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Interpolation of daily rainfall networks using simulated radar fields for realistic hydrological modelling of spatial rain field ensembles

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SUMMARY

Given a record of daily rainfall over a network of gauges, this paper describes a method of linking the Gauge Wetness Ratio (GWR) on a given day to the joint distribution of the parameters of the anisotropic correlogram defining the spatial statistics of simulated radar-rainfall fields. We generate a large number of Gaussian random fields by sampling from the correlogram parameters conditioned on the GWR and then conditionally merge these fields to the gauge observations transformed into the Gaussian domain. Availability of such a tool allows better spatially distributed hydrological modelling, because good quality ensemble spatial information is required for such work, as it yields uncertainty of the fields so generated. To achieve these ends, correlograms of many Gaussianised daily accumulations of radar images were developed using the Fast Fourier Transform to generate their sample power spectra. Empirical correlograms were fitted using a 2D exponential distribution to yield the 3 key parameters of the correlogram: the range, the anisotropy ratio and the direction of the major axis. It was found that the range follows a Gamma distribution while the anisotropy parameters follow a Loglogistic one; a t5 copula was adequate to capture the bivariate negative dependence structure between the range and ratio. The Radar Wetted Area Ratio (RWAR) drives the parameters of the correlogram, and its link with GWR is modelled by a transition probability matrix. We take each of the generated Gaussian random fields and conditionally merge it with Gaussianised rainfall values at the gauge locations using Ordinary Kriging. The method produces realistic simulated radar images, on a grid chosen to suit the data, which match the gauge observations at their locations. Ensemble simulations of 1000 samples were used to derive the median and the interquartile range of the fields; these were found to narrow near the control gauge locations, as expected, emphasising the value of high density gauge networks. Ongoing research is looking towards integration of the presented methodology with a stochastic daily rainfall generator for useful spatial rainfall simulation over catchments with gauged records.

1. Introduction

This paper sets out to present a new means of interpolating rainfall between gauges. The method draws from information where a network of daily rain gauges has recorded for a few years simultaneously with a weather radar. We constrain ourselves to daily rainfall at this stage. The idea is not to condition the observed radar rainfields on the gauges, as has been done in other studies, but rather to find the links between the statistics of both sets of records in order to allow intelligent spatial interpolation between gauges where there are no radars. This is in contrast with the commonplace application of Kriging to perform interpolation of expected fields over a gauge network. We offer something more valuable and informative.

With the advent of Geographic Information Systems (GISs) and advances in computer technology, grid-based (or Digital Elevation Model, DEM) spatial distributed hydrological modelling has become a viable option. These hydrological models include those used for water resources planning, modelling and simulation, assessment of climate change and anthropogenic activities on the hydrological processes, at the daily timescale. However, the basic input of daily rainfall, and other atmospheric variables such as temperature that drive the hydrological models, has historically been measured by gauges that provide information at points scattered over the catchments with gauge densities varying between 1 per 25 km^2 to over 10,000 km^2. Therefore, a quality spatial interpolation of the few available stations' daily records is required for

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better hydrological modelling, as the model outputs are dependent on the quality of the inputs. In particular, for small to medium catchments, simple averaging of the point estimates of rainfall may undermine the quality of the simulated runoff, and thus the day-to-day spatial variability of rainfall needs to be captured as far as possible.

It has been highlighted in the literature that the spatial variability of rainfall is the dominant controlling factor of runoff generation over catchments and needs to be captured properly (e.g., Shah et al., 1996; Segond et al., 2007). Also the locations of the limited rain gauges within the catchment play a crucial role in capturing and understanding the influence of the spatial variability of rainfall on runoff (e.g., Bell and Moore, 2000). Unfortunately rain gauge density is typically quite low due to the high cost of monitoring, calling for effective ways of interpolating the available records. In recent years, ground-based radar and meteorological satellites have been used to estimate rainfall. While these instruments provide a good source of understanding the spatial variability of rainfall, the rainfall intensities produced inherit some errors from the nature of the devices and the algorithms used for converting the radiometric measurements to rainfall (e.g., Krajewski et al., 2010).

