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How good are hydrological models for gap-filling streamflow data?

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Key Points:

- Gap-filling of streamflow data performs well when the missing rate is less than 10%
- Small number of catchments showing large trend bias when the missing rate is up to 20%
- Poor gap-filling occurring in some wet catchments even with reasonable model calibration

Abstract. Gap-filling streamflow data is a critical step for most hydrological studies, such as streamflow trend, flood and drought analysis and hydrological response variable estimates and predictions. However, there is lack of quantitative evaluation of the gap-filled data accuracy in most hydrological studies. Here we show that when the missing rate is less than 10%, the gap-filled streamflow data obtained using calibrated hydrological models perform almost as same as the benchmark data (less than 1% missing) for estimating annual trends for 217 unregulated catchments widely spread in Australia. Furthermore, the relative streamflow trend bias caused by the gap-filling is not very large in very dry catchments where the hydrological model calibration is normally poor. Our results clearly demonstrate that the gap-filling using hydrological modelling has little impact on the estimation of annual streamflow and its trends.

Keywords: streamflow, data, gap-filled, hydrological model, trend

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1 Introduction

Streamflow is channel runoff, i.e. the flow of water in streams and rivers and accumulated from surface runoff from land surface and groundwater recharge. It is one of the major water balance components in a catchment where precipitation is partially stored in surface water, soil and groundwater stores, and the rest is partitioned into two fluxes: evapotranspiration and streamflow. It is almost impossible to measure evapotranspiration dynamics at a catchment scale. In contrast, streamflow time series can be easily measured at a catchment outlet. Therefore, streamflow data becomes a fundamental dataset underpinning hydrological studies. Without such a dataset, it is hard to understand catchment hydrological processes under climate change and non-stationarity（Dai et al., 2009; Gedney et al., 2006a; Ukkola et al., 2015; Zhang et al., 2016b).

Unfortunately, streamflow data are not always continuously available and most gauges suffer from streamflow data missing issues（Dai et al., 2009). Often, the missing rate is important when selecting streamflow gauges, especially when the data is used for annual trend analysis. To choose qualified catchments, researchers often set up a threshold for the missing ratio, for instance 1%（Petrone et al., 2010), 5%（Ukkola et al., 2015), 10%（Déry et al., 2009), 15%（Liu and Zhang, 2017), and 20%（Lopes et al., 2016). Only those gauges with missing rate less than a particular threshold are selected, and the rest are excluded for further analysis because of high missing rates.

There are many methods used for gap-filling the missing data, including interpolation from nearby gauges（Lopes et al., 2016), statistical methods（Gedney et al., 2006b), and hydrological modelling（Dai et al., 2009). Among them, the hydrological modelling method is widely used since it fully considers the spatial heterogeneity and temporal variability of climate forcing data, and can achieve sufficient simulations when it is calibrated against a

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small number of observations (Rojas-Serna et al., 2016; Seibert and Beven, 2009). This is particularly important in Australia where hydrological modelling is a major tool for simulating continuous streamflow at a catchment scale. More recently, the Australian Bureau of Meteorology used a hydrological model –GR4J– to infill missing daily streamflow data for 222 Hydrologic Reference Stations (http://www.bom.gov.au/water/hrs/about.shtml). The gap-filled streamflow data are then used for trend analysis and providing hydrological information to all users.

One major concern for the hydrology community is to understand how reliable the gap-filled data is. Unfortunately there are no studies in the literature to comprehensively evaluate the reliability and accuracy of the gap-filled data that are influenced by different thresholds and by data missing patterns. Our study aims to provide a framework to evaluate the annual trends and annual variables obtained from gap-filled streamflow data using two hydrological models (GR4J and SIMHYD) together with a large streamflow dataset available across the Australian Continent（Zhang et al., 2013). This can guide researchers to more sensibly define a threshold for catchment selection and hydrological analysis.

2 Data and Methods

2.1 Data

We obtained daily streamflow data set from 780 unregulated catchments widely spread across Australia（Zhang et al., 2013). The dataset has undergone strict quality assurance and quality control, including quality codes check and spike (i.e. outlier points) control, and covered the period from 1975 to 2012. This dataset has been used by modellers for various hydrological modelling and extreme-event studies（Li and Zhang, 2017; Liu and Zhang, 2017; Ukkola et al., 2016; Yang et al., 2017). The missing rate for the pre-1980 and post-2010 periods were high. To meet our study requirement, we selected 217 catchments with a data missing rate less than 1% for the period 1981-2010 and the streamflow data for the 217 catchments are regarded as 'benchmark' data (Figure 1). Out of the 780 catchments there are 146, 91, and 61 with the missing rate of 1-5%, 5-10%, and 10-20% during 1981-2010, respectively (Figure 1), and these catchments account for 38% of total available catchments. Table 1 summarises major catchment attributes for the 217 selected catchments.

