 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~~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 ~~most variables~~the four seasons. Summer flow at ~~had~~ a large number of stations showed ~~with~~ no trend and 3 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 the trend test in this present study is to determine if the values of a series have a general increase or decrease in the observation time period. Detecting the ~~trend and non-stationarity~~trends in a hydrologic time series may help us to understand the possible links ~~between~~ among hydrological processes, anthropogenic influences and global environment changes. Many ~~hydrological~~ of the streamflow time series in this dataset exhibit trends or step-changes in the mean or median~~non-stationarity in the mean or median.~~. ~~The long-term gradual change in rainfall-runoff transformations could be represented by linear trend. The abrupt changes in a hydrologic time series could be due to hydrologic non-stationarity.~~ 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 (Chiew & Siriwardena, 2005) 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 ~~about 35% of the~~ stations showing decreasing trends (35% of stations) are in the southern part of Australia and all stations showing~~4%~~ 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, see Table 2. All sites showed consistent direction of change using MK test and ~~LSR~~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.

~~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. Table 2 gives the Rank-Sum test results and lists the year of change for the 22 stations. Details of step changes across Australia will be discussed in the following section.~~

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 various decades, 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 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 el. al (2009) where the most severe drought 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 outside that defined region exhibited step changes with mixed years of changes, including 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 ~~on the south east coast of Queensland~~in the Northern Territory and some in the northeast coast of Queensland showed a significant increasing step change~~ in the 1980s~~.

~~The results from step change analyse imply that changes in streamflow and the consequent hydrologic response are driven by changes in climatic forcing such as rainfall over the period of record. Investigating this causative relationship and quantifying the relative impacts of variations in climate on streamflow predictions is left for future work.~~

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 ~~7~~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 are notable for the number stations with non-random time-series and therefore an invalid MK test result, this can be seen most dramatically in Figure ~~7~~8d, and is 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 ~~7~~8a).

The spatial distribution of trends in seasonal flows was investigated ~~the seasonally~~to disaggregate~~d~~ total flow series into seasons ~~were investigated~~ (Figure ~~8~~9). The broad pattern from the analysis ~~is~~ was a collection of downward trends generally in the south and upward trends in the north across the seasonal variables~~;~~: summer (Q_{DJF}), autumn (Q_{MAM}), winter (Q_{JJA}), and spring (Q_{SON}). ~~However, contrasting Figure 5 and Figure 8 suggest that the trends detected in the annual total flows series~~All seasons presented ~~are~~ ~~predominantly a mixed~~

~~result of increasing summer~~significant downward trends predominantly in ~~northern~~ the southern parts of Australia, ~~and decreasing winter trends for southern Australia~~with autumn having fewer than others.

5. Discussion

We have demonstrated a~~A~~ comprehensive statistical and trend analysis in long-term streamflow data ~~was conducted~~ 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, whilest 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 by both studies. The streamflow data of Yarragil Brook at Yarragil Formation (614044) 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 changes, globally, regional and locally, 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 ~~all over the continent~~ as shown in the recent CSIRO sustainable yield study projects (CSIRO, 201~~3~~5). Drought conditions, the most persistent rainfall deficit since the start of the 20^{th} 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~~Figure 2~~). As a short summary of the trend test results in annual streamflow (Q_T) over the continent, ~~In~~ ~~Northern Territory and north-west of Western Australia, there was an~~most of the increasing trends were observed in northern part of Northern Territory, ~~annual streamflow (Q_T)~~ while there was ~~no significant trend~~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 ~~South~~

~~Australia and South Tasmania,~~ 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 totals ($Q_{JJA,}$ $Q_{SON,}$ 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 totals and also across different hydro-climatic regions. Most of Northern Territory and central Australia showed increasing trend in summer (Q_{DJF}) flow while no stations were found with increasing trend for winter flow ($Q_{JJA,}$) anywhere in Australia.

- The analysis of step changes revealed definite regional patterns: ~~stations in southeast Australia were characterised with step changes in the mid-1990s, while a key feature of a 1975 step change was identified for stations in south-west West Australia.~~ 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 unlike other studies, they are 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:

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

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:

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

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 nonparametric 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:

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

Z is approximately normally distributed.

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Table 1: Metadata of the drainage divisions and selected 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

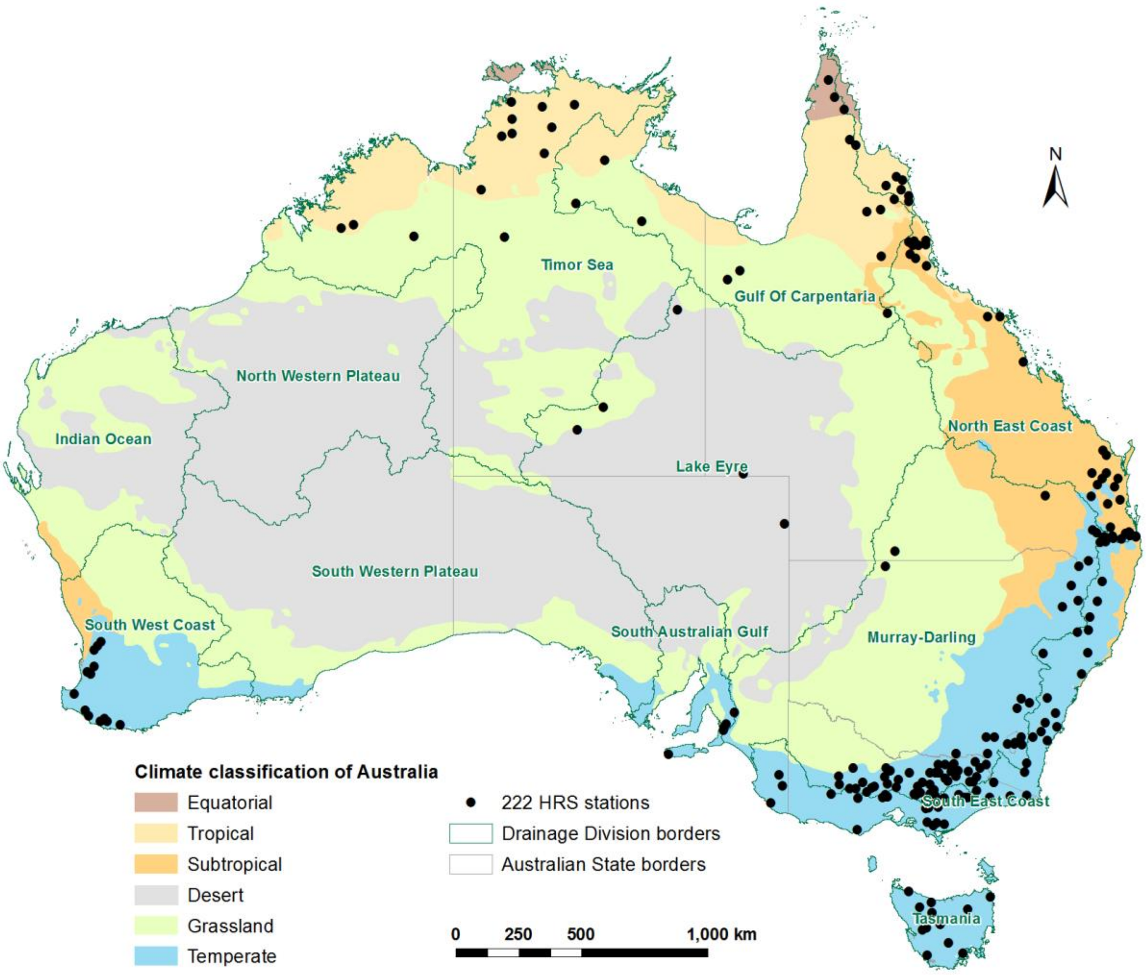
Div	State	Basin	Station ID	Site name	Area (km^2)	Data series Start year	time End year	Ave. annual flow (GL/yr)	BF index	Trend MK	Trend Sen Slp	Step change RS	Step change year
II	VIC	Snowy River	222206	Buchan River at Buchan	850	1951	2014	140.0	0.45--	**, ↓	-1.2%	**	1976
	VIC	Mitchell-Thomson Rivers	223202	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

