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CREATING SINGAPORE'S LONGEST MONTHLY RAINFALL RECORD FROM 1839 TO THE PRESENT

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INTRODUCTION

Rainfall in Singapore is highly variable on inter-annual and multi decadal timescales. For example, although annual rainfall has been increasing over the past 30 years until 2012 and decreasing more recently, observed trends are dominated by year-to-year variation and are therefore not statistically significant (Figure 1a; Meteorological Service Singapore (MSS), 2017). Future climate projections for Singapore are inconclusive about future trend of annual rainfall (Marzin et al, 2015). The single long-term record at the MacRitchie Reservoir in the central part of the Singapore island reveals significant decadal—interdecadal variability in Singapore rainfall, likely driven predominately by natural climate variability (Liu, 2012). Improved understanding of natural variability on long time-scales could significantly reduce uncertainty in future climate projections. Currently, the identification of decadal variability is limited by the lack of long-term meteorological datasets; Singapore's reliable contemporary network of automatic meteorological stations (AWS) provides about 30 years of rainfall data for the whole island. Besides the modern network of AWS, an important historical time series has been the official single station records from MacRitchie station, which extend as far back as 1879, providing 138 years of (monthly) rainfall data. This has proven to be the most useful dataset to evaluate long-term multi-decadal variability in this part of the world and indeed in most of the tropics.

Newly-discovered observations from historical archives and unofficial sources offer the possibility to extend further back in time (as far back as 1839) this long-term record unique to Singapore, which is particularly exciting considering the dearth of historical meteorological data typical of other tropical countries (Nash and Adamson, 2014). In this study, rainfall data, sourced from historical archives and recording monthly rainfall pre-dating the start of official MacRitchie observations, are compiled from various locations across the island. By making use of the contemporary AWS network, we evaluate the spatial relationship of rainfall between the historical sites and the current MacRitchie site. This enables us to reconstruct historical rainfall at MacRitchie using the archive data, thereby building a single-location extended rainfall record (though discontinuous) from 1839—present. In the

Table 1. Timeline of instrument changes for MacRitchie gauge managed by PUB and MSS respectively.

Date	PUB Instrument	Date	MSS Instrument
1879 – 1953	Simple manual gauge; only monthly records available from PUB from 1879 – 1948 (though daily readings were available, see footnote 1). Daily records available from 1949 – present.		
1954 – 1983	Autographic recorder system installed; (daily) strip charts manually read.	1948 – 25 May 1982	Natural siphon gauge.
1984 - 1994	Tipping bucket rain gauge; monthly rainfall charts generated.	26 May 1983 – 7 May 1987	Dines tilting siphon gauge.
1995 – present	Electronic data logging system installed.	8 May 1987 – 12 Feb 2009	Hellman recorder installed.
		13 Feb 2009 – present	3G tipping bucket recorder installed. Comparison of rainfall measured from old and new MSS gauge for 13 months after installation to ensure consistency of instrument measurements. Measurements from new gauge logged from May 2010 onwards.

process, we also examine the reliability of the official MacRitchie record, which is comprised of two separate data sources.

DATA

Three types of monthly rainfall data were used in this study: (1) the current long-term records from MacRitchie station (1879—2016), (2) historical observations of rainfall compiled from various sources (1839—1883), and finally (3) the contemporary 28-station record (1980—2014). Datasets (1) and (2) are detailed below.

(1) Official long-term MacRitchie station records (1879 – 2016)

Presently, there are two rain gauges located immediately adjacent each other in the MacRitchie station site near Pumping Station 1. To our best knowledge the gauges have not moved since their respective installation, though there remains some dispute on this matter (Saw, H. S. and Ang, C. H., pers. comm., 2018). The instruments are now managed by two separate agencies in Singapore, and hence two different MacRitchie datasets exist. Observations from the instrument currently managed by the Public Utilities Board (PUB) are available from 1879—present , whilst observations from the instrument managed by the Meteorological Services Singapore (MSS) are available from 1948—present (Figure 1a). However, it is apparent that the two records are notably different before and after 1989 (Figure 1b). From 1948—1989, there is a near perfect correspondence between the two gauges, with differences for the most part of 0.9 mm or less, which may have been due to different rounding approaches, human error, or a combination of both . It is therefore likely that only one instrument was in use during this period which both agencies used to compile their monthly statistics. Unfortunately, it is difficult with the existing metadata constrain the source of the differences between the two time-series.