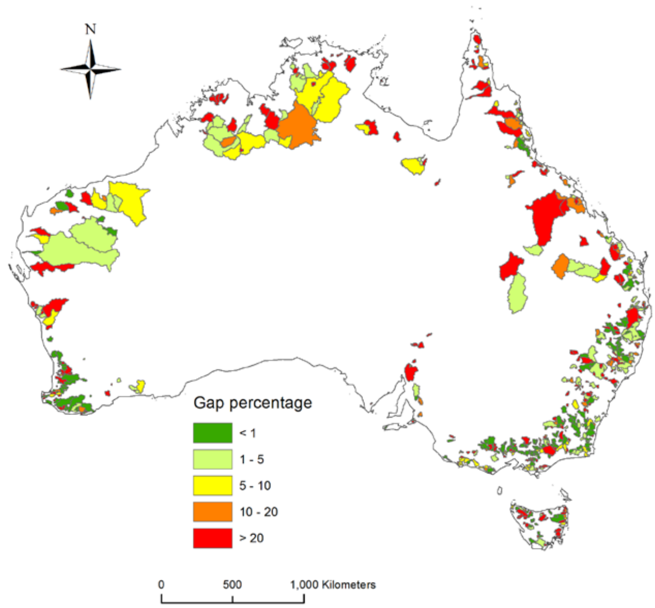

Fig. 1. The 780 unregulated catchments grouped by different streamflow data gaps for the period of 1981-2010.

Table 1. Major catchment attributes for the 217 catchments

Attribute	Definition	Unit	Min	2.5th	25th	Median	75th	97.5th	Max
Area	Catchment area	km^2	53	70	180	392	844	4562	72902
Elevation	Catchment average elevation above sea level	m	46	100	278	449	753	1194	1351
Slope	Catchment mean slope	Degrees	0.3	0.6	2.0	3.9	7.7	12.0	13.6
P	Mean annual precipitation	mm/year	256	371	703	853	1107	1966	2473

ET_p	Mean annual potential evapotranspiration	mm/year	906	968	1149	1235	1408	1791	1892
AI	Aridity index	-	0.38	0.55	1.11	1.44	1.89	4.75	6.47
Forest ratio	Ratio of forest to all land cover types	-	0.02	0.06	0.39	0.55	0.67	0.83	0.90

Out of the 217 catchments, about half of the catchments showed a significant decreasing trend, 37% showing non-significant decreasing trend, and 13% showing non-significant increasing trend (Figure 2), detected using Mann-Kendall trend analysis (see 2.3). This is because Australia experienced the Millennium drought over the period 2001-2009, which caused a dramatic streamflow reduction in this period (van Dijk et al., 2013). Trend analysis for the 217 catchments is explained in Section 2.3 and trend results are summarised in Section 3.

Out of the 217 catchments, about 46% of catchments have no missing data in 1981-2010, 12% with the missing rate <0.1%, 22% with the missing rate 0.1-0.5% and 20% with the missing rate of 0.5-1% (Figure 2).

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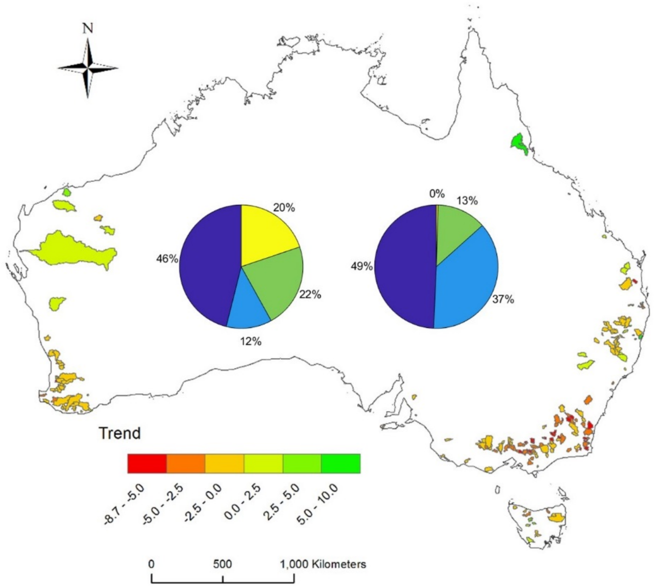

Fig. 2. Trends and streamflow data summary for the 217 catchments used in this study. Trend in annual streamflow is with a unit of mm/year/year. Left pie indicates the catchment percentage with different missing rates (dark blue with missing rate of 0%, navy blue with missing rate of 0-0.1%, green with missing rate of 0.1-0.5%, yellow with missing rate of 0.5-1.0%); right pie indicates the catchment percentage with different trends (dark blue with significant ($p \leq 0.05$) decreasing trend, navy blue with non-significant ($p > 0.05$) decreasing trend, green with non-significant ($p > 0.05$) increasing trend, and yellow with significant ($p \leq 0.05$) increasing trend).

To drive the two hydrological models, we obtained daily meteorological time series (including minimum temperature, maximum temperature, incoming solar radiation, actual vapour pressure and precipitation) from 1975 to 2012 at 0.05° (~5 km) grid resolution from the SILO Data Drill of the Queensland Department of Natural Resources and Water (www.nrw.gov.au/silo). The data quality is reasonably good, indicated by the mean absolute error for maximum daily air temperature, minimum daily air temperature, vapour pressure, and precipitation at 1.0°C, 1.4°C, 0.15 kPa and 0.40 mm/day（Jeffrey et al., 2001).