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 (km^2)	Data time series Start year	End year	Ave. annual flow (GL/yr)	BF index	Trend MK	LSR	Step change Rank-Sum	year
II	VIC	Snowy River	222206	Buchan River at Buchan	850	1951	2014	140.0	0.45^{-}	**, ↓	-1.5%	**	1976
	VIC	Mitchell-Thomson Rivers	223202	Tambo River at Swifts Creek	899	1951	2014	77.1	0.46^{-}	**, ↓	-1.8%	**	1978
	VIC	Werribee River	231213	Lerderderg River at Sardine Creek O'brien Crossing	152	1959	2014	25.9	0.34^{-}	**, ↓	-1.9%	**	1996
	VIC	Hopkins River	236213	Mount Emu Creek at Mena Park	448	1974	2014	13.6	0.18^{-}	**, ↓	-3.5%	**	1996
	VIC	Glenelg River	238208	Jimmy Creek at Jimmy Creek	23	1951	2014	3.4	0.47$^{**,\downarrow}$	**, ↓	-1.8%	**	1996
	SA	Millicent Coast	A2390519	Mosquito Creek at Struan	1550	1971	2014	21.7	0.25^{-}	**, ↓	-3.2%	**	1992
	SA	Millicent Coast	A2390523	Stony Creek at Woakwine Range	485	1973	2014	4.8	0.55$^{**,\downarrow}$	**, ↓	-2.9%	**	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$^{**,\downarrow}$	**, ↓	-1.6%	**	1996
	VIC	Kiewa River	402217	Flaggy Creek at Myrtleford Road Bridge	26	1970	2010	4.0	0.42$^{**,\downarrow}$	**, ↓	-2.5%	**	1996
	VIC	Goulburn	405238	Mollison Creek at Pyalong	164	1972	2014	19.5	0.29^{-}	**, ↓	-3.5%	**	1996
	VIC	Goulburn	405248	Major Creek at Graytown	288	1971	2014	13.2	0.10$^{**,\downarrow}$	**, ↓	-4.2%	**	1996
	VIC	Goulburn	405251	Brankeet Creek at Ancona	122	1973	2014	14.8	0.45^{-}	**, ↓	-2.2%	**	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$^{**,\downarrow}$	**, ↓	-2.1%	**	1996
	VIC	Loddon River	407230	Joyces Creek at Strathlea	156	1973	2014	9.2	0.17^{-}	**, ↓	-3.0%	**	1996
	NSW	Lachlan	412028	Abercrombie River at Abercrombie	2631	1951	2014	277.0	0.30^{-}	**, ↓	-2.0%	**	1978
	NSW	Lachlan	412066	Abercrombie River at Hadley No.2	1630	1960	2014	169.8	0.29^{-}	**, ↓	-2.1%	**	1978
	VIC	Avon	415226	Richarson River at Carrs Plains	125	1971	2014	3.7	0.04$^{**,\downarrow}$	**, ↓	-4.3%	**	1996
	VIC	Wimmera	415237	Concongella Creek at Stawell	244	1976	2014	9.1	0.12$^{**,\downarrow}$	**, ↓	-4.6%	**	1996
VI	WA	Murray River (WA)	613002	Harvey River at Dingo Road	148	1970	2014	29.7	0.58^{-}	**, ↓	-1.8%	**	1993
	WA	Swan Coast	616065	Canning River at Glen Eagle	537	1953	2014	18.9	0.36$^{**,\downarrow}$	**, ↓	-2.7%	**	1975

* Significant at $p < 0.05$ ** Significant at $p < 0.01$
$^{-}$ baseflow series non-random ^{o} baseflow no trend
↓ decrease trend ↑ increase trend


N
Timor Sea
Gulf Of Carpentaria
North Western Plateau
Indian Ocean
North East Coast
Lake Eyre
South Western Plateau
South West Coast
South Australian Gulf
Murray-Darling
South East Coast
Tasmania
Climate classification of Australia
Equatorial
Tropical
Subtropical
Desert
Grassland
Temperate
222 HRS stations
Drainage Division borders
Australian State borders
0 250 500 1,000 km

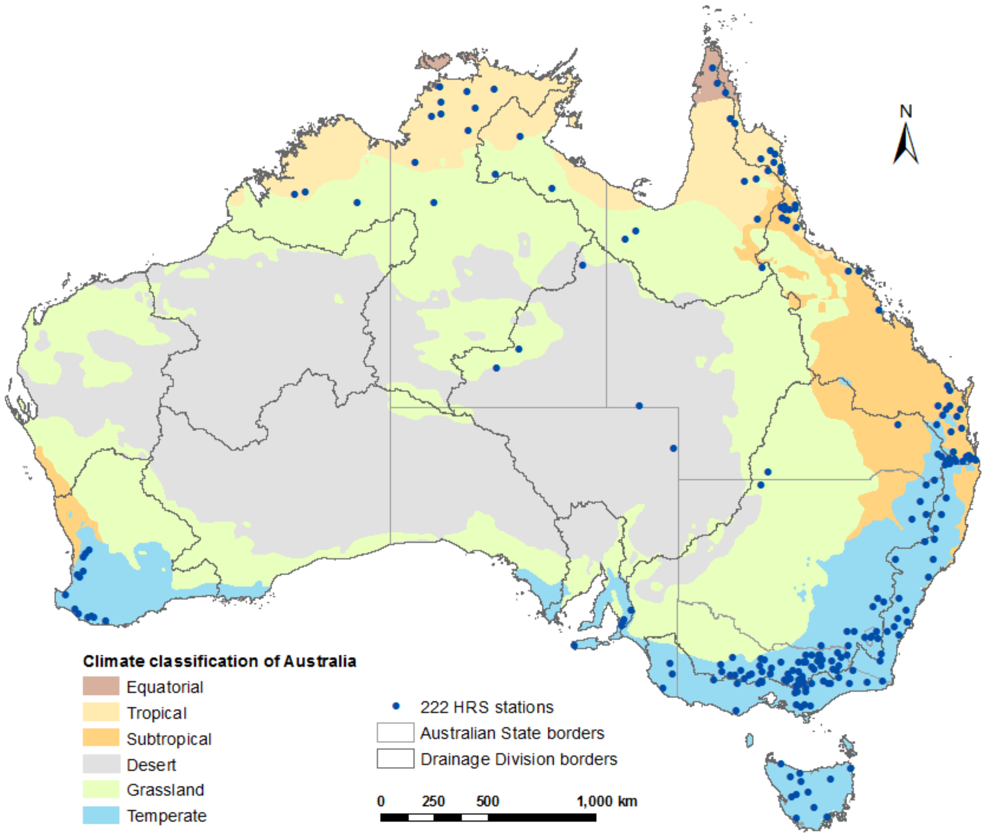


Figure 1: Location of the 222 high quality streamflow reference stations, the climatic regions and Australia drainage divisions (Geofabric Surface Hydrology Catchments, Geofabric V2.1, BOM 2012)