From Jan 1990, a pronounced wet bias for the MSS record in comparison to the PUB record is observed, suggesting that from 1990 onwards two different instruments were in use at the adjacent MSS and PUB sites. This wet bias in the MSS time-series persisted until December 1994, after which the relative bias was reversed (Figure 1b). Observed monthly differences are often very large, compounding in the annual totals (e.g. up to 507 mm for 2011 annual total). These differences and the reversals in biases, could be function of the instrumentation used in the two adjacent sites, as various changes in instrument type (in terms of both the measurement and data-logging systems) have occurred over time (Table 1). For example, the observed reversal in relative biases coincides with the shift in 1995 to an electronic data-logging system for the PUB instrument. The differences between the PUB and MSS time-series from 1990 onwards provide a useful opportunity to characterise for this location an estimate of the background measurement error due to instrumentation. We use this estimate as a baseline to evaluate the skill of our reconstructed historical record: i.e. if the estimate of the error of the reconstructed series is no larger than

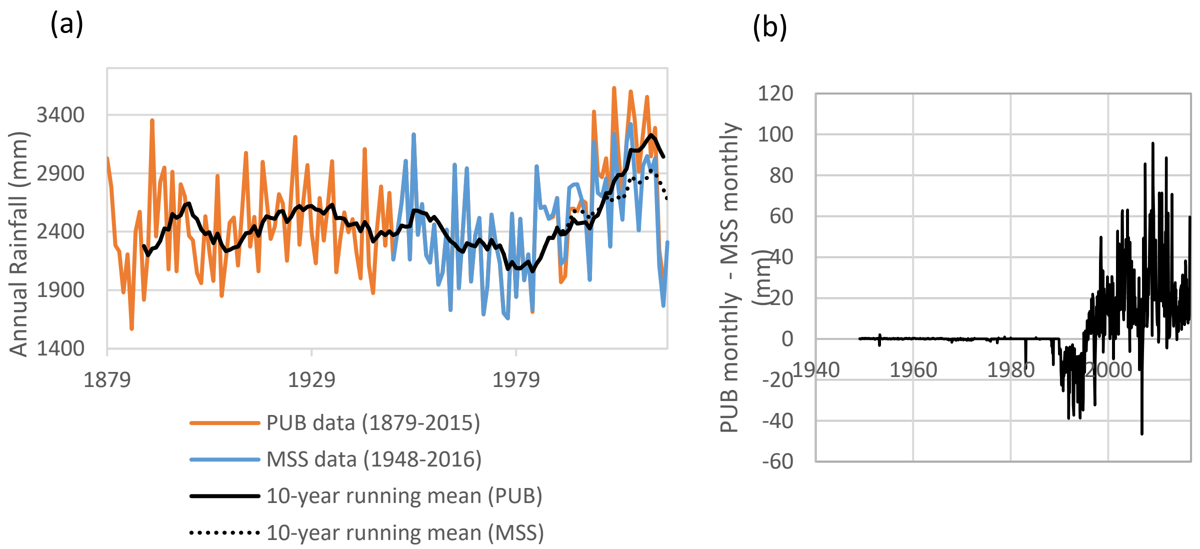

Figure 1. (a) Current long-term annual rainfall record for MacRitchie station, composite of data from the rain gauge managed by the Public Utilities Board (PUB) and the rain gauge managed by the Meteorological Services Singapore (MSS). Both gauges are located in MacRitchie Reservoir and are situated within 5m of each other. The difference in monthly values between PUB and MSS over time is in (b).

the differences between two acceptable instrumentations located at the same site than it falls within an "acceptable measurement error" at that particular location.

Rainfall totals for four months (Oct 1892, Jan 1942, Jan and Feb 1947) are missing from the PUB dataset. These have been replaced by 30-year centred-means for each particular month.

(2) Historical observations of rainfall (1839—1883)

Historical rainfall data was compiled from a variety of published sources, such as newspaper reports, journal articles and government records (Table 2). These observations were made by individuals as well as government bodies, and include not only rainfall measurements (in inches), but also descriptive accounts of the mean monthly weather.

While rainfall is a somewhat simple quantity to observe, we know from modern record (as described above) that large uncertainties exist. It is therefore worthwhile to review how instrumentation evolved in the 19th and 20th centuries. In the mid-1800s, 2 types of rain gauges, the newer 'common circular' and the older style 'graduated glass-measure' type, were often used together (British Association for the Advancement of Science, 1855). The new circular gauge was exported from Britain to the colonies by the late 1860s, though standards for using the instrument were not uniformly enforced till the 1880s. During the late 1860s, for example, the rain gauge of Colonial Surgeon H. L. Randall's observational series made at Singapore's Convict Jail was placed 2 foot above the ground, whereas Ward and Griffiths had recommended only 1 foot. For much of the nineteenth century too, many of the observational series were made by enthusiastic amateurs (volunteer observational network) rather than trained meteorological staff. These might be plantation owners, such as J. D.Vaughan at River Valley Road, who were given a gauge and some basic, practical

Table 2. List of identified historical sources of monthly rainfall observations and the location of observation as described in each source.

Period Available	Source	Location(s) of Observation
November 1839—February 1841	J. S. Travelli (1843), *American Journal Arts and of Science*	Ryan's Hill mission school (H11)
1841—August 1845	C. M. Elliot, *Singapore Magnetic Observatory Yearbook*	Singapore Magnetic Observatory (H8)
1862—1866	J. D. Vaughn, *Government Gazette*	River Valley Road (H5)
1864—1886	A. Knight, in Wheatley (1881), *Journal of the Straits Branch of the Royal Asiatic Society*	Mount Pleasant, Upper Thompson Road (H7)
1869—1883	Principal Civil Medical Officer (P.C.M.O) of the Medical Department, *Government Gazette* and *The Straits Times*	Goodwood Estate (H1) Pauper's Hospital (Tan Tock Seng) (H2) P & O Coy's Depot (H3) Perseverance Estate (H4) General Hospital (Sepoy Lines) (H6) Convict Prison (H9) Kandang Kerbau (KK) Hospital (H10)