2.2 Gap-filling experiments

For thoroughly investigating the potential impacts of infilled streamflow data on annual trend accuracy, we conducted three groups of experiments to test how the missing rates at 5%, 10% and 20% impact on streamflow trends. We followed three steps for each missing rate of experiments:

1. Missing patterns were obtained using actual streamflow data. We selected consecutive missing day pattern from actual data from the 780 catchments. For 5% group of missing rate experiments, we selected 44 catchments with missing rates in 4-6%; for 10% group of missing rate experiments, we selected 39 catchment with missing rate in 8-12%; for 20% group of missing rate experiments, we selected 22 catchments with missing rate in 18-22%. Figure 3 shows the probability distribution of consecutive missing days from each group of catchments, which is skewed toward the low end. We therefore used the two-parameter Gamma distribution to simulate probability distribution of consecutive missing days (Figure 3). The Gamma distribution is expressed as

$$X \sim \Gamma(k,\theta) = Gamma(k,\theta), \tag{1}$$

where X is the consecutive missing days number, k is shape parameter, and θ is scale parameter. The corresponding probability density function in the shape-scale parameterization is

$$f(x;k,\theta) = \frac{1}{\Gamma(k)\theta^k} x^{k-1} e^{-\frac{x}{\theta}}, \tag{2}$$

where $\Gamma(k)$ is the gamma function.

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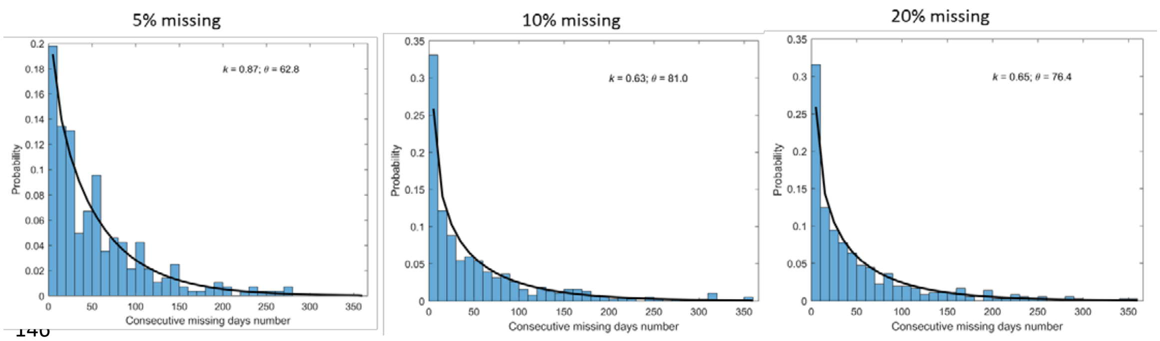

Fig. 3. Missing patterns for three groups of catchments with missing rates 4-6%, 8-12%, 18-22% that represent 5%, 10% and 20% missing rates, respectively.

As seen from Figure 3, the two parameters are stable under the three groups of catchments. The *k* parameter varies from 0.63 to 0.87 and the θ parameter changes from 62 to 81. It is noted that we removed all times when the number of consecutive missing days was > 365. We did that for a number of reasons. Firstly, gap-filling an entire year of missing data would likely impact annual trends. Secondly, the focus of this paper is on gap-filling short periods of missing data to be able to include more catchments in streamflow analyses. Thirdly, removing all periods of greater than 365 days allowed us to better fit a gamma distribution to the number of missing days.

2. Generating random consecutive missing day numbers using random number generator (sampling without replacement) based on the Gamma distribution. The random number generator was repeated 100 times to ensure the selected samples cover a wide range of streamflow time series.

3. Gap-filling streamflow data. The selected days were treated as 'missing' data and the unselected data were used for hydrological model calibration. The 'missing' data were then gap-filled using the simulated streamflow from the calibrated GR4J and SIMHYD models, respectively.

For consistent interpretation thereafter, the benchmark streamflow data is regarded as 'observed' and the experiment ones as 'filled' ones. For each of the three experiments, there are 100 x 217 (21,700) 'missing' time series, with 100 representing sample times using the random number generator and 217 representing the number of catchments.

2.3 Trend analysis

We used the Mann–Kendall Tau-b non-parametric test including Sen's slope method（Burn and Elnur, 2002) for annual streamflow trend analysis and significance testing for all the three groups of experiments and benchmark data.

We used the following equation to quantify the trend bias:

$$B_t = T_{filled} - T_{obs}, \tag{3}$$

where B_t is the bias in annual streamflow trend (mm/year/year), T_{filled} is annual trend for gap-filled streamflow (mm/year/year), T_{obs} is annual trend in observed streamflow (mm/year/year). It measures the trend error between the infilled and observed runoff trends with $B_t \approx 0$, which indicates that the trend in observed annual runoff is almost the same as that in the infilled annual runoff.

We also defined relative trend bias (P_{Bt}) as

$$P_{B_t} = \frac{T_{filled} - T_{obs}}{T_{obs}} \times 100 , \tag{4}$$

2.4 Hydrological models

Two widely used hydrological models SIMHYD and GR4J (Chiew et al., 2002; Chiew et al., 2010; Li et al., 2014; Oudin et al., 2008; Perrin et al., 2003; Zhang and Chiew, 2009; Zhang et al., 2016a) were used to infill daily 'missing' streamflow. Both models require daily

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precipitation and daily potential evaporation (Priestley and Taylor, 1972) as model inputs, and model outputs are daily streamflow at each gauge. The daily inputs of the maximum and minimum temperatures, incoming solar radiation, and vapour pressure data were used to calculate the Priestley–Taylor daily potential evaporation.

