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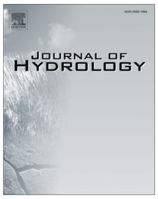

Research papers

Realistic sampling of anisotropic correlogram parameters for conditional simulation of daily rainfields

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ABSTRACT

This paper has established a link between the spatial structure of radar rainfall, which more robustly describes the spatial structure, and gauge rainfall for improved daily rainfield simulation conditioned on the limited gauged data for regions with or without radar records. A two-dimensional anisotropic exponential function that has parameters of major and minor axes lengths, and direction, is used to describe the correlogram (spatial structure) of daily rainfall in the Gaussian domain. The link is a copula-based joint distribution of the radar-derived correlogram parameters that uses the gauge-derived correlogram parameters and maximum daily temperature as covariates of the Box-Cox power exponential margins and Gumbel copula. While the gauge-derived, radar-derived and the copula-derived correlogram parameters reproduced the mean estimates similarly using leave-one-out cross-validation of ordinary kriging, the gauge-derived parameters yielded higher standard deviation (SD) of the Gaussian quantile which reflects uncertainty in over 90% of cases. However, the distribution of the SD generated by the radar-derived and the copula-derived parameters could not be distinguished. For the validation case, the percentage of cases of higher SD by the gauge-derived parameter sets decreased to 81.2% and 86.6% for the non-calibration and the calibration periods, respectively. It has been observed that 1% reduction in the Gaussian quantile SD can cause over 39% reduction in the SD of the median rainfall estimate, actual reduction being dependent on the distribution of rainfall of the day. Hence the main advantage of using the most correct radar correlogram parameters is to reduce the uncertainty associated with conditional simulations that rely on SD through kriging.

1. Introduction

The Great Barrier Reef (GBR) off the coast of Queensland, Australia, covers an area of 344,400 km^2 and is the largest coral reef system in the world. GBR has a significant economic importance to Australia as a major tourist attraction and efforts are being made to protect it from anthropogenic activities including agriculture and mining. One such effort includes modelling of the transport of sediments, nutrients and inhibiting herbicides from catchments to the reef system. A total area of 423,134 km^2 consisting of 35 major basins drain coastal Queensland to the GBR (Waters et al., 2014). Hydrological studies of such large catchments involving the use of spatially distributed hydrological models require adequate daily rainfall data. In order to make use of the long records of over 100 years daily rainfall, conditional simulation using kriging to estimate the mean and standard deviation (SD) of the Gaussian quantile is required to generate daily rainfields at 1 km^2 grid size over the catchments. Analysing radar images, Gyasi-Agyei and Pegram (2014) established that daily gauge network density should be better than one gauge per 16 km^2 to review the full spatial structure. Therefore, the daily rain gauge network density worldwide is not adequate to capture the spatial structure of rainfall. This shortfall calls for innovative ways of realistic spatial and temporal interpolation of the limited gauged data over the grid or functional units used in the hydrological models.

Several spatial interpolation techniques prevail in the literature, including inverse weighted distance (Teegavarapu and Chandramouli, 2005), nearest neighbours (Isaaks and Srivastava, 1990), thin plate splines (e.g., Jeffrey et al., 2001), kriging (e.g., Ly et al., 2011; Cressie, 1993) and spatial copula (e.g., Bárdossy and Pegram, 2009). However all the interpolation techniques share a common feature of weighted averages of the sampled data, and the differences are basically how the weights are calculated. A recent review on the spatial interpolation methods in environmental science can be found in Li and Heap (2014). With regards to rainfall, copula and kriging based methods are the most popular. Despite some problems, such as ground clutter and conversion methods of radar reflectivity to rainfall intensity (Villarini and

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Krajewski, 2010), interest in the use of radar sourced rainfall in hydrological modelling is increasing. Quirmbach and Schultz (2002) are among the few researchers that have directly used radar rainfall in water resources. Wang et al. (2013) and Rabiei and Haberlandt (2015) used mean bias reduction and error variance minimisation to adjust the radar data on limited gauged data. Verworn and Haberlandt (2011) and Velasco-Forero et al. (2009) used radar data in kriging with external drift. In the same vein, satellite-based high-resolution rainfall products (e.g. CMORTH, Joyce et al., 2004; TMPA 3B42 and TMPA 3B42RT, Huffman et al., 2007; PERSIANN, Hsu et al., 1997) are being looked into for regions without ground-based radar, despite problems associated with atmospheric effects and gaps in revisit times among others (e.g., Bitew and Gebremichael, 2011).

This paper further develops the work by Gyasi-Agyei and Pegram (2014) and Gyasi-Agyei (2016) on the use of rainfall radar to understand the spatial structure for possible transfer of information from radar regions, and time spans, to areas and time spans without radar records for maximum benefit in terms of uncertainty. In Gyasi-Agyei and Pegram (2014), daily accumulations of radar rainfall of a region within Free State, South Africa, were used to develop the spatial structure, and a weak link by way of a transition probability matrix was established between the Gauge Wetness Ratio (GWR) and Radar Wetted Area Ratio (RWAR). GWR and RWAR are defined as the ratio of gauges/pixels that equalled or exceeded 2 mm rainfall and the total number of gauges/pixels, respectively. Application of the methodology to Queensland, Australia, data set required major structural changes as outlined in the ensuing sections. Of particular significance are the:

- use of gauge correlogram parameters and maximum temperature as covariates for the radar correlogram parameters through a generalised additive model;
- use of zero inflated standard distributions for the daily rainfall amounts;
- establishment of a copula-based joint distribution of the correlogram axes lengths;
- introduction of a new harmonic distribution for the correlogram direction parameter; and
- validation of the model for different catchments and time spans.