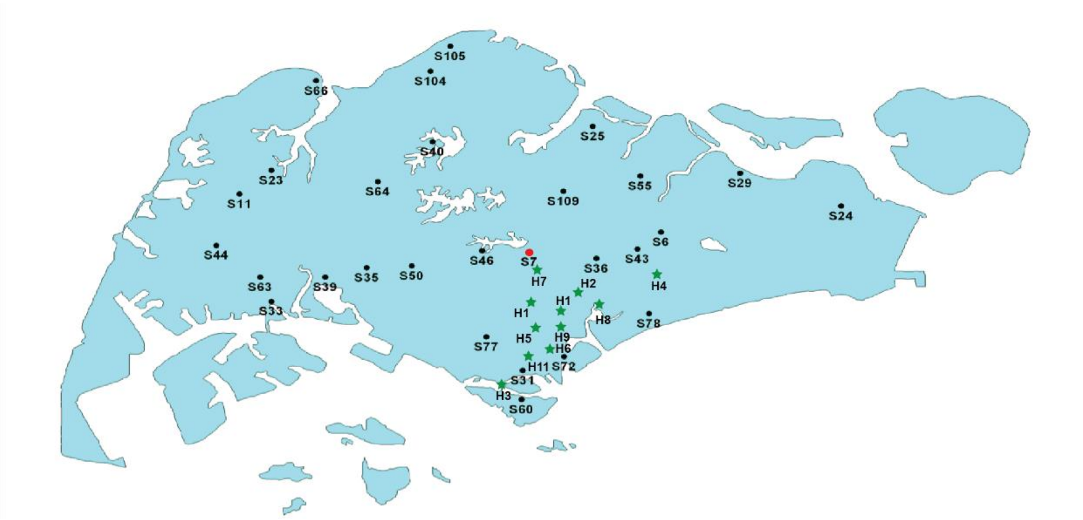

Figure 2. Current 28-station network and identified historical stations. Contemporary automatic stations are indicated with black circles and an alpha-numeric code. MacRitchie station (S7) is highlighted in red. Historical stations are indicated by green stars, and tagged as follows: H1—Goodwood Estate.; H2—Pauper's Hospital; H3—P & O Coy's Depot; H4—Perserverance Estate; H5—River Valley Road; H6—General Hospital; H7—Mount Pleasant; H8—Singapore Magnetic Observatory; H9—Convict Prison; H10—KK Hospital; H11—Ryan's Hill.

advice as to how to use it. However, like Vaughan, many of these volunteers had military or naval backgrounds and thus some basic scientific and meteorological understanding. Where observations were made by trained staff, for example at a hospital or a prison, it was under prescribed conditions. Although observational accuracy was to attract criticism by early twentieth century commentators, their argument applied more to registering station staff located at rural, isolated parts of Malaya, not in urban/peri-urban Singapore where it was easier to monitor conditions.

Only quantitative data from published rainfall tables were used in this study, with temporal resolution limited to the monthly scale as only a few sources provided consistent daily observations. Rainfall tables from the Raffles and Horsburgh Lighthouses, published in the Government Gazette, were excluded from the study on account of their considerable distance from MacRitchie. The compiled historical dataset spans 1839—1883, overlapping with the official MacRitchie meteorological record from 1879—1883 (Table 2, Figure 3). The coordinates of each station had to be determined by cross-comparison of archived historical maps with modern-day Singapore geography, since no source provided location data beyond qualitative descriptors (e.g. street/building names). In total, 11 station locations were determined (Figure 2), though with varying accuracy. For example, from 1862—1866, monthly rainfall measurements were taken by J. D. Vaughan and published quarterly in the Government Gazette, with the entire dataset later compiled by Wheatley (1881). Both sources state that the measurements were registered at River Valley Road, providing only a crude location estimate. A map from 1860 listing residences in Singapore places Vaughan's house near the intersection of Killiney Road and River Valley Road, which is assumed in this study to be the site of his observations (Figure 4). As rain gauges were not