The two models were calibrated using a global optimiser: genetic algorithm (The MathWorks, 2006) at each catchment, with the first six years (i.e., 1975–1980) for spin up and remainder (1981 to 2010) for modelling experiments. Since this study mainly evaluates the trends obtained using the gap-filled streamflow from hydrological modelling, it is crucial to predict high flow and mean flow as accurate as possible. To this end, the model calibration was to minimize the following objective function (F) (Viney et al., 2009; Zhang et al., 2016b):

$$F = (1 - NSE) + 5\left|\ln(1+B)\right|^{2.5}, \tag{5}$$

$$B = \frac{\sum_{i=1}^{N} Q_{sim,i} - \sum_{i=1}^{N} Q_{obs,i}}{\sum_{i=1}^{N} Q_{obs,i}}, \tag{6}$$

where NSE is the Nash-Sutcliffe-Efficiency of daily streamflow, B is the model bias, Q_{sim} and Q_{obs} are the simulated and observed daily runoff, i is the ith day, N is the total number of days sampled. The NSE gives higher streamflow more weight, and varies between $-\infty$ to 1 with $NSE > 0.6$ indicating a good agreement (Zhang and Chiew, 2009). The B measures water balance error between the observed and modelled daily streamflow, with $B = 0$ indicating that the average of modelled daily streamflow is the same as the average of observed daily streamflow.

For each catchment, GR4J and SIMHYD were calibrated using benchmark data and 100 time series of streamflow data with ‘missing’ data (see Section 2.2), respectively. For benchmark data without any missing data (46% catchments) there are no gap-filling required; for the benchmark data with missing rate less than 1%, the calibrated continuous streamflow data were used to fill the gaps. For the 'missing' experiments, the calibrated continuous streamflow data for each 'missing' replicate were used to infill the artificially-made 'missing' data. Table 2 summarises the model calibrations carried out for benchmark and each experiment. Finally, there were 1,302,434 model calibrations and 1,302,000 times of gap-filling carried out. Finally, the trends estimated from benchmark were used to evaluate those obtained from the 'missing' experiments.

Table 2. Summary of model calibration number carried out for benchmark and data 'missing' experiments

Model	Benchmark	5% missing	10% missing	20% missing	Sum
GR4J	217	217,000	217,000	217,000	651,217
SIMHYD	217	217,000	217,000	217,000	651,217
Sum	434	434,000	434,000	434,000	1,302,434

3 Results

The gap-filled data from the two hydrological models were evaluated against the benchmark data. Figures 4 and 5 summarise the performance of the gap-filled data for estimating annual trend, annual streamflow, monthly streamflow and daily streamflow, respectively. Overall, the two models perform similarly. The three missing rate experiments (5%, 10%, and 20%) perform almost the same as the benchmark (Figures 4 and 5). The coefficient of determination (r^2) between the gap-filled trends and observed trends is more than 0.98 for the three experiments and two hydrological models.

Since errors in gap-filled trends likely to be different and different time steps when daily infilled streamflow data is used, we further investigate how gap-filled errors are propagated from daily to monthly and to annual scales under the three gap-filling cases (5%, 10%, and

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20%) (Figures 4 and 5). It is expected that daily gap-filled streamflow has a larger standard deviation from the benchmark than monthly and annual streamflow since the streamflow was gap-filled at daily scale. This indicates that the temporal aggregation smooths the gap-filled error strongly, and it generates very reasonable monthly and annual streamflow estimates with less standard deviation. It is interesting to note that both models tend to underestimate very high flows though they are calibrated against the NSE of daily streamflow which puts a larger weight on correctly representing higher flows.

