Australian Network of Hydrologic Reference Stations – Advances In Design, Development and Implementation

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A hydrologic reference station network provides a platform to investigate long-term trends in water resource availability. This paper outlines a selection process that assessed, ranked and prioritised streamflow stations for inclusion into a national network of Hydrologic Reference Stations (HRS). The selection process includes streamflow stations in catchments with minimal regulation, landuse change or other factors that influence the hydrological data quality. Stakeholder consultation and feedback verified the high quality of the hydrological records and minimal impacts in the upstream catchment. Trend analysis identifies decadal variability and long-term trends in streamflow. Analysis shows that there is a statistically significant downward trend in streamflow within some hydro-climate regions, e.g. south-west of Western Australia, while in some other regions there is no significant trend. A web portal has been designed and developed to house trend analysis products, network details and relevant site data. Web portal users are able to see streamflow trends in a temporal context and will be able to download data. The web portal provides water managers and the research community with a national coverage of long-term status and trends in streamflow. These reference stations will serve as 'living gauges'; for detecting climate variability and change. Some of the stations will be useful for operational decadal and inter-decadal water availability service development.
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1. INTRODUCTION

Water resource managers in Australia are faced with the task of making sustainable planning decisions in a changing climate as pressures of water use demands continue to increase. Often the unknown in a supply versus demand scenario is the impact that climate variability and change will have on long term streamflow availability within a catchment. Establishing a benchmark from which to assess the impact of climate variability and change on long term trends in streamflow will aid the development of sustainable water resource management decisions.

Global Climate Models (GCMs) released as part of the IPCC Fifth Assessment Report (AR5) provide long term projections of climate variables that are key drivers of streamflow availability (i.e. temperature and precipitation). The GCMs provide an opportunity to establish a foundation on which to assess the long term impact of climate change on streamflow availability. However, the relationship between such climate parameters and streamflow availability at a regionalised catchment scale is often blurred by multiple anthropogenic catchment hydrology drivers that can vary, sometimes substantially, within and between climate regions. This hinders the development of streamflow benchmarks to establish long term trends and provide clarity on the impact of climate variability and change with a catchment.

Networks of hydrologic reference stations have been developed in the United Kingdom (National River

Flow Network), Europe (Environmental Water Archive), the United States of America (Hydro-Climatic Data Network) and Canada (Hydrological Basin Network). The networks are a collection of streamflow stations with near natural catchments, long term streamflow records and high quality data. Studies have used these networks to investigate long term trends in streamflow availability (Zhang *et al*. 2001; Dixon *et al*. 2006; Stahl *et al*. 2010), habitat suitability for aquatic communities (Monk *et al*. 2011), compare multiple catchments and climate regions (Stahl *et al*. 2010) and identify potential impacts on future water supply within a region (Petrone *et al*. 2010). The potential for a network of hydrologic reference stations to aid water resource management decisions in Australia is apparent. It would provide an avenue to assess the impact of climate variability and change on long-term trends in key aspects of the flow regime such as variability of the low flow regime, predictability of extreme events and alteration of inter and intra seasonal patterns. A number of unregulated reaches contribute significantly to major water supply catchments across Australia. However, to date a network of hydrologic reference stations had not been established.

This paper describes the development, design and implementation of the Australian Network of Hydrologic Reference Stations. The method used to select the included reference stations is outlined in Section 2.1. The trend analysis method that identified spatial variability of long term streamflow trends across contrasting climate regions of Australia is defined in section 2.2 and section 3. Finally, the development of a web portal to house the network of hydrologic reference stations, related station information, trend analysis and related data for each station is discussed is section 4.

