Interpolation of water balance components for Costa Rica

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Abstract Patterns of spatial variation of precipitation and runoff have been studied at the annual time scale for Costa Rica. Stochastic interpolation using data from the meteorological and hydrological networks were used to produce digital precipitation maps, as well as runoff maps. In the latter case the basin area has been taken into account. The maps were produced by integrating along the rivers to achieve basin-average values. Linking these estimated basin values for the two studied variables assists in developing the water balance constraints. It proved to be an excellent diagnostic tool for data in an exploratory phase of studying patterns of variability. The development of the maps assisted in gaining insight into the basic processes such as systematic underestimation of precipitation in areas with cloud forest due to "horizontal precipitation", local patches of very high precipitation or of rain shadow as well as basins with leakage to deep groundwater.

Key words stochastic interpolation; water balance; Costa Rica

INTRODUCTION

Map representation of spatial and temporal variability of water balance components has many areas of application. Mean annual runoff (MAR) is the basic variable for the majority of hydrological studies (Gottschalk & Krasovskaia, 1998) and it has been chosen as a starting element for estimation of all other runoff characteristics (e.g. Krasovskaia *et al*., 2006; Pacheco *et al*., 2006) in the frame of a larger study of minimum acceptable flow (Laporte *et al*., 2006). Mean annual runoff is a robust characteristic that can be estimated with relatively high accuracy. At the annual scale the small time scale dynamic processes are smoothed. At this level, both input data and interpolated output can be controlled as the water balance should be closed. Indeed, the interpolated (and observed) runoff values should not exceed the precipitation values for the same basin.

The study presents the interpolation of precipitation and runoff for the basins of Costa Rica. Special attention is given to the accuracy of the results for the available data using the interpolated basin precipitation to diagnose discrepancies in runoff and precipitation data.

DATA USED

Annual precipitation for 178 stations and annual runoff for 66 runoff stations for the period 1979–2000 have been used in the study. There are gaps in the data series and only years with at least 80% of data were considered. The number of series used varied between the years; on average 87% of precipitation and 79% runoff series were used each year. Hydrological years (from May to April) were used for both precipitation and runoff. The location of stations is shown in Fig. 1.

There are many places with no stations at all (e.g. southwestern Pacific) or very few stations (e.g. northwestern Pacific, northeastern and southeastern Caribbean). As the interpolation schemes are based on the observed data, in the regions without observations the error in the interpolated values might be large. In regions close to the high mountain chain dividing Costa Rica into Caribbean and Pacific parts which have different environmental and climatic conditions, the interpolation results need to be treated with caution due to the very steep gradients.

A digital elevation model (DEM) with a resolution 500 × 500 m represents the second important data source used in interpolation routines. For comparisons and as a support for identification of the drainage net, the digitized river net of Costa Rica was used. Manually produced maps of mean annual precipitation for the period 1970–1989 (isohyets); mean annual discharges (isolines); specific runoff (isolines) and potential evapotranspiration (isolines) for the same period were used for comparisons.

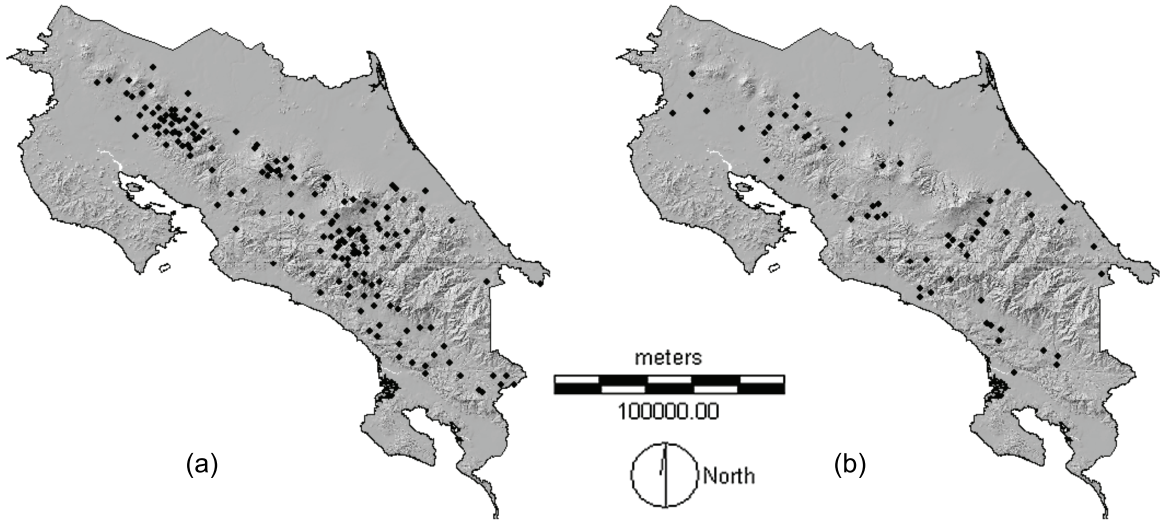

Fig. 1 Location of precipitation (a) and hydrological (b) stations.