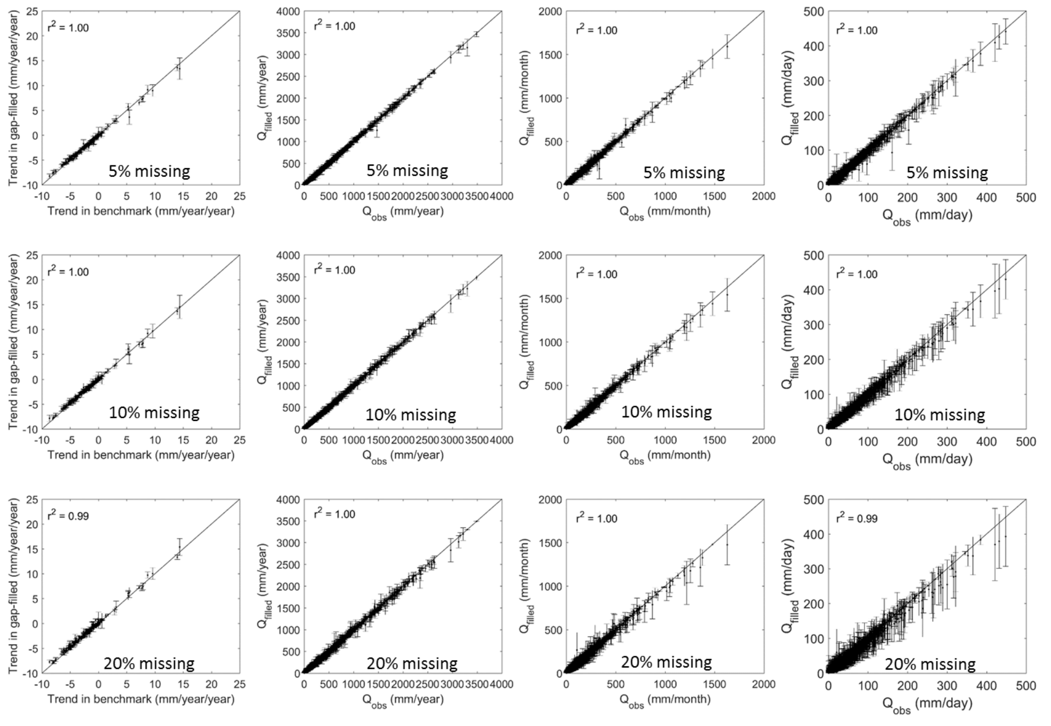

Fig. 4. Comparisons between the observed streamflow (x-axis) and gap-filled ones (y-axis) for streamflow trend (mm/year/year, left panels), annual streamflow (mm/year, second left panels), monthly streamflow (mm/month, second right panels) and daily streamflow (mm/day, right panels). The gaps were filled using GR4J. Error bar represents standard deviation of the 100 replicates for each group of 'missing' experiments.

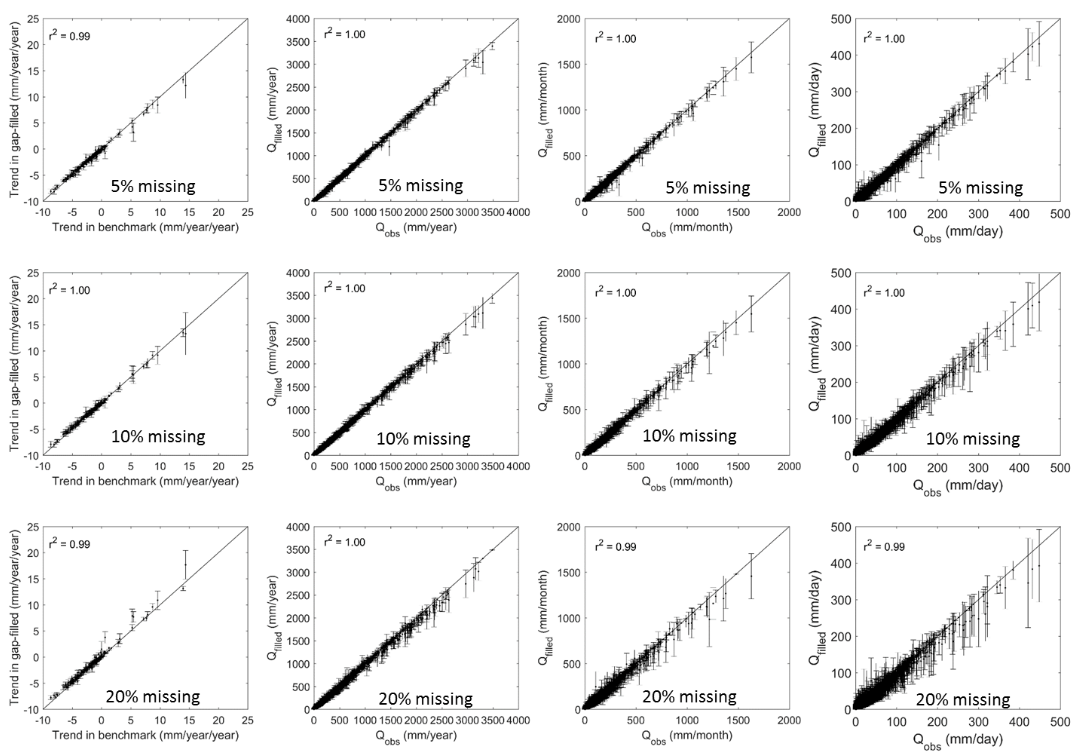

Fig. 5. Same as Fig. 4 but using SIMHYD.

Figure 6 further summarises the catchments with trend direction mismatch between the benchmark and gap-filled data (i.e. change from negative to positive or change from positive to negative). For the experiments with 5% and 10% missing rates and for GR4J, there are less than 8 out of the 217 catchments showing a trend mismatch and almost all of them show non-significant trends ($p > 0.05$). For the experiments with a 20% missing rate for GR4J, there are less than 10 out of the 217 catchments showing trend mismatch and all of them show non-significant trends. SIMHYD results are almost the same as GR4J results. All these indicate that there is very marginal influence on annual streamflow trend directions when the missing rate is less than 20%.