2. METHODS

2.1. Hydrologic Reference Station Selection

Guidelines to identify Hydrologic Reference Stations (HRS) that are sensitive to climate variability and change and useful for long term and seasonal streamflow prediction were applied in all catchments across Australia (Table 1). Developed by SKM (2010), the guidelines were adapted for this study into four project phases. The aim of phase 1 of the guidelines was to identify reference stations in unregulated catchments with minimal land use changes and a high quality long term data series. ArcGIS was used to collate a preliminary list of streamflow stations dependent on the length of streamflow series (minimum 1975 onwards), data availability (stage, rating curve and discharge) and location upstream of major dams. Streamflow reference stations were also considered that were previously included in benchmarking studies (Stewart *et al.* 1991, Peel *et al*. 2000 and Viney 2010). This initial spatial analysis identified 246 potentially unregulated reference stations across Australia.

In the second phase following the collation of the preliminary list, an extensive stakeholder engagement program was carried out. The aim of the consultation process was to discuss the objectives and purpose of a network of Hydrologic Reference Stations, identify any stations that had been omitted from the preliminary list of stations and discuss any hydrological issues or impacts within the upstream catchment that could compromise the quality of monitored streamflow at the proposed reference stations.

Seventy stakeholders from government agencies (federal, state and territory) including the Regional Hydrology Managers of the Bureau, and water authorities across Australia provided feedback on impacts in the upstream catchments of each streamflow reference station identified in the preliminary analysis (participating organisations listed in acknowledgements). Each participant responded to a number of questions relating to diversions upstream, irrigation structures within the catchment, point source discharges upstream, past land use (farm dams, clearing, forestry, urbanisation, fire and water resource development) and potential future impacts (see Table 1, Phase 2 for the questions). Stakeholders also commented on the importance (water supply or ecological) and hydrological data quality of each streamflow station. Where available, stakeholders provided data on the volume of farm dams, diversions and land use practices in upstream catchment to aid the prioritization of hydrologic reference stations. The stakeholder consultation program identified an additional 116 streamflow stations across Australia for consideration to include into the Australian Network of Hydrologic Reference Stations.

Table 1. Selection guidelines to identify hydrologic reference stations*

Phase	Aim	Criteria applied to achieve aim
1	To collate a list of potential hydrologic reference stations	1.1 Not clearly identifiable as a drain, weir or non-river site 1.2 No dams, weirs or irrigation infrastructure upstream 1.3 Long-term time-series (Minimum of 1975 onwards) 1.4 Minimum 15 years continuous data in each climate phase (dependent on series length)
2	Undertake stakeholder consultation to identify and understand impacts in upstream catchments that may impact on the quality of the streamflow reference stations	2.1 Are there minimal farm dams in upstream catchment (capturing <10% of runoff)?
		2.2 Does the list provide adequate representation of reference stations located on unimpacted reaches in the region?
		2.3 Are there any reference stations that are not currently included but would be more relevant?
		2.4 What is an estimate of the volume of diversions occurring upstream of the selected reference station?
		2.5 What is the likelihood of the volume of diversions increasing in the future?
		2.6 Are there any regulatory structures upstream of the reference station?
		2.7 If a coastal region, is there any tidal influence on the reference station?
		2.8 Are there any point source discharges upstream of the selected reference station?
		2.9 Have there been any significant land use changes that would impact on catchment hydrology? Land use practices could include farm dams, clearing, forestry, urbanisation, fire and water resource development
		2.10 Are there any land use practices likely to increase in the future?
		2.11 Does the reference station have a particularly importance, for example, water supply or ecological?
		2.12 What is the hydrological data quality of each reference station?
		2.13 Is the rating curve sensitive to all facets of the flow regime?
		2.14 Is there any uncertainty related to the streamflow series?
3	Quantify land use changes and hydrological quality of streamflow series	3.1 Is there <10% land use change in the catchment upstream from the streamflow station
		3.2 Is there minimal missing data (<5% over the period of record)?
		3.3 Is the rating curve sensitive to all facets of the flow regime?
		3.4 Minimal data outside the gauging limits 3.5 Minimal data anomalies and unusual flow patterns
4	To identify climate region	4.1 Köppen climate classification region