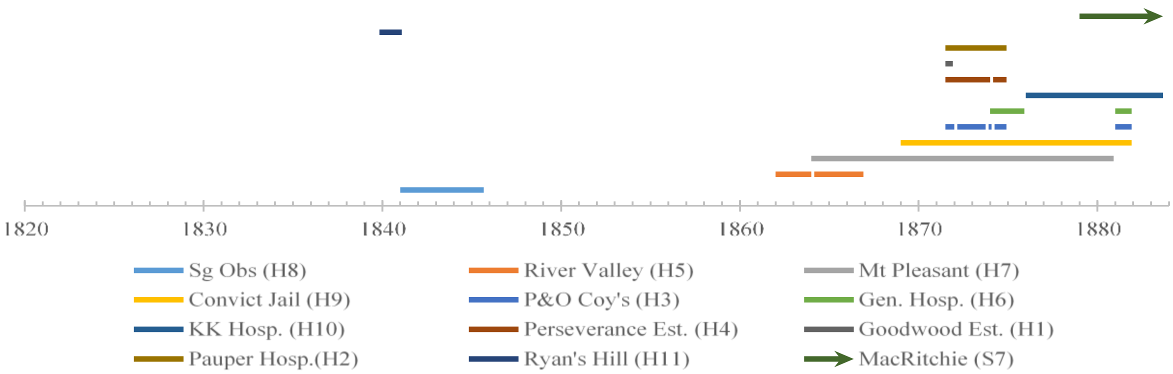

Figure 3. Monthly rainfall data availability for identified historical stations, in comparison with the current official MacRitchie record (dark green line). Dashed lines highlight the 1879—1883 period used to validate the reconstructed estimated historical MacRitchie series. The shortest station record, Goodwood Estate (dark brown line), is 6 months, whereas the longest station record, Mt Pleasant (grey line), is 204 months (17 years).

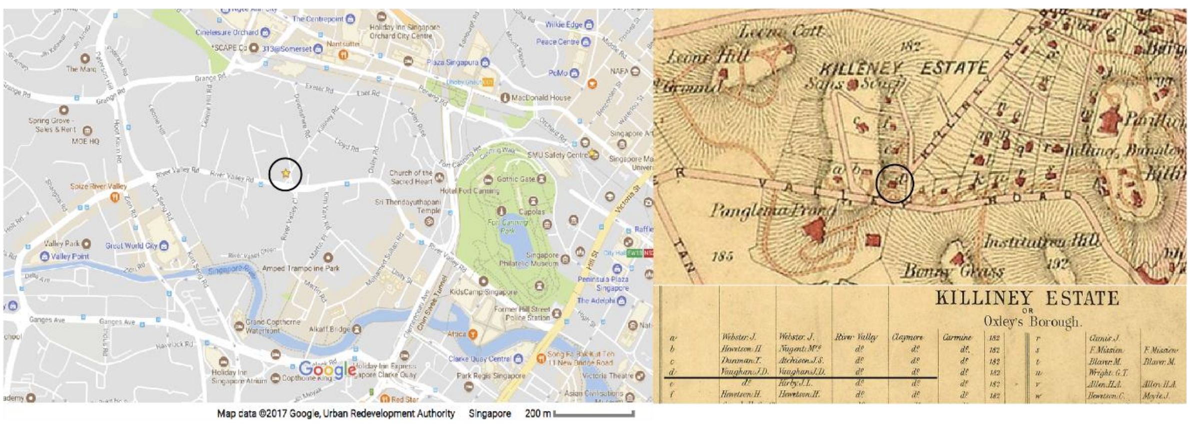

Figure 4. Location of River Valley station, as identified through map of Killiney Estate from Singapore Residency (1860). Map retrieved from the National Archines of Singapore online database. Site of station assumed to be Mr J. D. Vaughan's residence.

explicitly labelled in historical maps (excepting KK Hospital station), stations located in large plantation estates, namely the Perseverance Estate and Goodwood Estate stations, could not be very precisely located. Nevertheless, the impact of location imprecision is likely to be small in comparison with the other uncertainties faced doing this historical reconstruction.

Unfortunately, the historical record is highly fragmented and discontinuous. At present, no data has emerged for the 17-year period between October 1845 and December 1861. In addition, individual station records are relatively short; even the longest station record, Mount Pleasant, is only 17 years long and therefore insufficient on its own to distinguish patterns of decadal variability. Finally, the compiled historical records cannot be directly compared against the contemporary record as none of the identified historical stations are included in the current 28-station meteorological network (Figure 2). Hence, rather than analyse rainfall variability in each individual historical record, the historical data which has been compiled are exploited to attempt to extend the existing MacRitchie record back in time, thereby providing an estimate of historical rainfall for a single site.

METHOD

SPATIAL INTERPOLATION BY INVERSE DISTANCE WEIGHTING (IDW)

In order to reconstruct historical rainfall at MacRitchie station, the spatial relationship of rainfall at the 11 historical stations relative to MacRitchie must first be determined. To do so, we are assuming that the spatial pattern is stable over time since the 19th century. We can then make use of the spatial characteristics of rainfall registered by the current 28-station network and averaged from 1980 to 2014 as an approximation of the spatial relationship between historical locations in the 19th century. Spatial interpolation by Inverse Distance Weighting (IDW) was chosen as it is fast and easy to implement, enabling new estimates to be rapidly generated whenever revisions to historical station locations are made, or new stations are added:

$$h_{pm} = \frac{\sum_{i=1}^{n}\left(\frac{z_{im}}{d_i^W}\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i^W}\right)} \qquad (1)$$

where h_{pm} is the interpolated rainfall at the location of historical station p for the month m, z_{im} the measured rainfall at contemporary station i for the same month m, d_i the distance between station p and i, and w a positive real number determining the rate of decay in weighting as a function of distance (Shepard, 1968). Hence, the monthly rainfall for a historical station is determined by a weighted combination of the set of observed 28-station rainfall for that particular month. As w increases, data from stations further from the interpolated p will have much smaller influence (Figure 5); in most geospatial studies, w = 2 is used (e.g. Yang et al, 2015). However, there is no theoretical basis for this number and the optimal value that minimises interpolation error will be heavily dependent on the spatial distribution of known data points (Babak and Deutsch, 2008). Here, several values were tested: w = 0.5, 1, 2, 3, 4, and 5. It was found that variations in w had minimal effect on all cross-validation statistics investigated, likely due to the high density of stations across Singapore. In the absence of strong rationale to use a different value, the commonly used value of 2 for w was retained.