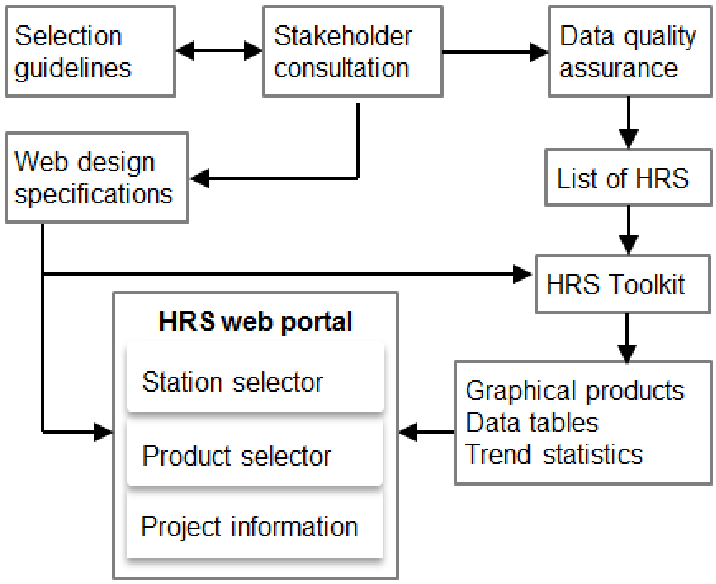


Figure 2: Framework of developing Hydrologic Reference Stations

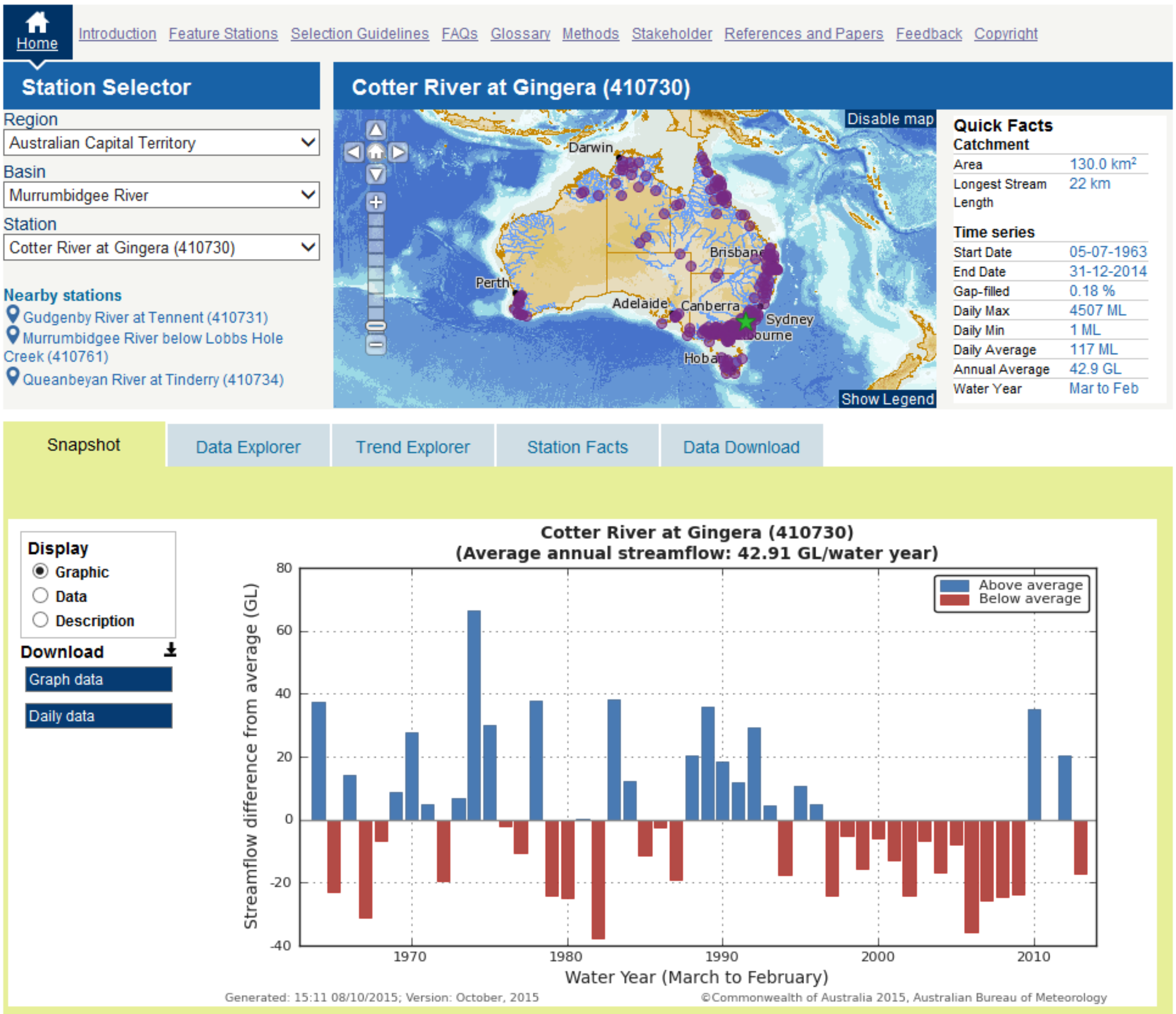


Figure 3: Snapshot of the HRS web portal

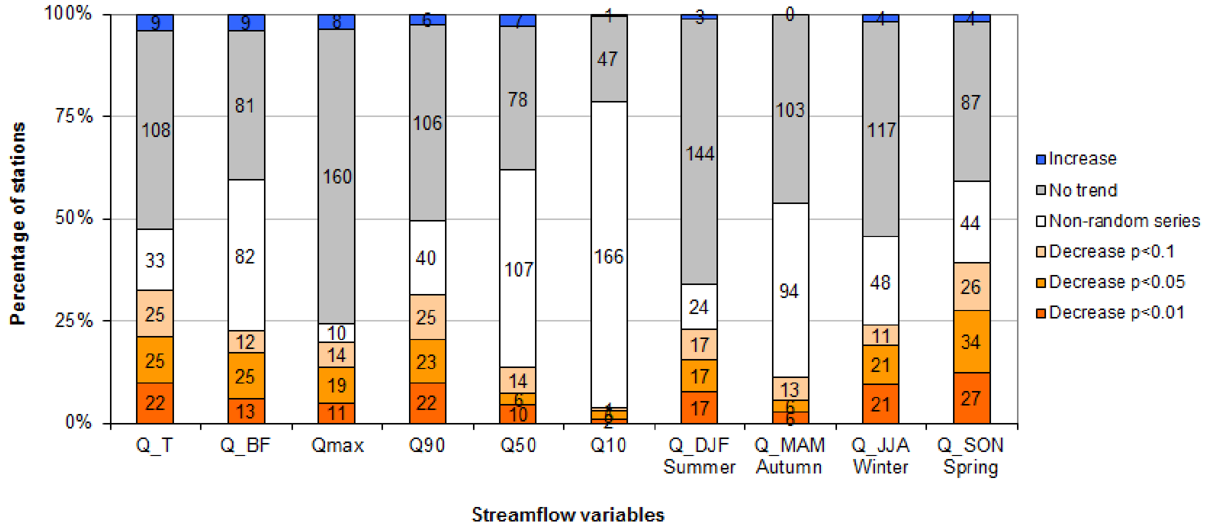
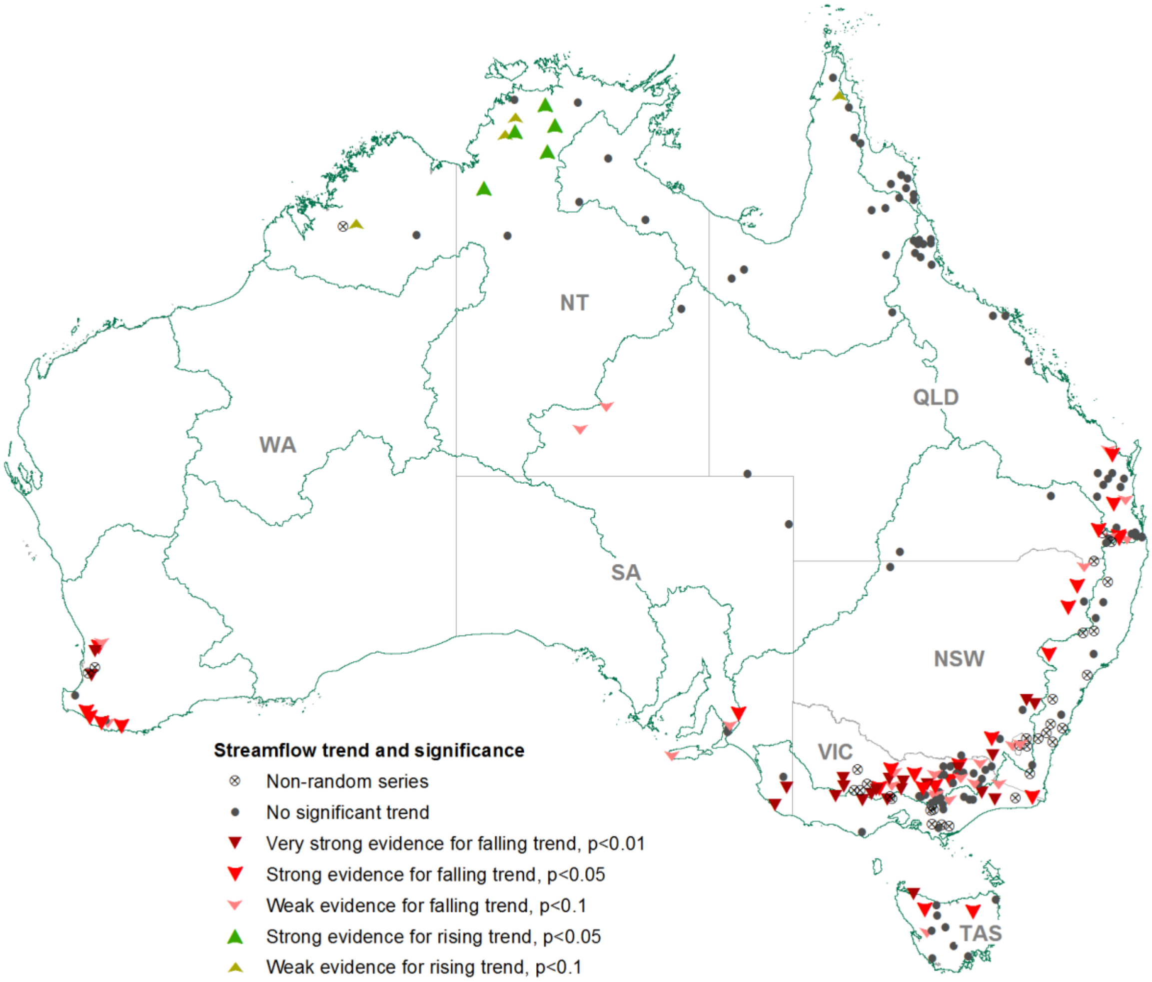


Figure 4: Stacked bar-plot summarizing the MK trend test results for the 222 HRS stations, with data labels showing the number of stations in each category (Q_T: annual total flow, Q_BF: annual baseflow, Qmax: daily maximum flow, Q90: 90th percentile daily flow, Q50: 50th percentile daily flow,Q10: 10th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


NT
WA
QLD
SA
NSW
VIC
TAS
Streamflow trend and significance
Non-random series
No significant trend
Very strong evidence for falling trend, p<0.01
Strong evidence for falling trend, p<0.05
Weak evidence for falling trend, p<0.1
Strong evidence for rising trend, p<0.05
Weak evidence for rising trend, p<0.1