* Adapted from SKM (2010)

Based on feedback from the stakeholder consultation process we developed a classification system to assess, rank and prioritise 362 streamflow stations. Consistent classification of stations provided us an avenue to compare the quality of and impacts in the upstream catchments of the proposed streamflow stations. The prioritization of stations provided three groups of streamflow stations. Group 1: a priority shortlist of streamflow stations that are considered as a) pristine, b) a station with minimal land use impacts or c) a station with currently minimal impacts but there is potential for future impacts. These stations were used for investigation in phase 3 of the project. Group 2: a set of streamflow stations that are in catchments where landuse impacts need to be investigated further before being included in analysis. Group 3: a set of streamflow stations that should be removed from consideration because of: a) impacts of land use change in the upstream catchment or poor hydrological quality, b) stations that are planned for closure or c) stations in a cluster of stations of similar quality and land use impacts.

Group 1 and 2 combined total 259 potential hydrologic reference stations (Figure 1). There were 128 priority reference stations identified in group 1 for inclusion into phase 3 analysis, i.e. land use analysis and data reporting. Land use impacts and or the hydrological quality of 131 stations in group 2 will be investigated further for inclusion into a second investigation in 2012-2013. Finally, group 3 included 103 stations that were removed from consideration.

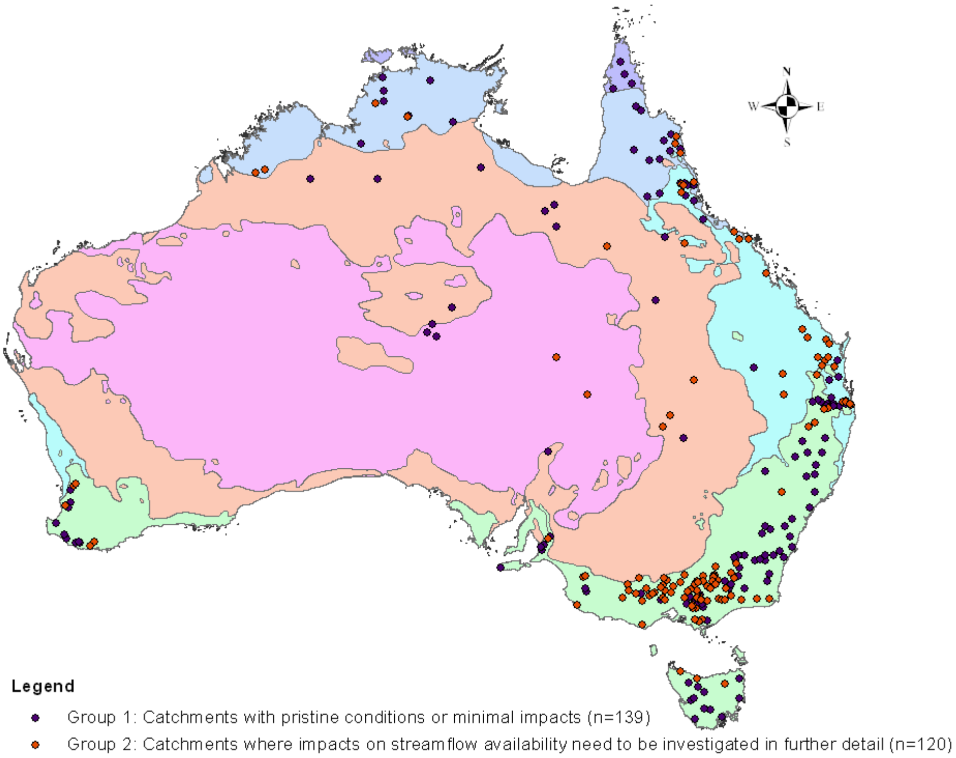

Figure 1. Distribution of the Australian Network of Hydrologic Reference Stations (n =259) (See text for Group 1 and Group 2 definitions)