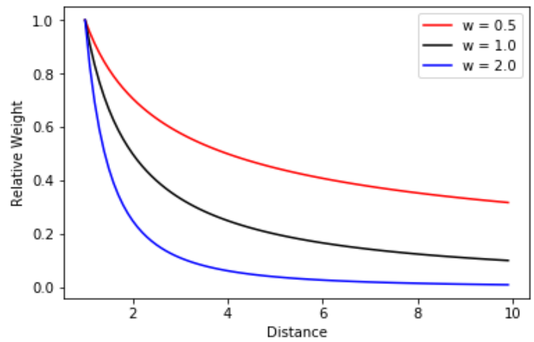

Figure 5. Decay of weighting as a function of distance for various values of w.

Another factor affecting the accuracy of IDW is the size of the domain over which stations are selected for interpolation. For this study, we found that limiting the number of stations used (e.g. to the 3, 6, and 10 closest stations) had only a minor effect on mean errors, with accuracy generally improving for higher numbers. However, as missing values are a persistent occurrence across the 28-station rainfall record, on a month-to-month basis not all of the chosen stations may be contributing data for the interpolation. Hence, to mitigate the effect of missing station data, all 28 contemporary stations were used for the IDW interpolation.

The performance of IDW in interpolating station rainfall for Singapore is assessed by recreating the observed monthly rainfall at Kampung Bahru station (S31, Figure 2) from 1980 – 2014, KB_m, by IDW interpolation using contemporary data from 27 stations (i.e. excluding Kampung Bahru). The hypothetical $KM_{m'}$

is then cross-validated against the actual KB_m using the coefficient of correlation (r), the mean absolute error (MAE), mean relative error (MRE), and root mean squared error (RMSE) (Table 2). This station was chosen as it possesses a nearly complete monthly rainfall record, enabling more accurate cross-validation, and more importantly, is located in proximity to the cluster of identified historical stations. Since IDW is built upon a non-linear distance function, its effectiveness as an interpolator is dependent on the relative geometric distribution of known data points. This is unique for each station location but will be similar for stations in close proximity. The comparison between $KB_{m'}$ and KB_m should therefore approximate the effectiveness of IDW in interpolating for rainfall at the locations of the historical stations.

On a monthly scale, the recreated $KB\_{m'}$ correlates very well with the observed KB_m (Figure 6, Table 3). The calculated r value (0.941) greatly exceeds the threshold for statistical significance ($r\_(0.05,n=411)$= 0.0978). Both the MAE (28.9) and RMSE (37.4) are small and on par with the measurement uncertainty reported from the MacRitchie observations site between MSS and PUB instruments, and considering the MRE (0.140), also relatively minor. The correlation decreases slightly when aggregating the data annually ($r = 0.83$; $r_{0.05,\ n=30} = 0.35$), due to the effect of 2 outliers in 1983 and 2014 (in which IDW severely underestimated observed annual station rainfall). Nonetheless, on annual scales the MRE is only 0.05 (MAE = 127.4, RMSE = 204.9), which is in fact smaller than the current MacRitchie instrument error (MAE = 223.8, RMSE = 260.3) However, there appears to be a tendency for IDW to slightly underestimate KB_m. Considering Figure 6, this seems to stem from inaccurate representation of extreme rainfall events, as errors tend to be significantly larger, and consistently negative, for the wettest months. As IDW is an exact deterministic interpolator, maxima and minima can only occur at known data points. The interpolated point, being a weighted average, will always be less than the maximum of the set of values used in its calculation (Tomczak, 1998). High rainfall months arising from spatially localized convective precipitation centred over Kampung Bahru will thus be consistently underestimated by IDW. Fortunately, systematic errors are mitigated by the density of meteorological stations in Singapore, since the distance separation between stations is far less than the characteristic length scales of the weather systems affecting Singapore.

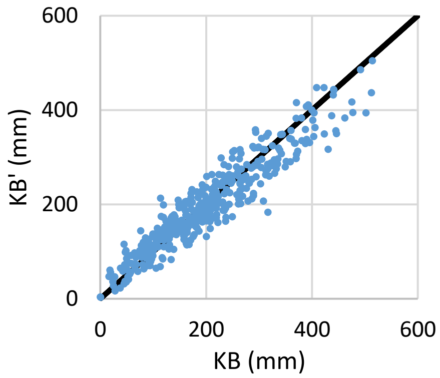

Figure 6. Recreated monthly rainfall at Kampung Bahru for 1980—2014 using IDW spatial interpolation of data from 27-station meteorological network (*$KM_{m'}$*) against actual *KB_m*. The black line represents a 1:1 relationship.