Gyasi-Agyei (2016) examined the effect of the locally varying anisotropy exhibited by radar rainfall within the same square region used in this paper. It was concluded that locally varying anisotropy did not significantly improve the estimates, and hence the use of the global anisotropy suffices.

The next section presents the data sets and processing used in this paper followed by the two-dimensional (2D) spatial correlogram development. What follows is the detailed analysis and modelling of the dependence structure (marginal and joint distributions) of the correlogram parameters. Application of the model to a test catchment and time span for validation is then presented before the concluding summary points. All analyses were done with R (R Core Team, 2015) statistical software.

2. Study area and data processing

The study area includes the Brisbane river catchment (13,533 km^2), and a square region (128 km × 128 km) within the range of the Mt. Stapylton weather radar station near Brisbane, Australia. As shown in Fig. 1, the two regions, which will be referred to as the catchment and the square region, have an intersection area of 4982 km^2. The square region was chosen primarily because of the high density of daily rain gauges nearest to the radar station. The weather radar of a Meteor 1500 S-band Doppler type with a range of 256 km is located at latitude 27.718°S and longitude 153.240°E. In order to conform to the spatial unit of the radar data of 1 km^2 resolution, the latitude and longitude coordinate system of the daily rainfall gauged stations were converted to the Universal Transverse Mercator (UTM) easting and northing using the *spTransform* function of R package *rgdal* (Bivand et al., 2015) with the datum set to WGS84 for zone 56 (Fig. 1). This study area is located in a subtropical climate with an average temperature of 26.5 °C, and an annual mean rainfall of about 990 mm with an average of 124 wet days per year. It experiences hot humid summers (December–February) and moderately dry winters (June–August), with torrential rain associated with thunderstorms being very common.

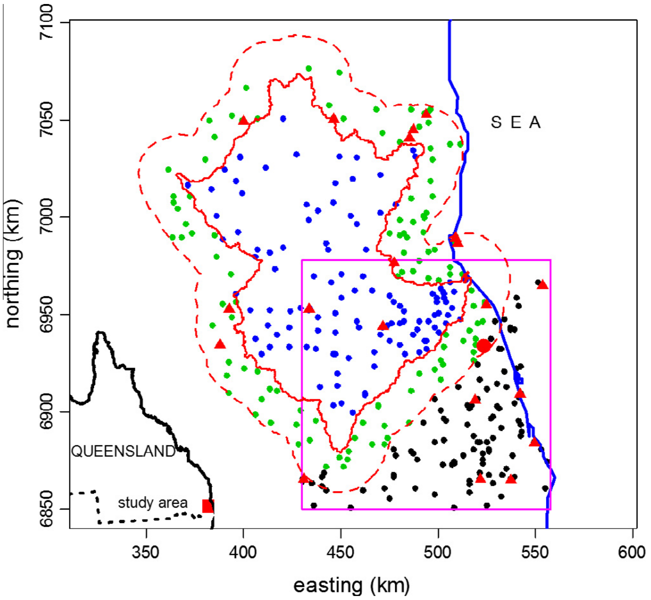

Fig. 1. Study area: red solid irregular boundary defines the Brisbane river catchment; red dashed boundary defines the 20 km buffer; blue dots are the daily gauges inside the catchment boundary and the green dots are those within its 20 km buffer; violet square boundary defines the 128 km × 128 km region within the range of Mt. Stapylton (near Brisbane) weather radar station (red solid circle), Australia; black dots are gauges within the square region but not used as catchment data; red triangles are the temperature stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

It needs to be mentioned that the square region is the same as used in Gyasi-Agyei (2016). However, the period considered in this paper is from 2000-01-01 to 2015-06-30. There were 234 daily rainfall gauges located in the square region (1 gauge per 70 km^2), 115 within the catchment (1 gauge per 118 km^2), and 238 within the 20 km buffer of the catchment (Fig. 1, dashed red line, 27,227 km^2), for the period under investigation. Gauges outside the catchment boundary and within the buffer were included to minimise edge effects in the kriging process. Some of the gauging stations were closed and new ones opened during the study period. For each day, only the operational gauges were used as the days were considered independent. This caused the number of gauges to vary between 148 and 200 for the square region, and between 67 and 100 within the catchment (130–196 including the buffer zone). Gyasi-Agyei (2013) found that the maximum daily temperature of the day has significant effects on the sub-daily rainfall characteristics, so it was considered as a covariate, notwithstanding that its correlation with the variables of interest was checked. Within the study area there were 19 temperature stations. For each day, the maximum daily temperature values of the operational stations were interpolated over the region by inverse weighted distance method and the average values within the catchment

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