Land use change can include farm dams, clearing, forestry, urbanisation, fire, water resource development and increases or alteration of agricultural practices. Catchment boundaries for each potential hydrologic reference station were derived by the Bureau of Meteorology's Geofabric team. The Department of Climate Change, Environment and Energy provided spatial analysis of the changes in the area of forest and non-forest cover between 1972 and 2010 in each catchment. The area of forest cover was chosen as an indicator of land use change that would be sensitive to changes in urbanization, clearing for agricultural practices and forestry. Analysis of the 128 streamflow stations identified in group 1 showed that 63 hydrologic reference stations had <5% missing data over the period of record and <10% land use change from 1972 to 2010. These stations were used in the trend analysis of long-term streamflow availability across Australia. They also provided a foundation for the development of a web portal to house the Australian network of hydrological reference stations and associated station information, catchment data, key streamflow stations and trend analysis results (Discussed in Section 4).

Spatial variability of reference stations across hydro-climate regions is important to verify climate variability and change across Australia. The long-term temporal variability in climate drivers of hydrology, i.e. temperature and precipitation, will differ between hydro-climate regions. Selecting hydrologic reference stations in multiple hydro-climate regions will aid the investigation of long-term trends in streamflow availability across Australia. The selected reference stations are not equally distributed across all hydro-climate regions as station selection was also dependent on the existing streamflow gauge network in Australia (Figure 1).

2.2. Trend Analysis Method

The Mann-Kendall trend test is a nonparametric test that ranks and compares data to identify statistically significant increasing or decreasing trends (Miller and Piechota 2008; Petrone et al. 2010; Zhang et al. 2010). The Mann-Kendall test was applied to the annual streamflow of the 63 hydrologic reference stations (Identified in group 1) (using TREND software, Chiew *et al*. 2005). The independence or randomness of each series was tested using the non-parametric Median Crossing test. Annual streamflow series showing statistically significant 'non-randomness' ($p < 0.01$) were excluded from trend analysis. The distribution free CUSUM test was applied to identify the year of change or step changes in streamflow series. The distribution test statistic follows the Kolmogorov-Smirnov two-sample statistic with the critical values defined. A step change is identified by the value of the test statistic. A negative value indicates the latter part of the record has a higher mean than the earlier part and vice versa (Chiew *et al*. 2005). Finally, significant difference between the median and mean of the streamflow series before and after the year of change (YoC),was tested by Rank-Sum and Student's t-test respectively (Chiew and Siriwardena 2005; Miller and Piechota 2008; Zhang et al. 2010).

3. LONG-TERM TRENDS IN STREAMFLOW

Mann-Kendall trend test results show a negative trend in streamflow is occurring at 57 out of the 63 hydrologic reference stations (Figure 2). A statistically significant ($p < 0.05$) decreasing trend is evident at 47% of those stations (Table 2). A step change in streamflow availability is most common in the mid to late 1970s and 1990s (Table 2). The Rank-Sum and Student t-test results show that the mean and median annual streamflow are significantly different before and after the year of step change at all stations. However, the median crossing analysis identified a large portion of stations at which the annual streamflow is non-random. That means the annual streamflow is generally non-normal and may have positively skewed distribution, and may be dependent upon previous year's rainfall and streamflow. Excluding sites with non-random data, a total of 28 streamflow stations have a statistically significant negative trend in long-term streamflow availability.