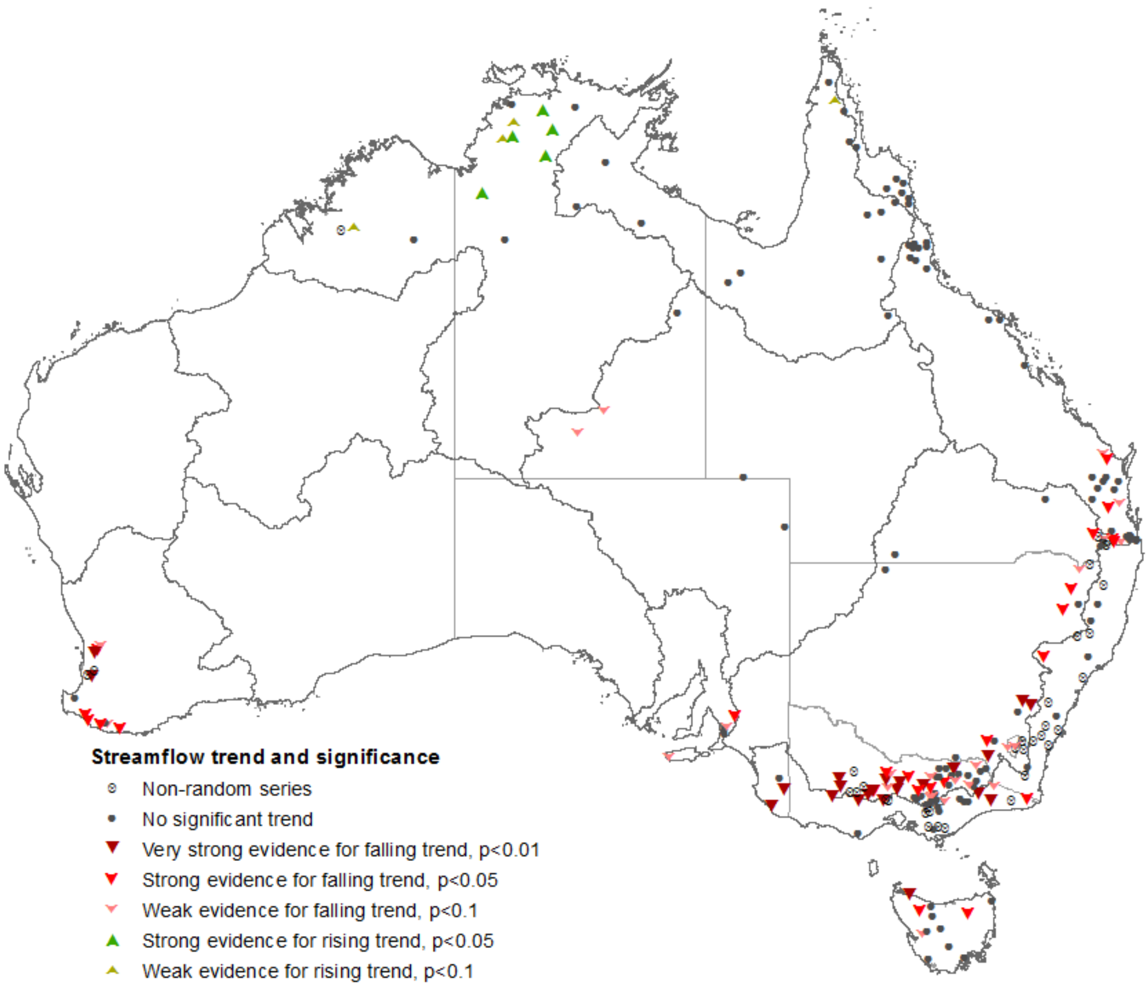
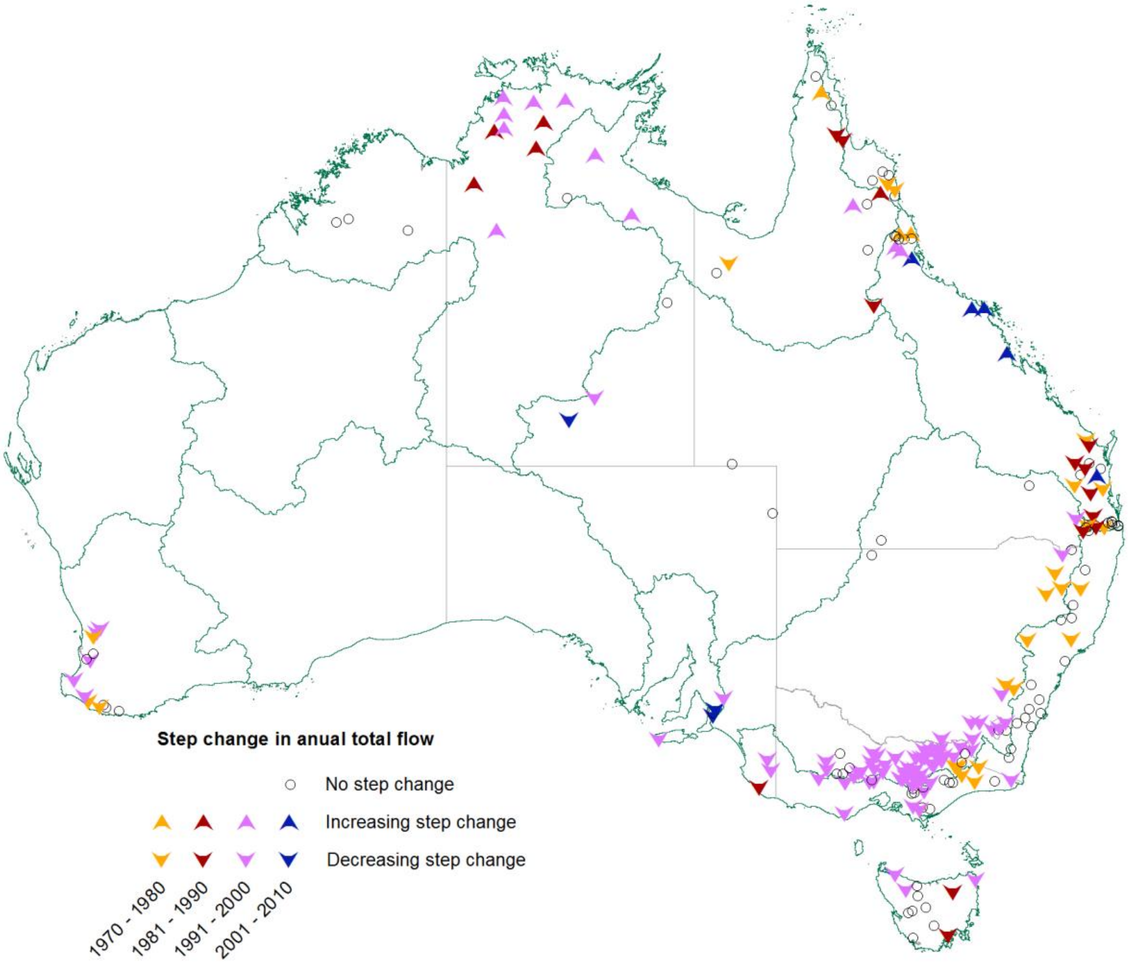


Figure 5: Spatial variation in trend results of annual total flow((Q_T), decreasinge trends were shown in significance levels at 0.01, 0.05, and 0.1


Step change in anual total flow
No step change
Increasing step change
Decreasing step change
1970 - 1980
1981 - 1990
1991 - 2000
2001 - 2010