The problem this paper addresses is that, given a network of rain gauges which has recorded daily rainfall for several years, how can we meaningfully interpolate the rainfall between them to give an estimate of the average depth of daily rain over a range of spatial scales, as well as a measure of the variability of the estimate? And how can we then use these links to interpolate fields between gauge networks not covered by radar? These are questions of interest to hydrologists conducting rainfall-runoff modelling studies of catchments. We felt the need to go beyond (i) arithmetic averages and (ii) Thiessen polygons and to extend the ideas of Bras and Rodríguez-Iturbe (1985) and Pegram and Pegram (1993) who used integration of Kriged surfaces to estimate the areal depths. We generate random fields modelled on daily accumulations of radar images with the appropriate spatial correlation structure as the interpolating functions, which are combined with the gauge observations, using the method of conditional merging introduced by Sinclair and Pegram (2005) and Ehret et al. (2008). The method used in those studies was designed to improve the rainfall estimates offered by radars over gauge networks and has been successfully applied by Verworn and Haberlandt (2011) amongst others. In contrast, the application of conditional merging here is not to condition actual observed radar measurements, but to condition random fields which have the same statistical properties as radar rain fields, taking note of the gauge network statistics. The technique of generating appropriately spatially correlated random fields was used by Pegram and Clothier (2001) in the development of the String of Beads Model. The innovation introduced herein is that we extend the method to random fields with anisotropic two-dimensional (2D) correlation structures, to model daily rain fields which commonly exhibit the effects of advection. These correlated Gaussian random fields are then conditionally merged onto the gauge network, matching the values at the gauges exactly, whether the network values at the gauge sites be observations or simulations as produced by a daily rainfall model like that of Srikanthan and Pegram (2009) or Bárdossy and Pegram (2009). These modelled fields can then be used for sensitivity analysis in hydrological applications. However, we note in passing that the 5-min radar scans we used to extract the spatial dependence of the daily accumulations were not bias corrected, because we were not using them directly in the interpolation exercise. We consider that any existing bias would not affect the spatial correlation structure, given that the relative spatial differences are maintained, even after shifting and scaling any such field, because technically the correlations between raw and standardised variables are identical. In addition, we did not consider the serial correlation between the fields on successive days, because the serial correlation between daily gauged rainfall amounts is typically of the order of 0.14, which means that only 2% of the variance of one day following another can be predicted and is usually neglected in the simulation of daily rainfall network (e.g., Srikanthan and Pegram, 2009).

What follows in this paper is the description of the method used to achieve the objectives in a meaningful way. The study region and data used are first presented. This is followed by the description of the Gaussian transformation applied to the wet days' gauge daily rainfall records in order to meaningfully treat the zeroes in the data, a method which brings associated advantages. Special attention is given to the modelling of the 2D spatial correlogram in order to allow for simulation of the correlogram. A simplified explanation of the 2D copula used for modelling the bivariate distribution of the correlogram range and anisotropy ratio is then presented. Ordinary Kriging and the overview of the Gaussian random field simulation strategy is briefly discussed before presenting the results, comparisons and conclusions.

2. Methodology

To provide a relatively detailed summary of the methodology used in this paper, we outline the technical steps here:

a. Accumulate 5-min radar rainfall estimates of available wet days.
b. Extract the statistics of the daily radar field accumulations, including the Radar Wetted Area Ratio (RWAR) and the 2D spectrum and hence derive the 2D correlogram for the day. Fit an anisotropic (elliptical exponential) model correlogram and extract its relevant statistics.
c. Analyse matching spatial gauge rainfall data on the day concerned and extract relevant statistics, including the marginal distribution and the Gauge Wetness Ratio (GWR), of the Gaussianised rainfall amounts, taking zero rainfall into account.
d. Find links between the statistics of the daily gauge and radar rainfall to permit choosing radar rainfield properties that might match a selected day's observed rainfall. In particular, model statistical connections between the variables describing the fields to exploit the linkages between gauge and radar information on each day.
e. In order to conditionally infill the space between historical gauge observations, take each day's gauge statistics and choose a set of matching radar characteristics.
f. Simulate many Gaussian radar fields using these statistics and conditionally merge each field with the transformed gauge values.
g. Compute the spatial quartiles of the sets of conditioned fields, to allow determination of the precision of the conditioned simulation.
h. Reverse transform the Gaussianised fields (with means and quartiles if desired) to the rainfall domain, for use as spatial ensembles of plausible rainfields (with uncertainty) on each day for hydrological applications.

2.1. Study region and data

The region under study is in the Free State, South Africa, using the set of gauges used in Pegram and Bárdossy (2013) which had been carefully selected in that project (Fig. 1, left) as they required minimal infilling. The climate for the region is characterised as semiarid with average annual rainfall of about 650 mm, most