The high proportion of stations on the east coast, where the network has a higher density, with a statistically significant decreasing trend is evident. However, the statistically significant decreasing trend is not confined to one region with similar results evident in the South Australian, West Australian and the Northern Territory. Further development of the HRS, with the confirmation of the inclusion of hydrologic reference stations in group 2, will enhance understanding of spatial variability in long-term streamflow across each climate region. For brevity in this paper, it is not possible to present the impact on the long-terms of streamflow availability and variability at each site across Australia. A web portal has been developed and built to house the results for each hydrologic reference station included in the national network (Discussed in section 4)

An example of the site specific results that is the foundation of this study are presented here for Stanley River at Peachester (Streamflow gauge 143303A). The Stanley River is located in Southern Queensland, North of Brisbane. The catchment upstream of the streamflow gauge at Peachester has minimal landuse disturbance and was rated highly during the station selection and stakeholder consultation process. Trend analysis results show that a decreasing trend in long-term streamflow availability is occurring in this region ($z = -2.144$; $p = 0.016$) (Figure 3a). The Distribution Free Cusum test shows a step change in streamflow occurred from 1974. The Rank Sum test ($p < 0.01$) and Student's t-test ($p <0.01$) show that the mean and median are significantly different before (1951 to 1974) and after (1975 to 2010) the year of change. The alteration of the long-term magnitude and variability of streamflow is shown by the 3-year moving average Figure 3(b) and decadal flow duration curves (Figure 3(c)). The impact on seasonality is shown by the reduction in mean monthly flow after the year of change in all but three months (Figure 3(d)).

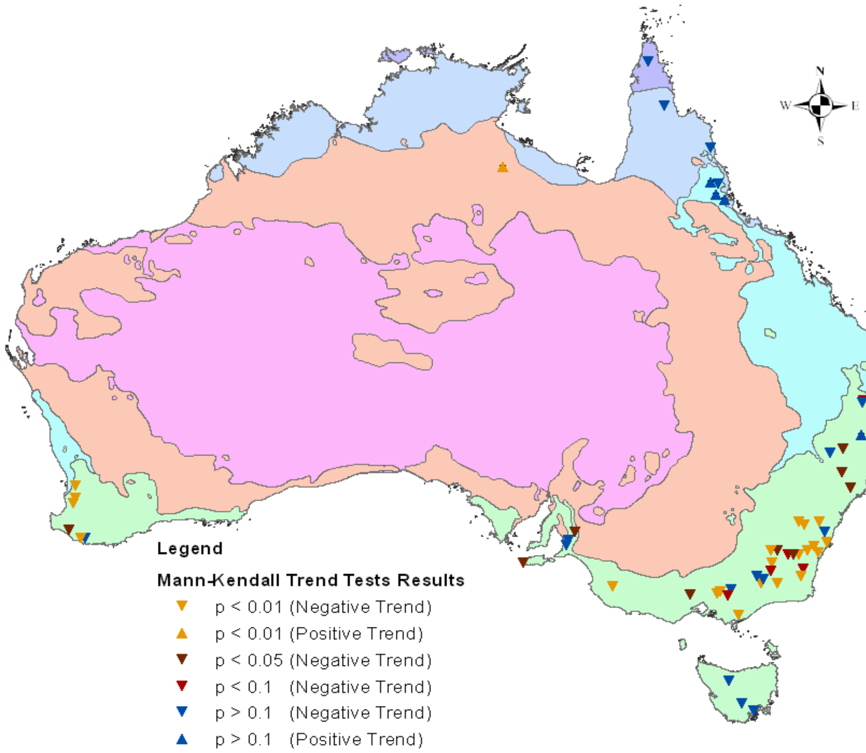

Figure 2. Mann-Kendall trend test results at priority Hydrologic Reference Stations (n= 63)

Table 2. Hydrologic reference stations with statistically significant streamflow trends

