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Sensitivity of a lumped and semi-distributed hydrological model to several methods of rainfall interpolation on a large basin in West Africa

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Summary This paper examines the sensitivity of a hydrological model to several methods of spatial interpolation of rainfall data. The question is investigated in a context of scarcity of data over a large West African catchment (100,000 km^2) subject to a drastic trend of rain deficit since the 1970s. Thirteen widely scattered rainfall stations and their daily time series were used to interpolate gridded rainfall surfaces over the 1950–1992 period via various methods: Thiessen polygons, inverse distance weighted (IDW) method, thin smooth plate splines (spline), and ordinary kriging. The accuracy of these interpolated datasets was evaluated using two complementary approaches. First, a point-by-point assessment was conducted, involving comparison of the interpolated values by reference to observed point data. Second, a conceptual rainfall–runoff model (Hydrostrahler) was used in order to assess whether and to what extent the alternative sets of interpolated rainfall impacted on the hydrological simulations. A lumped modelling exercise over a long period (1952–1992) and a semi-distributed exercise over a short period (1971–1976) were performed, using calibrations aimed at optimizing a Nash–Sutcliffe criterion. The results were evaluated for each interpolated forcing dataset using statistical analysis and visual inspection of the simulated and observed hydrographs and the parameters obtained from calibration. Assessment of the interpolation methods by reference to point data indicates that interpolations using the IDW and kriging methods are more efficient than the simple Thiessen technique, and, to a lesser extent, than spline. The use of these data in a daily lumped modelling application shows a different ranking of the various interpolation methods with regard to various hydrological assessments. The model is particularly sensitive to

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the differences in the rainfall input volume produced by each interpolation method: the IDW dataset yields the highest hydrological efficiency while the spline dataset gets the poorest results. Although the calibration procedure makes it possible to partly compensate for the differences (or errors) between rain input datasets, the semi-distributed hydrological model remains sensitive to volumetric and spatial differences. Then, assessment of these combined differences through the sensitivity of the semi-distributed model provides us with more complete discrimination between the interpolated data inputs. The output results at the basin outlet do not decrease between the lumped and semi-distributed modelling exercises with the IDW and kriging datasets, in contrast to the Thiessen and spline datasets, which tends to indicate the superiority of the former two interpolated inputs. In this hydrological application, the IDW dataset is still shown to provide the most realistic results. Moreover, despite the scarcity of rainfall data, coherent semi-distributed values of the model parameters are obtained by calibration over a large gradient of climate conditions. Finally, it is observed that although the model reproduced the rainfall–runoff relationship before 1970 very well, regardless of which interpolated datasets were used, it was not able to satisfactorily simulate the basin behaviour after the change in rainfall regime. This inability needs further investigation and is the subject of ongoing research.

Introduction

The climate of West Africa is controlled by a monsoon system of atmospheric circulation, driven by the seasonal oscillation of the Intertropical Convergence Zone. This oscillation has relatively little effect on temperatures, but it generates a particularly stable, well-marked seasonal cycle of precipitation. Dry and rainy seasons alternate once or twice a year, depending on whether the area concerned is closer to the tropic (Sahelian zone, semi-arid) or to the equator (Guinean zone, humid). Total annual rainfall increases rapidly from north to south. Rainfall is close to zero for long periods, and is thus less than potential evapotranspiration (PET) for most of the year, particularly in the Sahel. This makes the region very sensitive to rainfall deficits; its water stores (soil, groundwater, surface water) cannot serve as a buffer against long periods of insufficient rainfall. Any deficit, even for a relatively brief period during the rainy season, can have significant consequences because it reduces the short period during which evapotranspiration demand can be satisfied – a period that is crucial for reconstituting surface and subsurface water stores and for meeting the water requirements of plants, animals and human beings. For thousands of years, human populations have adapted to several long cycles of moist periods and drought. However, several authors (Hubert et al., 1989; Nicholson et al., 1998; Servat et al., 1998; L'Hôte et al., 2002) have shown that around the year 1970, rainfall dropped in most of the countries of West Africa, and there followed an unprecedented period of persistent drought that has now lasted for nearly four decades. Depending on the area considered, the decrease in annual precipitation between 1950–1960 and 1970–1980 ranged from 15% to 30%, the hardest-hit area being the Sahel, where the isohyets shifted more than 100 km south (LeBarbé et al., 2002). Opinions vary as to whether there is any sign of an end to this adverse climatic trend, which has yet to be explained. Tapsoba (1997) has shown that rainfall events have declined in number rather than in average yield and that the deficits are due mainly to the extension of rainless periods within the rainy season, and, to a lesser extent, to the shortening of the rainy season. Considering the limited storage capacity of the surface environment, mentioned above, these variations have an obvious impact on hydrological, agronomic and ecological functioning.

The large West African rivers, which are fed primarily by the Guinean and Sudanian humid zones, have especially suffered from the drought, as their runoff deficits exceed the rainfall deficit by a factor of 2 on average (Servat et al., 1997). Paradoxically, however, small Sahelian hydrosystems have attenuated or even compensated for the runoff deficit; for instance, hydrological analysis taking climatic and anthropogenic changes into account has shown that the transition from a wet period under 'natural' land cover (1950s) to a dry period under a cultivated land cover (1980s, 1990s) has resulted in a 30–70% increase in runoff on Sahelian catchments (Séguis et al., 2004; Mahé et al., 2005). The mechanisms underlying these opposite behaviours and this non-linear rainfall–runoff relationship are far from fully understood. A role is probably played by: (i) the differences between the hydrological processes prevailing in each regional zone, in association with their respective biogeoclimatic conditions; (ii) changes (varying between zones) in plant cover and surface conditions that have occurred simultaneously with the climatic disturbance and that may have changed runoff and soil infiltration conditions; (iii) the respective scales of the systems considered (B. Cappelaere, personal communication). Over the last 50 years, the region has seen a general degradation of its plant cover, with a particularly sharp decline in the Sahelian zone. This environmental degradation, though probably partly due to the effects of the drought, is primarily a consequence of human activity, in the form of more intense farming and excessive harvesting of forest resources (Tappan and McGahuey, 2007; Ruelland et al., submitted for publication).

To evaluate the impact of these changes on runoff, it is necessary to represent the processes governing the links between climatic data (rainfall and PET) and river flow regimes. Hydrological modelling is one way of representing