Preparing geographical information: identification of the drainage net

The HydroDem software (Leblois & Sauquet, 2000) has been used for the identification of the drainage net using the DEM for Costa Rica. This software is specially developed for hydrological purposes and its main advantage is that it allows building of a hierarchically consistent drainage pattern. It also allows determination of a drainage basin for each identified segment of a drainage net so preserving hierarchical consistency in all algorithms. The digitized map of the river network of Costa Rica has been used for comparisons and as a reference in cases where manual corrections were needed. The automatically obtained drainage net showed good agreement with the digitized one except for the plain regions (northern Caribbean region), for which the resolution of the DEM was too coarse. The accuracy of identification of the drainage patterns was tested using the routines within HydroDem based on comparing estimated basin areas to the actual ones. The drainage pattern obtained served as the basis for all interpolation routines for both basin precipitation and different runoff characteristics.

Interpolation of precipitation

In meteorology automatic methods for interpolation of random fields are referred to as "objective methods" (Gandin, 1963). These methods are referred to very little in hydrological literature. On the other hand, kriging methods (Krige, 1951; Matheron, 1973) developed in geology, have been used frequently in hydrology. Kriging or Gandin interpolation is of wide use for interpolation and integration of precipitation fields (Rodriguez-Iturbe & Mejia, 1974; Creutin & Obled, 1982).

In this study, Gandin interpolation is applied for mapping precipitation for each individual year of the 22 years of observations. Climatic anisotropic semivariograms (Lebel & Labord, 1988) have been constructed for each year. An exponential semivariogram with a constant range of 12 km was fitted to the empirical semivariograms. An example is shown in Fig. 2(a). The analysis accounted for anisotropy by considering angles with the following directions: 36º (perpendicular to the main mountain system of the country); 126º (parallel to the mountains) and omnidirectional. The variation of the sill parameter (variance in space) during the period of observations seems to be independent of ENSO during 1979–2000. On average the difference in the standard deviation in space between the individual years was about 1400 mm.

Precipitation maps for the whole of Costa Rica for each year in the period 1979–2000 were obtained by applying Gandin interpolation based on the theoretical climatic semivariograms keeping the range constant and allowing the sill to vary between years. An example of such a map is shown in Fig. 2(b). These maps give precipitation as point values. They have been averaged along rivers to obtain the basin mean annual precipitation. The algorithm for obtaining basin values from point values within HydroDem is based on conventional downstreaming procedures (for details see Leblois & Sauquet, 2000).