AWRC Number	Catchment	Trend	Mann – Kendall (p)	Distribution Free Cusum Test (dfct) – Year of Change (YOC)	Rank Sum Test (dfct) p	Student's t-test (dfct) p	Median Crossing p
208009	Manning	Negative	0.016	1978	0.003	0.006	0.098
210011	Hunter	Negative	0.046	1956	0.005	0.014	0.219
215002	Shoalhaven	Negative	0	1993	0	0.001	0.015
215004	Shoalhaven	Negative	0.004	1964	0.002	0.003	0.061
216002	Clyde River – Jervis Bay	Negative	0.002	1992	0	0.001	0.045
222213	Snowy	Negative	0.01	1976	0.008	0.016	0.163
231213	Werribee	Negative	0.016	1996	0	0	0.238
401009	Upper Murray	Negative	0	1996	0	0	0.398
401203	Upper Murray	Negative	0.01	1956	0.001	0	0.043
405209	Goulburn	Negative	0.002	1996	0	0	0.3
410057	Murrumbidgee	Negative	0.05	1996	0.001	0.001	0.393
410061	Murrumbidgee	Negative	0.008	1996	0.001	0.008	0.448
410731	Murrumbidgee	Negative	0.008	1996	0	0.001	0.019
410734	Murrumbidgee	Negative	0	1993	0	0.002	0.013
410761	Murrumbidgee	Negative	0.04	1998	0.004	0.012	0.125
412028	Lachlan	Negative	0.004	1996	0	0.005	0.303
412066	Lachlan	Negative	0	1976	0.002	0.015	0.104

AWRC Number	Catchment	Trend	Mann – Kendall (p)	Distribution Free Cusum Test (dfct) – Year of Change (YOC)	Rank Sum Test (dfct) p	Student's t-test (dfct) p	Median Crossing p
606185	Shannon	Negative	0.002	1975	0.003	0.004	0.433
608002	Donnelly River	Negative	0.026	2000	0.001	0.002	0.028
613002	Harvey	Negative	0.01	1993	0.003	0.003	0.019
616065	Swan Coast	Negative	0.01	1975	0	0	0.296
143303A	Brisbane	Negative	0.018	1974	0.001	0.001	0.151
145018A	Logan-Albert	Negative	0.008	1990	0.001	0.004	0.021
227225A	South Gippsland	Negative	0.002	1996	0	0	0.08
A2390519	Millicent Coast	Negative	0	1992	0	0	0.057
A5050517	Gawler	Negative	0.02	1992	0.003	0.01	0.152
A5130501	Kangaroo Island	Negative	0.02	1993	0.001	0.002	0.013
G8110004	Victoria	Positive	0.004	1990	0.001	0.001	0.074