Table 3. Errors associated with IDW interpolation for Kampung Bahru on monthly and annual timescales

KB' vs KB 1980—2014	*r*	MAE	RMSE
Monthly	0.941	28.9	37.4
Annual	0.826	127.4	204.9

Reconstructing MacRitchie rainfall from historical station data

IDW spatial interpolation yields 420 rainfall time series data points (monthly values for 1980 – 2014) for the location of each historical station, which are then compared against the observed monthly MacRitchie rainfall, $MacRF_m$, over the same period. The ratios of $h_{pm}/MacRF_m$ are averaged by month to give $h_{p\bar{m}}/MacRF_{\bar{m}}$. For example, a $h_{p\bar{m}}/MacRF_{\bar{m}}$ value of 1.11 for January for River Valley Road indicates this station received on average 11% more rainfall than MacRitchie station during January in the 1980—2014 reference period. The historical rainfall measurements compiled for each station, H_pm, can then be inverted to give an estimate of historical monthly rainfall at MacRitchie:

$$HMacRF_{pm} = H_{pm} \times \left({h_{p\bar{m}}}/{MacRF_{\bar{m}}} \right)^{-1} \qquad (2)$$

where $HMacRF_{pm}$ is the estimate of historical rainfall at MacRitchie by a particular station p for month m. Separate MacRitchie time series are produced from each historical station depending on the period in which station data is available, allowing the skill of each individual station reconstruction to be assessed. The final monthly $HMacRF_m$ (1835—1883) compiles all the historical time series, averaging across individual station reconstructions when more than one is available.

Since $MacRF_m$ overlaps with $HMacRF_m$ from 1879 to 1883 (PUB instrument record only), the fit of each historical rainfall reconstruction (equations 1 + 2) against the observed record can be evaluated using the same validation metrics described above (*r*, MAE, MRE, and RMSE). Errors associated with the historical reconstruction are evaluated against the errors registered between the PUB and MSS instruments in the current MacRitchie record, the latter of which provides an estimation of the reasonable expectation of error even with a perfect reconstruction. Unfortunately, the relatively short period of overlap, only enables the fit of 5 individual station $HMacRF_{pm}$ time series to be validated (H3, H6, H7, H9, and H10). Finally, the correlation of each $HMacRF_{pm}$ time series against each other, where there is temporally overlapping data, is also assessed to determine the robustness of the reconstruction technique.

RESULTS AND DISCUSSION

The reconstructed historical MacRitchie monthly rainfall time series, $HMacRF_m$, is presented in Figure 7(a). A large gap exists between October 1845 and December 1861, where no published historical data have surfaced yet. Much of the meteorological data collected begins in the late 1860s onwards, giving a continuous rainfall record from Jan 1862—Dec 1883.

RELIABILITY OF HISTORICAL MACRITCHIE RECONSTRUCTION

As stated earlier, in reconstructing HMacRF, equation (2) assumes that the (mean) temporal and spatial relationship of rainfall between stations has not changed as a result of natural and anthropogenic climate change, nor recent urbanisation factors. Obviously, ignoring the effects of urbanisation is highly tenuous, especially considering the rapidity of Singapore's urban development since the 19th century, but is perhaps reasonable in this study as the identified stations were located in historically urban areas, and