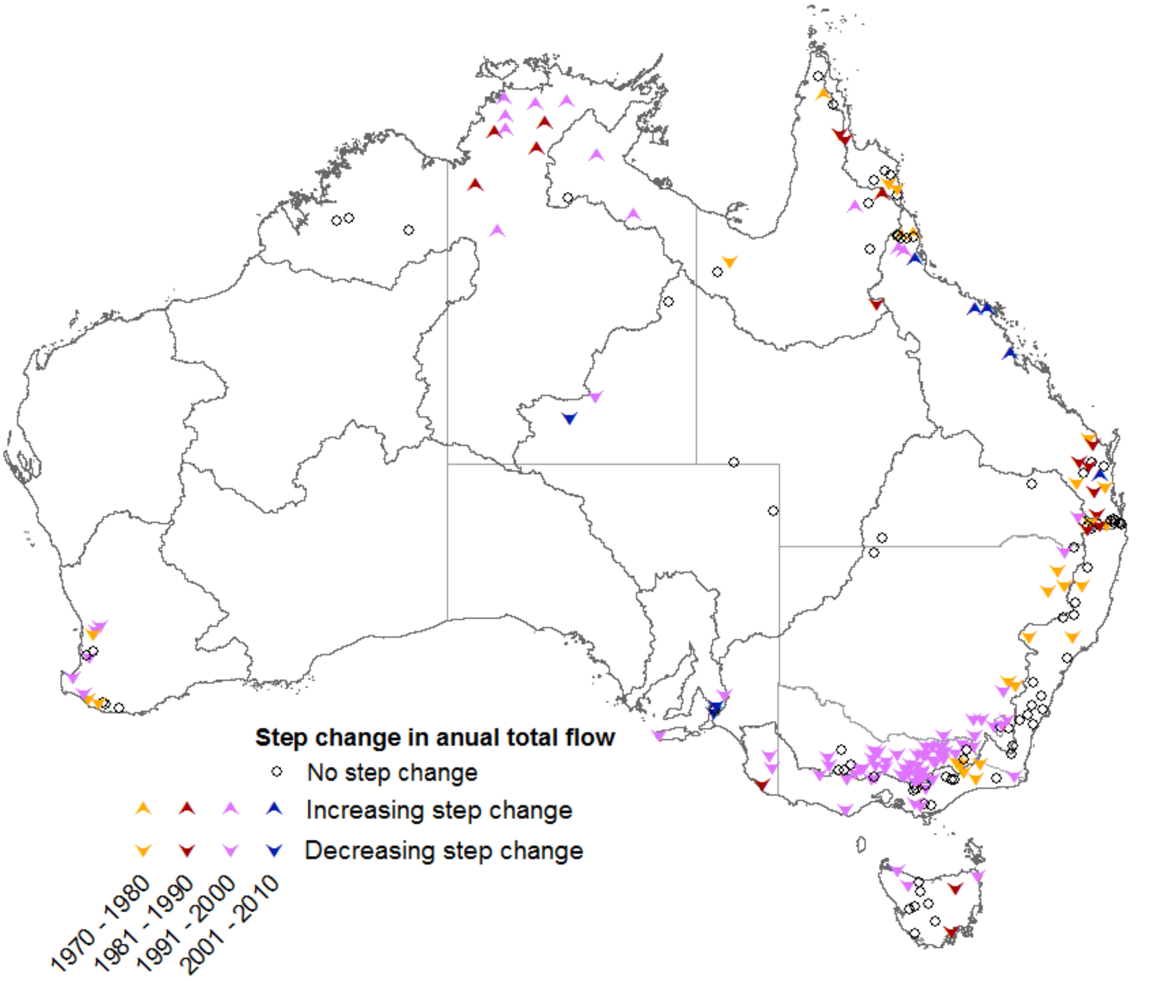


Figure 6: Variations of step change in annual total flow (Q_T) for stations showing significant increase or decrease trend

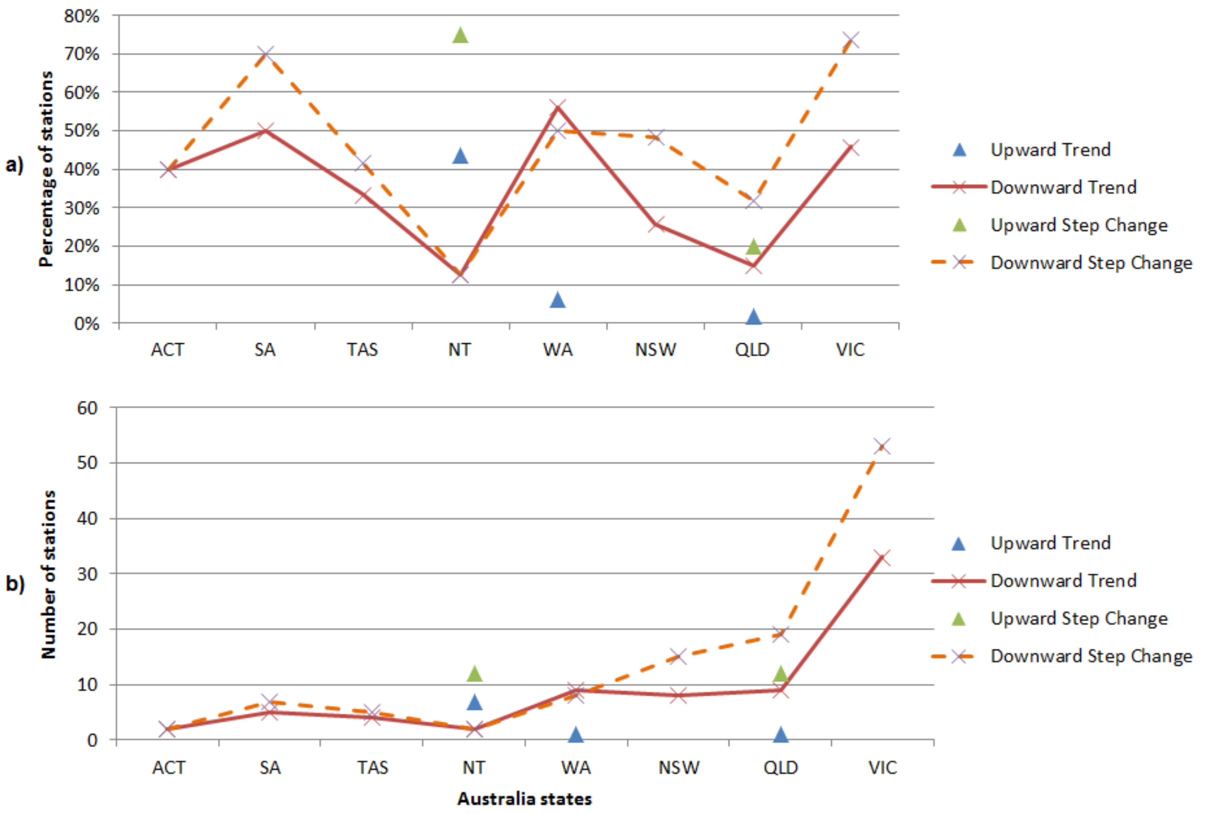
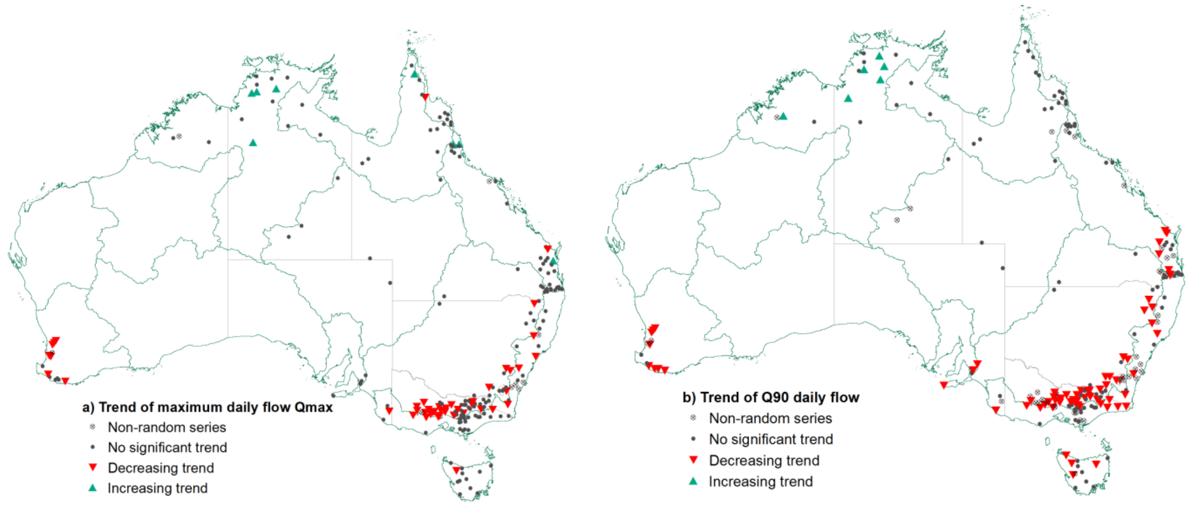
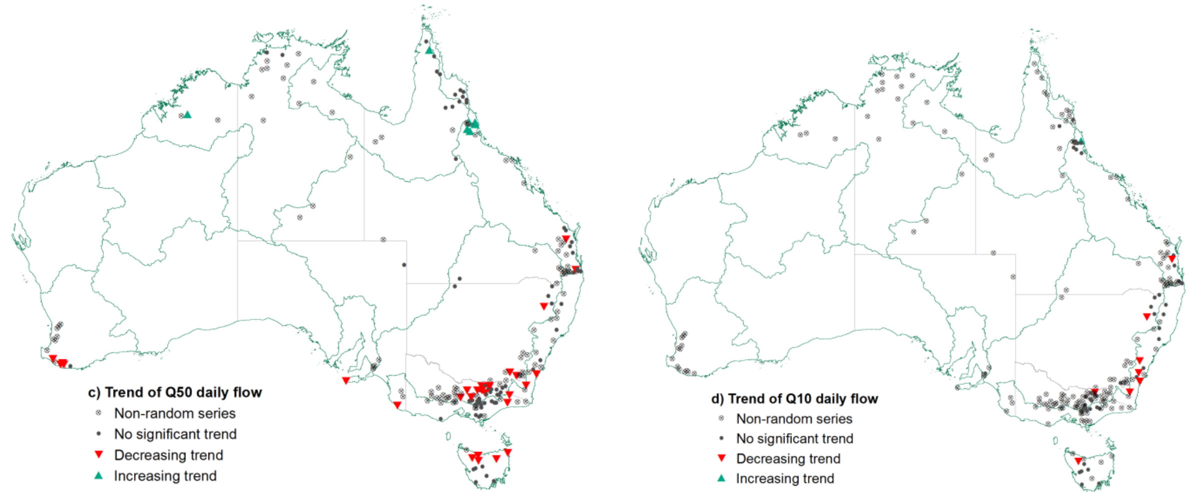