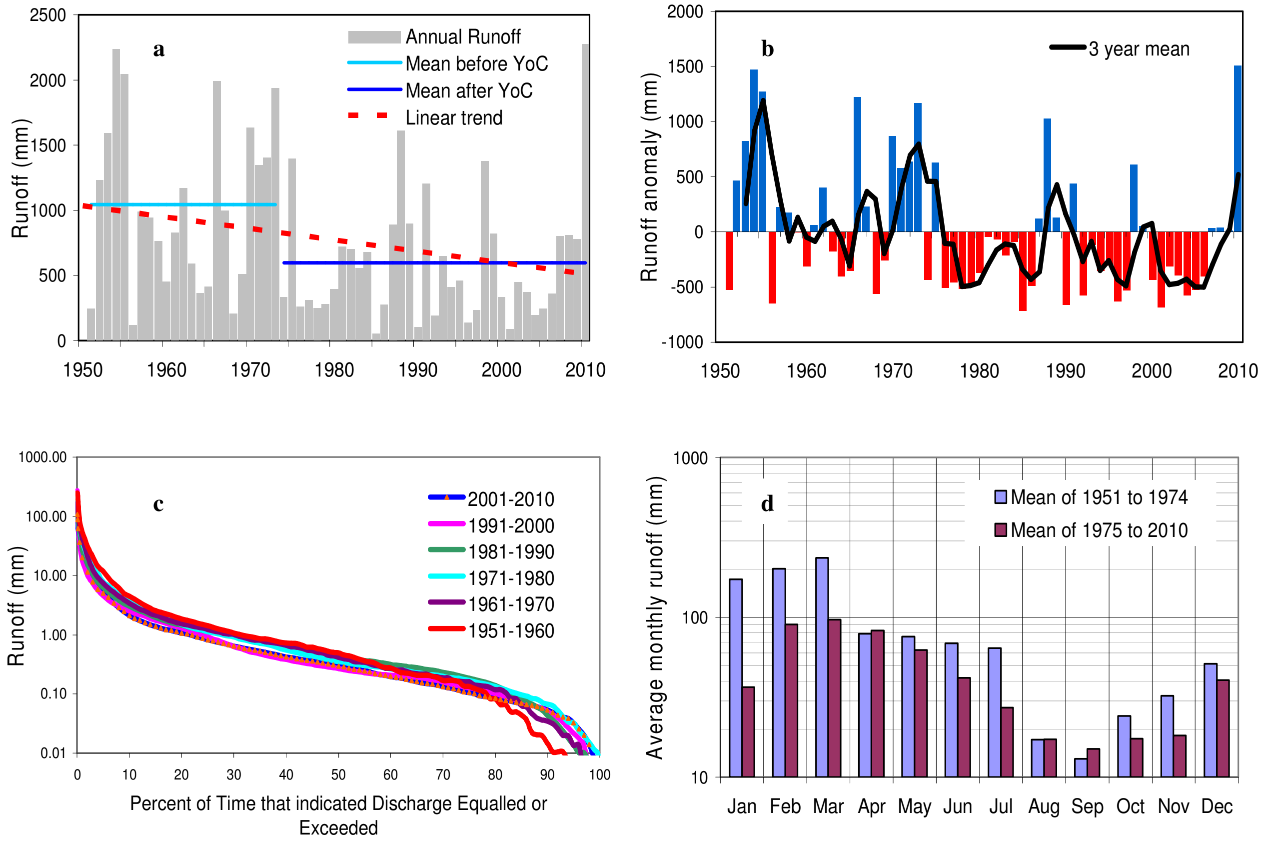

Figure 3. For Stanley river at Peachester (a) Trend and mean annual flow before and after YoC (b) 3-year moving average (c) Flow duration curves for 6 decades and (d) Mean monthly flow before and after YoC.

4. WEB PORTAL DEVELOPMENT TO HOUSE THE NETWORK AND ASSOCIATED SITE INFORMATION, DATA AND ANALYSIS

A web portal has been developed to house the Australian Network of Hydrologic Reference Stations and provide access to site information, analysis results and associated data for all sectors of the water resource management community (see the Bureau of Meteorology website for details: www.bom.gov.au). The framework of the web portal is shown in Figure 4. The entry point page, data explorer page and trend explorer page build upon each other to facilitate users searching the web portal dependent on their needs and particularly the level of information that they require. All original data, results of analysis and graphical products are downloadable from the Entry Point, Data Explorer and Trend Explorer pages. The web portal also contains details on the station selection process, stakeholder consultation and analytical methodology. A feedback form allows users to request further information or report issues regarding the website, hydrologic reference stations or data availability.

A reference station locator and selection tool based on geographic filters (jurisdiction basin and station name), is located on the Entry Point (Home) page. An interactive map is also provided to show the geographic location of the selected station and allow the user to zoom in and out and between regions of interest. Catchment characteristics including: the upstream maximum elevation, stream length, catchment area, and major contributing tributaries in the catchment are downloadable for each hydrologic reference station.

The station features outlined for the entry page are also available on the data explorer and trend explorer pages. The difference in the pages being that the data explorer expands data availability to annual, seasonal and daily streamflow statistics, whereas the trend explorer page provides users the facilities to conduct analysis of long-term trends in streamflow at the priority hydrologic reference stations. Users can apply statistical test to identify long term streamflow trend (Mann-Kendall trend test) step changes in streamflow series (Distribution Free CUSUM), independence or randomness (Median Crossing, Rank Difference) and the significant difference between median (Rank-Sum) and mean (Student's t-test) of a streamflow series before and after a step change in streamflow trends (As presented in Section 4).