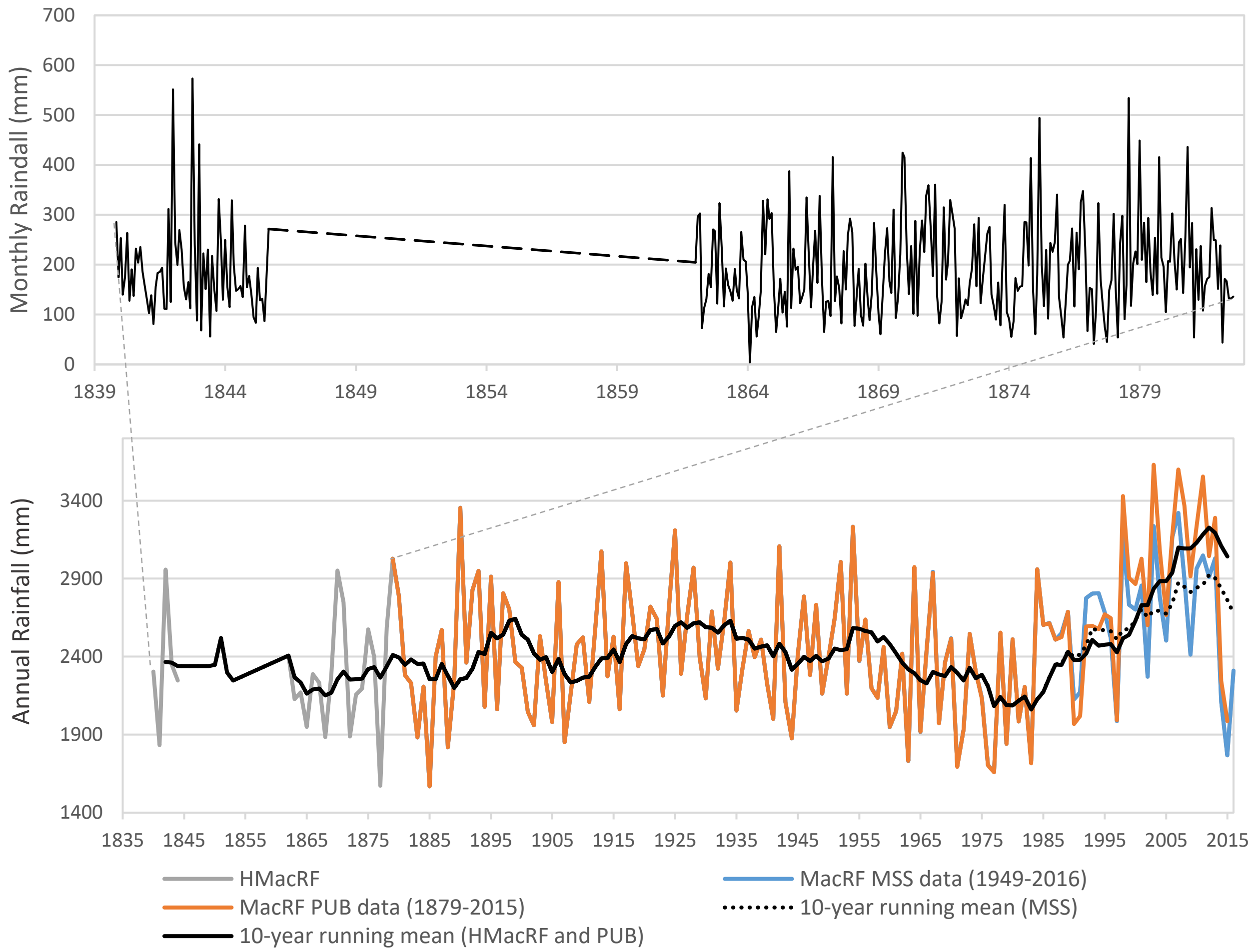

Figure 7. (a) Reconstructed historical MacRitchie monthly rainfall time series ($HMacRF_m$), based on straight averaging of available historical station estimates ($HMacRF_{pm}$) for the period 1835—1883. (b) Annual rainfall time-series, including official records, with 10-year running mean.

therefore experienced much less land use change than typical of other parts of Singapore. Indeed, the consistency of station-by-station $HMacRF_p$ (r > 0.8 typically, based on comparisons between stations with temporally overlapping records) supports the long-term stability of spatial relationships.

Table 4. Cross-validation statistics between reconstructed HMacRF and official monthly and annual MacRitchie rainfall (MacRF) for the period 1879—1883. Statistics for the December months are based on individual station estimates.

$HMacRF_m$ vs $MacRF_m$		n	r	MAE	RMSE	MRE
Monthly	All	60	0.81	43.6	56.7	0.21
	Dec	12	-	94.0	110.7	0.46
Smoothed 3-Monthly		58	0.84	21.2	26.9	0.09
Annual		5	0.97	147.9	165.7	0.06
KK Hospital (H10)		60	0.78	46.6	62.6	0.24
Convict Jail (H9)		36	0.80	49.8	63.8	0.24
Mount Pleasant (H7)		24	0.93	26.1	33.4	0.11

Cross-validation of the composite $HMacRF_m$ time series against $MacRF_m$ for the period of 1879—1883 suggests that, although errors on a monthly scale are indeed larger than IDW interpolation alone, these errors are relatively small. r (0.806) is still well above thresholds of statistical significance ($r_{0.05,n=60}$ = 0.25), though MAE (43.6) and RMSE (56.7) are slightly larger, giving a MRE of 0.21 (Table 4). Both MAE and RMSE are considerably lower than the mean standard deviation in monthly rainfall observed for $MacRF_m$ from 1980 – 2014, which ranges between 70.3mm for the month of June to 149.9mm for the month of January. There also appears to be no systematic bias in error magnitude as a function of monthly rainfall. Meanwhile, notwithstanding the small sample size, errors associated with annual rainfall estimates are effectively no different from IDW (Table 3) and only slightly larger than the modern instrument error baseline (r = 0.91) with similarly high correlation (r = 0.97; $r_{0.05,n=5}$ = 0.81), and low MAE (147.9), RMSE (165.7) and MRE (0.06). Surprisingly, there is a reduced tendency for underestimation of annual rainfall, which could be the result of averaging estimates, both across stations in building $HMacRF_m$ and within stations in using the mean monthly $h_{p\bar{m}}/MacRF_{p\bar{m}}$.