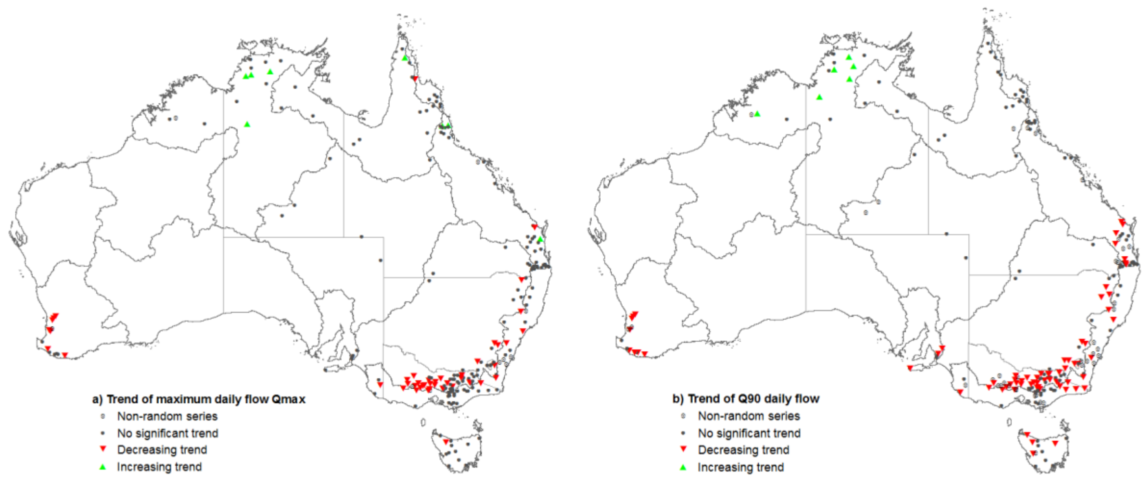
Figure 7: a) Percentage and b) number of stations showing significant upward and downward trends or step changes in different regions.



a) Trend of maximum daily flow Qmax
Non-random series
No significant trend
Decreasing trend
Increasing trend
b) Trend of Q90 daily flow
Non-random series
No significant trend
Decreasing trend
Increasing trend



c) Trend of Q50 daily flow
Non-random series
No significant trend
Decreasing trend
Increasing trend
d) Trend of Q10 daily flow
Non-random series
No significant trend
Decreasing trend
Increasing trend



a) Trend of maximum daily flow Qmax
Non-random series
No significant trend
Decreasing trend
Increasing trend
b) Trend of Q90 daily flow
Non-random series
No significant trend
Decreasing trend
Increasing trend

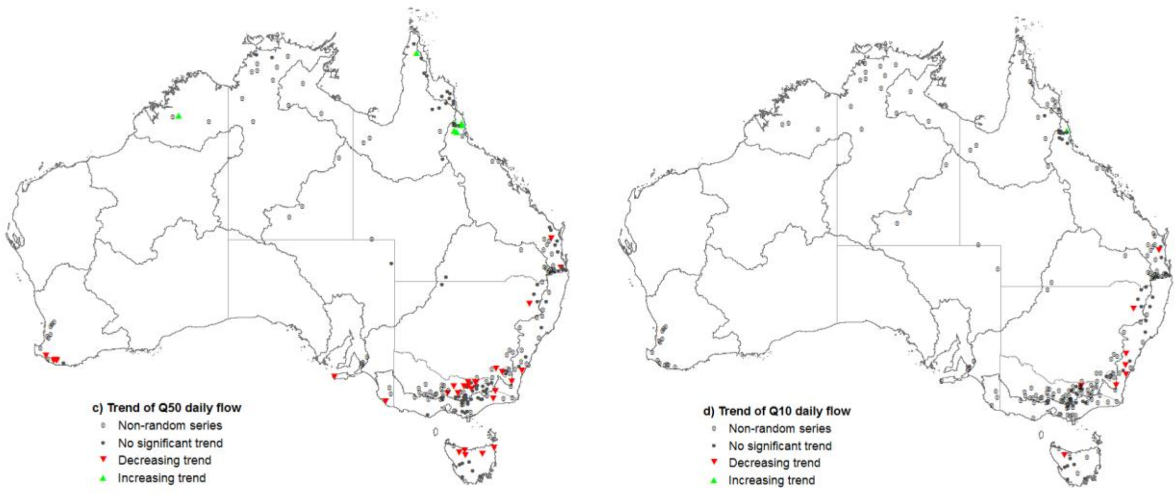
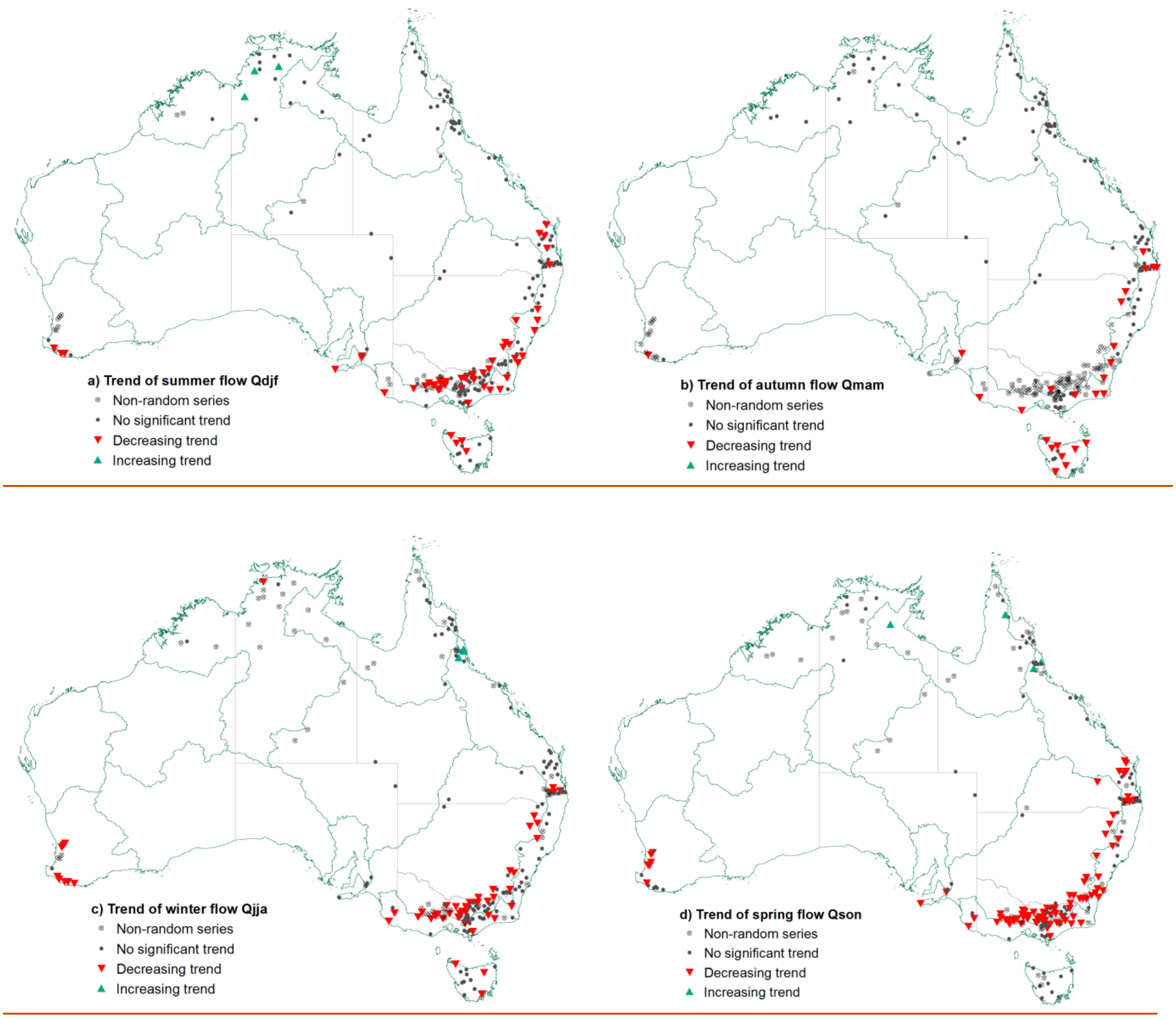