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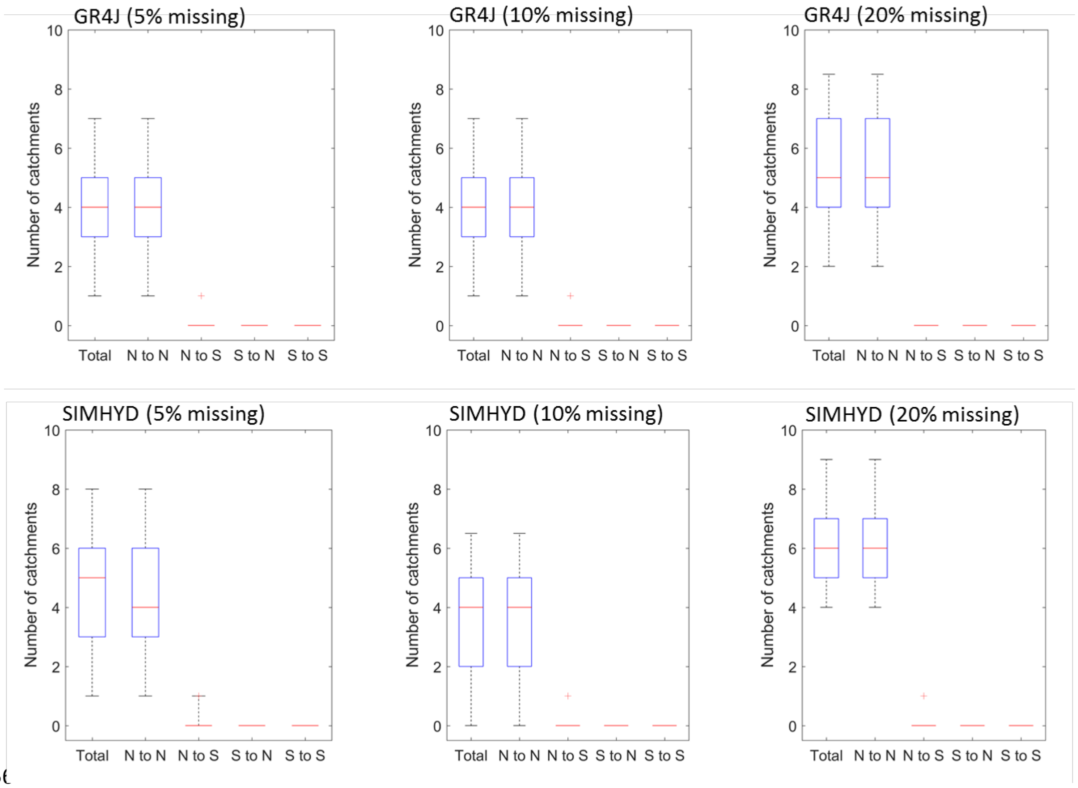

Fig. 6. Trend mismatch analysis between the gap-filled and benchmark. Total means all mismatch catchments; ‘N’ means not significant trends ($p > 0.05$); ‘S’ means significant trends ($p \leq 0.05$). The bottom, middle and top of each box are the 25th, 50th and 75th percentiles, and the bottom and top whiskers are the 5th and 95th percentiles.

Though the three groups of experiments show small trend direction changes (Figure 6), it is not clear how the trend bias (Eq. 3) looks. To this end, Figure 7 further compares the trend bias between the experiments. It is clear that the trend biases between 5% and 10% missing experiments are similar. For GR4J, both have the trend bias varying from -1 to 1 mm/year/year; For SIMHYD, the trend bias between the two is similar when it varies from -0.5 to 1 mm/year/year, and the trend bias for 5% missing experiment is even larger than that for 10% missing experiment. The trend bias for 20% missing experiment is noticeably larger

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than that for 10% and 5% missing experiments for both models, and the underperformance is more noticeable from SIMHYD gap-filled than that from GR4J gap-filled. This result suggests that the trend bias is reasonable when the missing rate is less than 10%, and can be large for small number of catchments when the missing rate is to 20%.