However, the use of the annual mean $h_{p\bar{m}}/MacRF_{p\bar{m}}$ may underestimate changes in rainfall variability over time, compounding the shortfalls of the IDW interpolation. $h_{p\bar{m}}/MacRF_{p\bar{m}}$ is fairly constant throughout the year and across stations (Table 5), suggesting that seasonal rainfall variability is more or less spatially consistent, with the exception of December, January and February. For these three months, the standard deviation of calculated ratios over 35 years is substantial, implying significant temporal variability, and this is consistently so across all stations. The use of the annual mean $h_{p\bar{m}}/MacRF_{p\bar{m}}$ ratio in the historical reconstruction may thus be unsuitable for DJF season, possibly due to the dominance of the large scale rainfall (e.g. monsoon surges) characteristic of the early wet phase of the Northeast Monsoon season. Considering the average standard deviation of December $h_{pm}/MacRF_{pm}$ across all stations (1.49), the 95% confidence interval for the December mean ratio is captured by a range of ±0.49, which gives variation in the historical MacRitchie reconstruction on the order of ±50-100mm. Nevertheless, the average monthly

Table 5. Standard deviation of $h_{pm}/MacRF_{pm}$ by station from IDW interpolation for the period 1980 – 2014.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Goodwood (H1)	0.289	0.833	0.155	0.187	0.244	0.240	0.291	0.160	0.225	0.225	0.172	1.298
Pauper's (H2)	0.213	0.890	0.164	0.179	0.233	0.268	0.309	0.167	0.223	0.222	0.177	1.229
P&O's Depot (H3)	0.692	0.389	0.269	0.314	0.337	0.311	0.365	0.286	0.366	0.397	0.293	2.214
Perseverance Est. (H4)	0.195	1.390	0.257	0.227	0.318	0.413	0.341	0.214	0.276	0.290	0.225	1.253
River Valley Rd (H5)	0.440	0.606	0.202	0.245	0.289	0.290	0.357	0.211	0.292	0.282	0.226	1.694
SGH (H6)	0.700	0.379	0.298	0.327	0.373	0.342	0.394	0.304	0.377	0.376	0.303	2.280
Mount Pleasant (H7)	0.114	0.571	0.084	0.089	0.126	0.123	0.145	0.080	0.108	0.113	0.084	0.616
Sg Observatory (H8)	0.221	0.926	0.178	0.193	0.261	0.297	0.356	0.189	0.254	0.255	0.197	1.354
Convict Prison (H9)	0.370	0.670	0.182	0.226	0.277	0.282	0.368	0.201	0.280	0.274	0.218	1.594
KK Hospital (H10)	0.290	0.828	0.160	0.194	0.252	0.260	0.325	0.173	0.243	0.240	0.187	1.384
Ryan's Hill (H11)	0.289	0.833	0.155	0.187	0.244	0.240	0.291	0.160	0.225	0.225	0.172	1.298

standard deviation for the MacRitchie (PUB) time-series (1879 – 2016) during December is 127.9mm, so it should be possible to detect signals of natural variability even during the most uncertain month of the year. Smoothing $HMacRF_m$ using a 3-month running mean also reduces errors considerably (Table 4), suggesting the reconstructed time series may be useful for seasonal analyses.

Part of the monthly variability in $h_{p\bar{m}}/MacRF_{p\bar{m}}$ may be mitigated by preferentially selecting/weighting stations nearest MacRitchie when building the composite $HMacRF_m$ time series. For example, Mount Pleasant, which is the station closest to MacRitchie, has the lowest spread of $h_{p\bar{m}}/MacRF_{p\bar{m}}$ ratios in December. Looking at the reconstructed time series from individual stations (Table 4), once again it is apparent that errors are reduced with proximity to MacRitchie (KK Hospital to Mt Pleasant) note that stations in Table 5 are listed in descending order of distance with respect to MacRitchie), though in this case the variable amount of data available for comparison must also be considered. Determining how this weighting function should evolve with distance from MacRitchie requires further study. In the absence of other evidence characterising the spatial nature of rainfall around MacRitchie, the final $HMacRF_m$ time series is built using a simple average of available $HMacRF_{pm}$ data, with all station reconstructions given equal weighting regardless of distance to MacRitchie,

Conclusion

Singapore is fortunate to have possibly the longest single-site historical monthly rainfall record within the tropics for the MacRitchie station extending as far back as 1879, although the reliability of reported measurements is not without question with various data sources indicating different values. We have shed new light on the differences between the various data sources to help come up with an authoritative time-series.

In addition, newly discovered historical source materials provide monthly observations as far back as 1835, albeit incomplete. Through careful review of archived historical map data, the locations of the identified meteorological stations have been determined. By estimating the spatial relationships of rainfall over Singapore using the modern meteorological station network, a reconstructed historical rainfall at the MacRitchie location has been generated, thereby integrating these fragmentary historical datasets with the official long-term Singapore rainfall record.

This single time-series extended back in time and documented in terms of the difference between various records for the modern area provides a strong basis for studies on decadal to inter-decadal climate variability in Singapore and the neighbouring Western Maritime Continent. Meanwhile, the search for alternative sources of rainfall data during the 1840s to 1860s will continue to help fill in the remaining gaps in the current historical reconstruction.

An important caveat to note for future usage of this time series, is that due to uncertainties regarding the variability of spatial rainfall distributions, as well as the precise location of some of the historical measuring stations, analysis of the reconstruction should be limited to seasonal and annual time scales, and relying on single month values should be avoided at least for the winter months (December, January and February).

Further studies, examining the spatial pattern of rainfall in Singapore, could help constrain the appropriateness of the parameters used in the IDW interpolation, as well as investigate other interpolators that could perform better than IDW. This could enable the inclusion of a wider range of historical station data, for example measurements taken at the Raffles and Horsburgh Lighthouses, which could help fill the gaps in the reconstruction.

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