Figure 8~~7~~: Maps showing trends of daily flow in various magnitude categories a) maximum daily flow Q_{Max}; b) Q_{90} daily flow; c) Q_{50} daily flow; d) Q_{10} daily flow at 10% significant level ($p<0.1$)



a) Trend of summer flow Qdjf
Non-random series
No significant trend
Decreasing trend
Increasing trend
b) Trend of autumn flow Qmam
Non-random series
No significant trend
Decreasing trend
Increasing trend
c) Trend of winter flow Qjja
Non-random series
No significant trend
Decreasing trend
Increasing trend
d) Trend of spring flow Qson
Non-random series
No significant trend
Decreasing trend
Increasing trend

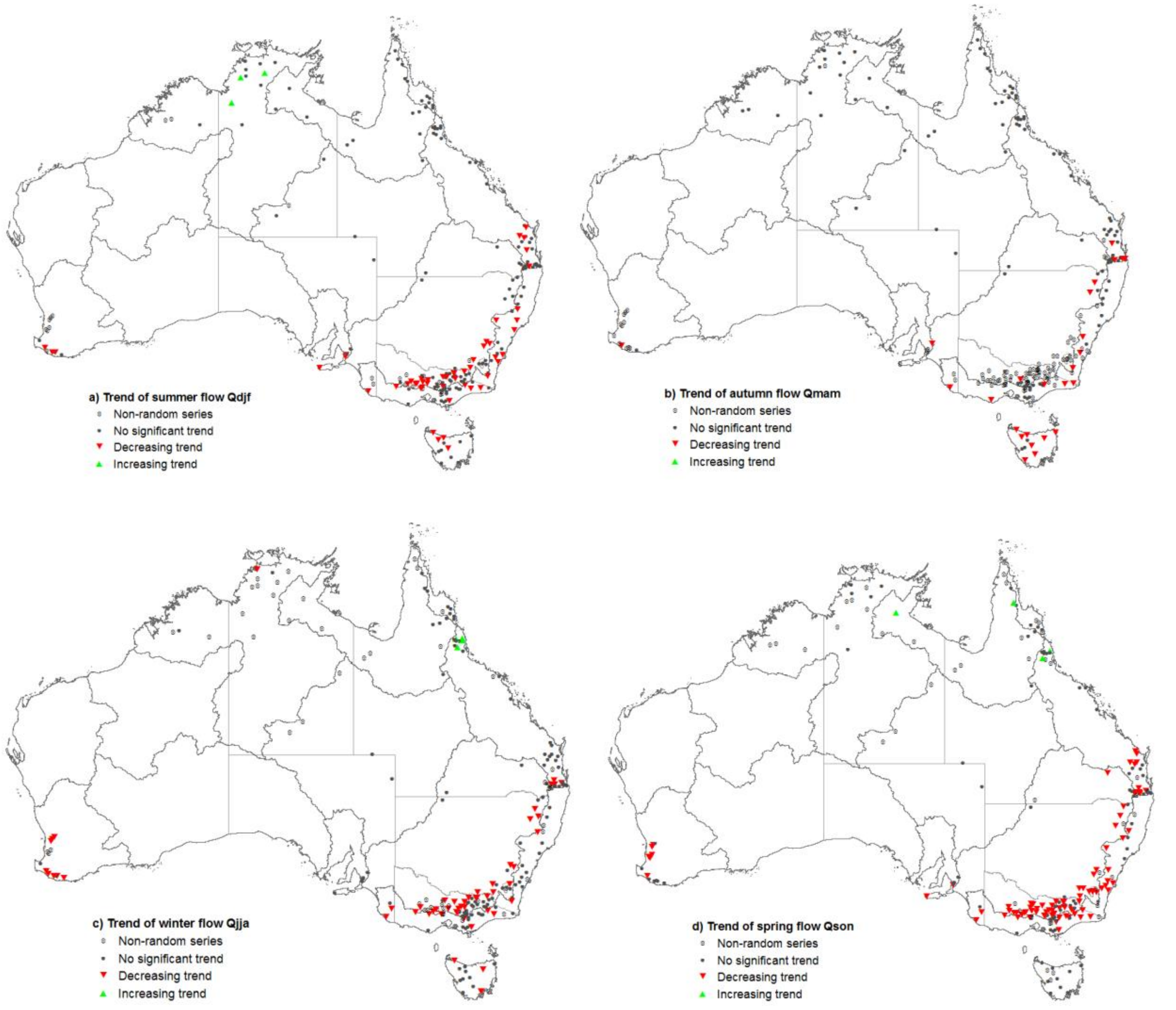


Figure 98: Maps showing trends of seasonal flow in a) Summer (Q_{DJF}); b) Autumn (Q_{MAM}); c) Winter (Q_{JJA}); d) Spring (Q_{SON})