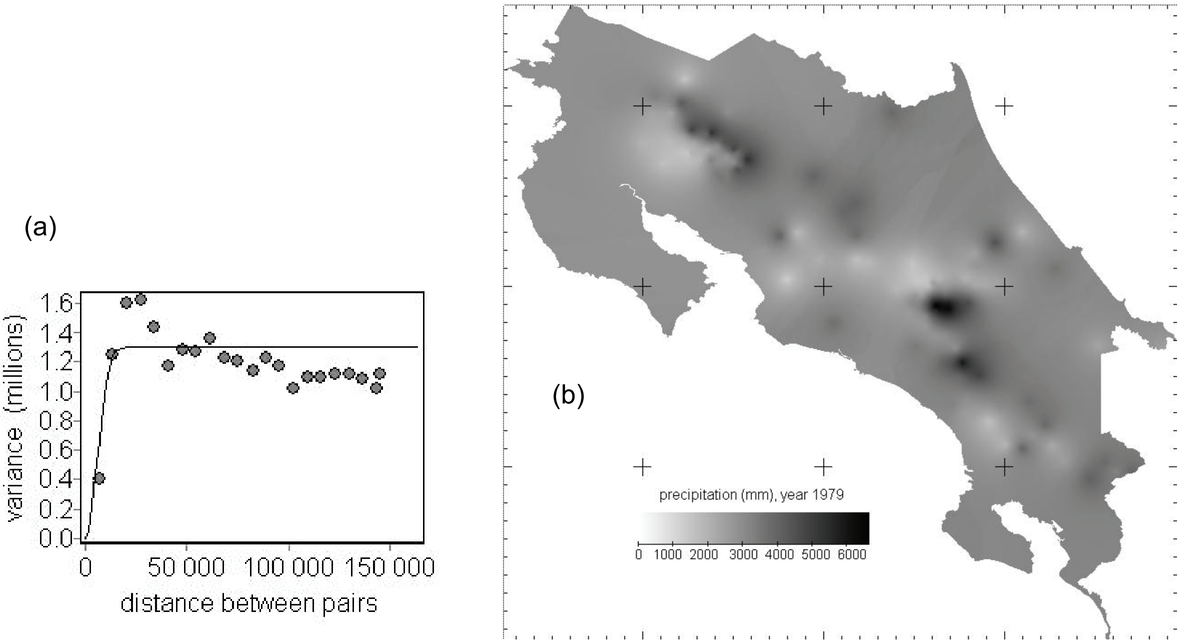

Fig. 2 (a) Empirical and theoretical (exponential) semivariograms of annual precipitation for 1979. (b) Map of annual average rainfall for 1979.

Interpolation of annual average basin runoff

Various methods have been used in hydrology for mapping annual runoff. Empirical relationships between streamflow and land use, geomorphology and climate have been frequently used for this purpose (e.g. Solomon *et al.*, 1968; Liebscher, 1972; Gustard *et al.*, 1989). The main disadvantage of this empirical approach is that the empirical relationships are valid only for the region for which they have been developed and thus are not transferable. An alternative is given by objective methods based on stochastic interpolation widely used to map point processes. There have been some attempts to apply such methods using simplified assumptions and directly interpolating runoff as a point process (Villeneuve *et al.*, 1979; Hisdal & Tveito, 1993). If this approach is used properly, only data from small drainage basins can be applied so that a "point" covariance model can be constructed. A more general approach is to use Gandin interpolation with local support (Gottschalk, 1993). The support is related to the basin area. Distances between stations are in this case replaced by the average distances between basins, here referred to as Ghosh distances (Ghosh, 1951). The suggestion by Gottschalk has been followed here. The interpolation is performed in two steps. First a "point" map is produced, then secondly it is averaged to give basin runoff along rivers. Figure 3 shows an example of an integrated map along rivers for the whole period of observations.

DIAGNOSTIC TESTS OF DATA USING MEAN ANNUAL BASIN PRECIPITATION AND RUNOFF

The final precipitation as well as runoff maps for each individual year were basin averaged maps along rivers in accordance with the example in Fig. 3. Subtracting the runoff map from the corresponding precipitation map for an individual year, or as an average for the whole period, should thus result in an estimate of the actual evapotranspiration for that period. Preliminary existing estimates give the range 500–1000 mm for this variable (E. R. Chacon, personal communication). Figure 4 shows one example when the average precipitation for each basin was plotted against the registered average runoff for one year (1980). Three lines are plotted as support: one to one; 500 mm deviation and 1000 mm deviation. The discharge outliers in the graph are not confirmed by local rain estimates. On the other hand some stations show very low runoff compared to the estimated basin precipitation. In most cases with discrepancies the deviations are systematic for all years of observations. Figure 5 offers an example of a station with a systematic higher runoff than precipitation (marked with a circle in Fig. 4). The very high deviation in 1988 might have been caused by hurricane "Juana". Most of the larger deviations of this kind apply to