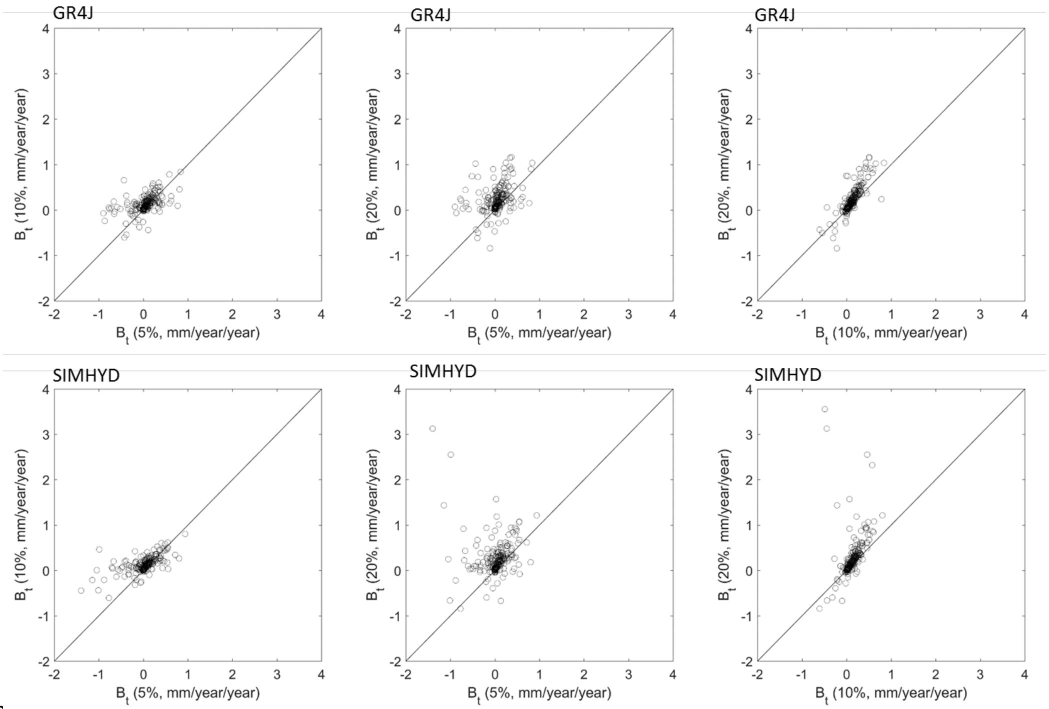

Fig. 7. Trend biases comparison between the three groups of gap-filling experiments (5%, 10% and 20%). Top three are for GR4J and bottom three are for SIMHYD.

4 Discussion and conclusions

Researchers are keen to have a comprehensive understanding of rules for excluding catchments with gaps in the streamflow record. Our results indicate that when the streamflow data gaps are up to 10%, the gap-filled data obtained using hydrological modelling are very reasonable for annual trend analysis and annual streamflow estimates. Choosing the threshold of 10% missing rate will allow the use of many more catchments in modelling and data analysis studies. For example, of the 780 unregulated Australian catchments available for modelling studies（Zhang et al., 2013), there are 237 catchments with the missing rate of 1-10% during 1981-2010, accounting for 38% of total available catchments (Figure 1). Of these 237, 67 (~28%) also have gaps lasting more than one year (which we did not consider in this analysis), and therefore these may not be suitable for use. With an increased number of catchments, more reliable large-scale hydrological modelling studies can be carried out（Beck et al., 2016; Parajka et al., 2013; Zhang et al., 2016a).

The 'missing' rate experiments designed in this study are based on the actual data missing patterns obtained from the 780 catchments. In most cases, the consecutive missing days are less than 10, as indicated by Figure 3, indicating brief periods of gauge malfunctions. It is however interesting to note that there are streamflow gaps lasting much longer than this in many catchments, with gaps of many months in some cases, noting that we excluded gaps lasting one year or more. It is highly likely that filling a gap of one year or more will result in biases larger than those presented here.

Furthermore, we also tested the quality of random gap-filled daily streamflow. In that case, the missing patterns were randomly selected using a random number generator. The results obtained from the random gap-filling (not shown) are similar to the results presented here. Thus, it is likely that the length of the gaps (as long as it is less than one year) is unlikely to impact the results of the gap-filling experiment. We would conclude from this that the use of hydrologic modelling for filling the substantially gapped data (up to 10% missing rate) described here for Australia will not impact annual trends of streamflow. Impacts on other streamflow characteristics also need to be examined, as well as seeing if the results obtained in Australia are comparable with those in other parts of the world, where the length of observational gaps may be quite different to those shown in Figure 3.

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To understand if the quality of gap-filled streamflow is related to catchment attributes and calibration accuracy, we conducted further analysis among the trend bias, model calibration efficiency (i.e. *NSE*) and catchment aridity index (mean annual potential evaporation divided by mean annual precipitation) (Figure 8). The model calibration results at dry catchments are normally poorer than those at wet catchments. However, the trend bias (mm/year/year) obtained from dry catchments is usually smaller. The large biases are observed from the catchments with aridity index less than 2 and with the calibrated NSE being larger than 0.60. In part, this is to be expected since the streamflow is also lower in more arid catchments, meaning that the trend bias is also likely to be lower.

Figure 9 shows the relationship between relative trend bias (%, Eq. 4) and aridity index. It shows that not only is the actual trend bias lower in drier catchments, but so too is the relative (%) trend. This result suggests that the large bias in annual trends as a result of gap-filling is observed in relatively wet catchments where model calibrations are reasonably good. This result seems counter-intuitive and requires further exploration, which is beyond the scope of the current paper.