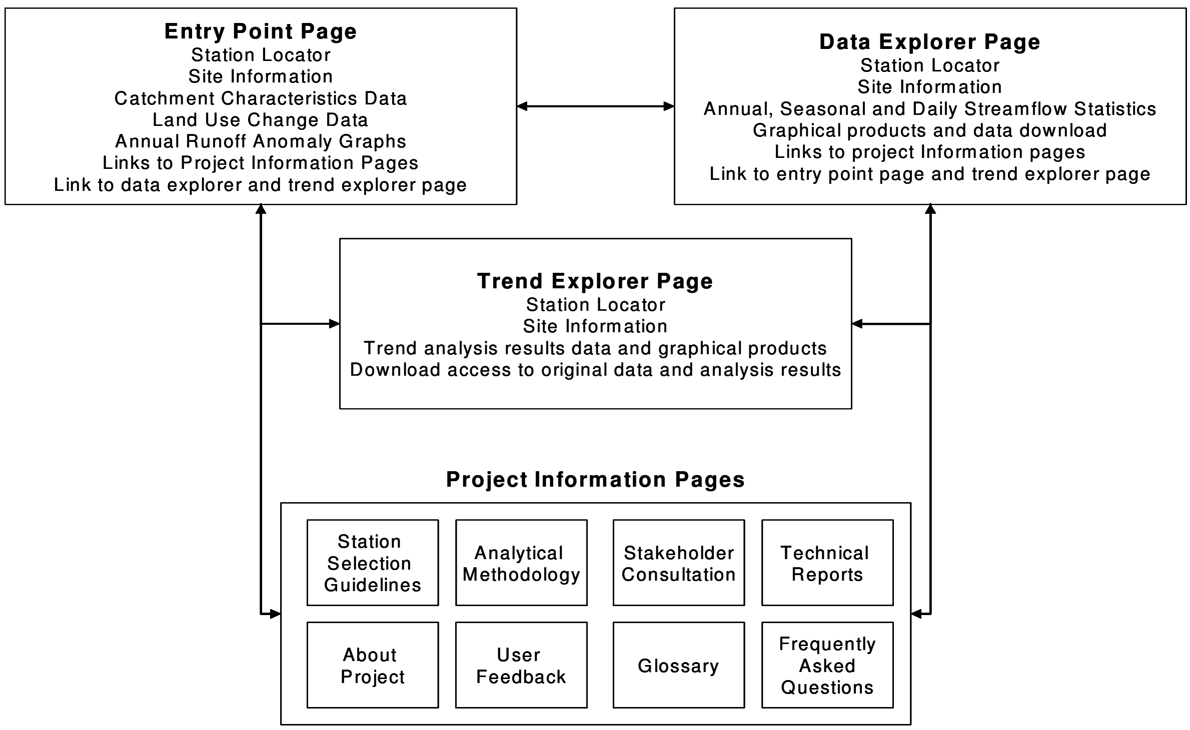

Figure 4. Framework for the Australian Hydrologic Reference Station web portal

5. SUMMARY AND FUTURE DEVELOPMENTS

Preliminary analyses of long term trends in streamflow availability show statistically significant decreasing trends in many regions across Australia. The next phase of hydrologic reference station selection, and the subsequent expansion of the Australian Network of Hydrologic Reference stations, will provide further insight into the spatial variability of streamflow availability across multiple hydro-climate regions. The hydrologic reference stations selected to date will also be considered as site candidates for a new long term forecasting service and an extended seasonal forecasting service of the Bureau of Meteorology.

The present state of the web portal will be released to stakeholders as a pilot by December 2012. Trend analysis of the remaining stations will be completed by December 2012 and added to the web portal. Additional features will also be added, including dynamic charting, with the web portal fully operational and publically available in 2013.

6. ACKNOWLEDGMENTS

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