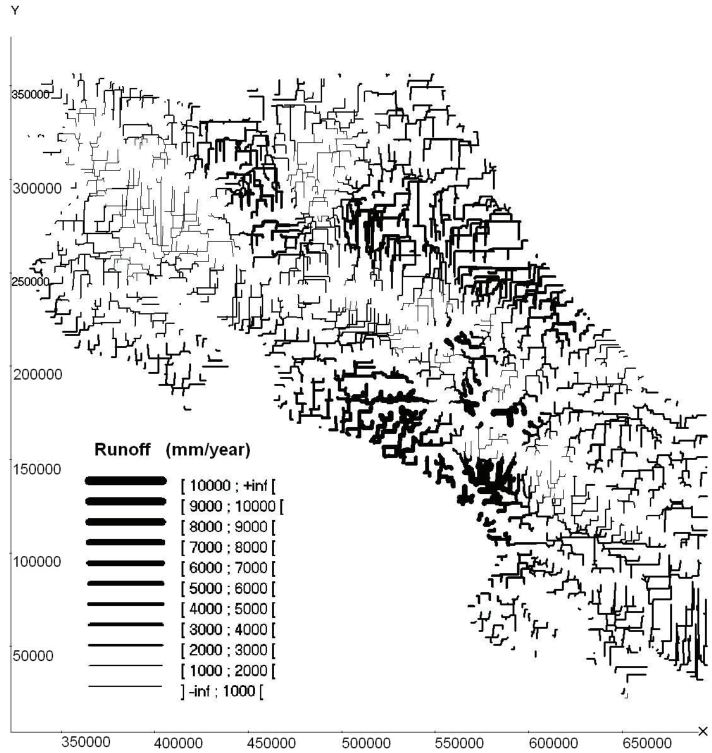

Fig. 3 Map of long-term runoff for Costa Rica averaged along rivers for basins bigger than 50 km^2.

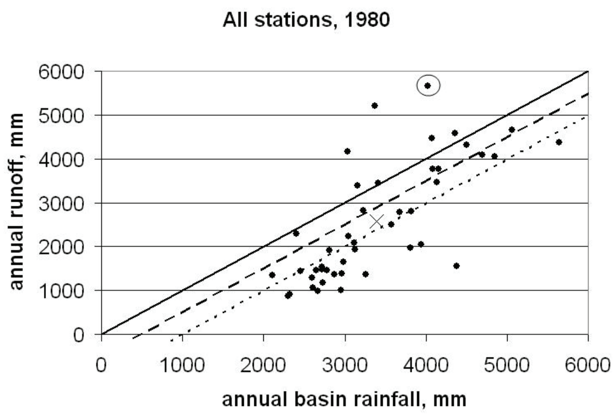

Fig. 4 Average annual basin precipitation plotted against registered average annual basin runoff for 1980. The asterisk shows the average annual precipitation and runoff for all stations for a respective year. Three lines are plotted as support: one to one; 500 mm deviation (coarse dashed) and 1000 mm deviation (dashed). The station with a systematic error is circled.

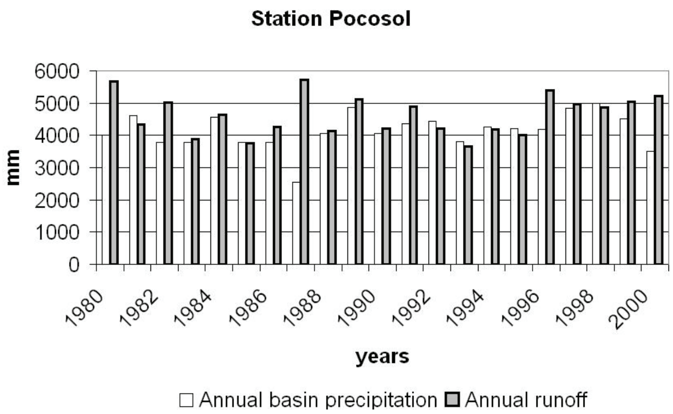

Fig. 5 Average annual basin precipitation plotted against registered average annual basin runoff for a station with systematically higher runoff than precipitation (Pocosol).

small basins in mountainous areas with strong gradients in precipitation and a lack of gauges at higher altitudes. The immediate explanations for the inconsistencies might be errors in the recorded data, poor rating curves, as well as errors induced by the interpolation methods. However, several other factors might explain the inconsistencies in the water balance, which at present are not investigated well enough:

(a) underestimation of precipitation in areas with cloud forest due to "horizontal precipitation",
(b) local patches of very high precipitation or of rain shadow not reflected by the observation network,
(c) basins with leakage to deep groundwater in volcanic/karstic areas.

CONCLUSIONS

The results of a first attempt of interpolation of water balance elements in Costa Rica using objective methods are presented. Unlike many other studies on interpolation of water balance components, these were estimated not only as point values but also as integrated values for the basins. This allowed identification of inconsistencies in data. Comparisons of the maps produced with the previous manually produced versions (E. R. Chacon, personal communication) demonstrated a good agreement except for the regions with scarce or no data. In such regions manual maps reflect implicitly the subjective experience of the meteorologist/hydrologist, which is not readily transferable. An attempt was made to coarsely close the balance using manually produced evaporation maps, and was successful in some parts and less successful in others. Such a comparison gives insight to the order of magnitude of possible errors in interpolation. The analysis also points to processes that at present are not well understood like "horizontal precipitation", local variability in precipitation and groundwater leakage. The maps obtained are now in the process of revision to incorporate changes due to the discrepancies revealed. The final version of the mean annual runoff map will be used as the basis for interpolation/regionalization of other hydrological characteristics for the basins of Costa Rica.

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