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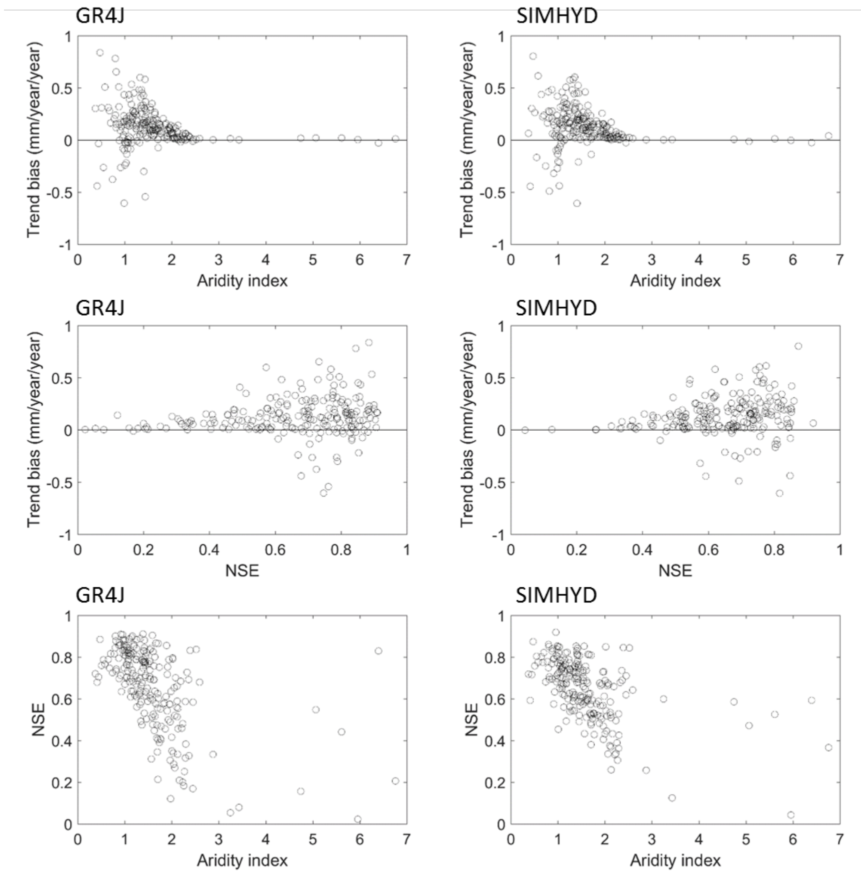

Fig. 8. Relationships among trend bias (mm/year/year), model calibration Nash-Sutcliffe Efficiency and aridity index for each catchment and for the experiment of 10% missing rate.

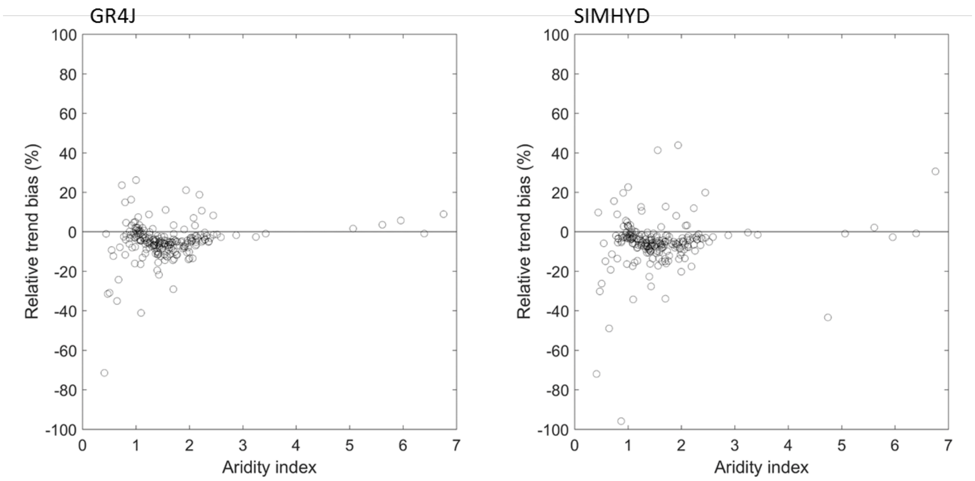

Fig. 9. Relationships between relative trend bias (mm/year/year) and aridity index for each catchment and for the experiment of 10% missing rate.

This study focuses on evaluating annual streamflow and its trends. Therefore, we used the Nash-Sutcliffe Efficiency plus model bias (Eqs. 5 and 6) to calibrate the two hydrological models. If other hydrological response variables such as low flow metrics are required, other model calibration schemes should be used since the NSE model calibration scheme gives more weight to reproducing high flows at the expense of low-flows (Zhang et al., 2014). Low flow metrics have important ecological implications (Mackay et al., 2014; Smakhtin, 2001). In general however, it is challenging to use hydrological modelling for low flow simulations and predictions (Pushpalatha et al., 2012; Staudinger et al., 2011). To have credible low flow gap-filling, model calibrations should use an objective function that puts more weights on low flows, such as NSE of daily inverse streamflow and the direct low flow metrics. Another possible method is to combine hydrological modelling with other methods for gap-filling, such as using nearby gauges (Lopes et al., 2016) and statistical methods (Gedney et al., 2006b).

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It is noted that the infilled data purely refers to the 'missing' data. All streamflow gauges are only rated to a certain flow. Once the flow exceeds that level during flooding, the results are interpolated using stage-discharge relationships (Peña-Arancibia et al., 2015). These interpolations could be a major source of observation error. However, investigating high flow interpolation and data quality is beyond the scope of this study.

In summary, our results clearly demonstrate that the gap-filled data is most accurate when examining trends at the annual scale, followed by monthly scale, and with least satisfaction at the daily scale. This gives researchers confidence for annual trend analysis, a hot topic in hydrological and climate sciences. Our results also clearly indicate that the gap-filling of Australian streamflow data using hydrological model is very reasonable when the missing rate is less than 10%, with only a small number of catchments showing a large trend bias when the missing rate is to 20%. The results also indicate that gap-filling drier catchments appears to be more successful than gap-filling wetter catchments.

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