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Review papers

Optimization of a hydrometric network extension using specific flow, kriging and simulated annealing

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A B S T R A C T

In hydrometric stations, water levels are continuously observed and discharge rating curves are constantly updated to achieve accurate river levels and discharge observations. An adequate spatial distribution of hydrological gauging stations presents a lot of interest in linkage with the river regime characterization, water infrastructures design, water resources management and ecological survey. Due to the increase of riverside population and the associated flood risk, hydrological networks constantly need to be developed. This paper suggests taking advantage of kriging approaches to improve the design of a hydrometric network. The context deals with the application of an optimization approach using ordinary kriging and simulated annealing (SA) in order to identify the best locations to install new hydrometric gauges. The task at hand is to extend an existing hydrometric network in order to estimate, at ungauged sites, the average specific annual discharge which is a key basin descriptor. This methodology is developed for the hydrometric network of the transboundary Medjerda River in the North of Tunisia. A Geographic Information System (GIS) is adopted to delineate basin limits and centroids. The latter are adopted to assign the location of basins in kriging development. Scenarios where the size of an existing 12 stations network is alternatively increased by 1, 2, 3, 4 and 5 new station(s) are investigated using geo-regression and minimization of the variance of kriging errors. The analysis of the optimized locations from a scenario to another shows a perfect conformity with respect to the location of the new sites. The new locations insure a better spatial coverage of the study area as seen with the increase of both the average and the maximum of inter-station distances after optimization. The optimization procedure selects the basins that insure the shifting of the mean drainage area towards higher specific discharges.

Contents

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1. Introduction

A hydrometric network is aimed at giving the hydrological information to be used for ecological survey, hydrological survey, hydrological regionalization as well as infrastructures design. Flood estimates are of major importance since they are needed for designing civil engineering works, inundation risk zoning and an estimation of ecological flows. Both water source infrastructure design and management (reservoirs, water distribution systems, irrigation networks, etc.) are based on flood estimation. Due to the increase of riverside population and the associated flood risk issues, the hydrological networks need to be developed.

According to Mishra and Coulibaly (2009), a hydrometric network should be optimized to collect most hydrological information and in the most precise way. More generally, the commonly used processes for network optimization include statistical approaches, a user survey procedure, a hybrid approach, and sampling plans (Vivekanandan, 2012). *Statistical approaches* for hydrometric network optimization range from clustering methods (Bum and Goulter, 1991) and spatial regression (Tasker and Stedinger, 1989) to entropy-based techniques (Caselton and Husain, 1980). *Clustering methods* are usually used to identify groups of hydrometric gauging stations with similar flow characteristics on the basis of a similarity matrix defining the similarity of each station to every other station. This constitutes an important step in the network design procedure. The annual average runoff is a main flow characteristic and spatial regression is often used to predict it at ungauged locations (Daigle et al., 2011). *Entropy methods* may also assist network design by quantifying the relative information content and by estimating incertitude (Vivekanandan, 2014). Moreover, the *User survey procedure* is based on the users' needs to continue or discontinue stations depending upon the type of data needed in the basin. This investigation by its nature relies on a certain amount of personal decisions (Davar and Brimley, 1990).

The hybrid method combines models by adopting the output from one method as an input into another model for network optimization. For example an algorithm of numerical optimization permits to improve the optimal network design by variance reduction and allows the insertion of other criteria in the objective function such as the economic cost of the data collection (Mishra and Coulibaly, 2009). *Hydrologic sampling* plans are based on the influence of rainfall on stream flow processes. The effectiveness of sampling plans is evaluated by the variance of error in the estimate stream flow (Tarboton et al., 1987).

On the other hand, the rainfall network design is often achieved by using the kriging interpolation method combined with optimization algorithms such as simulated annealing (see for example Barca et al., 2008; Chebbi et al., 2013). Kriging has also been used for piezometric networks optimization. For instance, Rouhani (1985) used two criteria for piezometric network optimization: the first concerns the reduction of the kriging variance while the second is related to the expected economic gain, measured by loss reduction. One fundamental upshot of kriging is that it results in the estimation of the variance of interpolation errors, making it possible to evaluate network performance. Whereas entropy method is worth for existing networks, the kriging interpolation method may be extended for planned networks. Kriging often employs a semivariogram function representing the structure of the spatial variability of the data. The semivariogram effectively gives the same information as an auto-correlation function. However, it has a big advantage of being an unbiased estimator as it does not depend on the mean of the data set. So, it is proposed here to get profit of the kriging approaches in order to improve the design of a given hydrometric network. The main difficulty here resides in defining a suitable hydrometric study variable and a suitable objective function, as well in addition to a suitable kriging method.

In this study, we have adopted a specific discharge as a prime study variable representing the ratio of the river discharge to the drainage area and which is also called average specific annual module. For a long time in flood studies, the record specific discharges are adopted as a key variable to obtain regionally-developed curves (Castellarin, 2007). So, a specific discharge is considered here as a key watershed descriptor.

There are many other ways to handle the issue of hydrometric network optimization since the hydrologic response is multidimensional. Therefore, instantaneous hydrograph responses to rainfall events are described by at least three variables: flood duration, flood peak and flood volume. An objective function including these variables may be achieved but we cannot rely on this approach because of data limitations. We have no information about the flood series (except at daily resolutions). Basins have signatures which can be described by using some statistics of the basis of the flow-duration curve (Sadegh et al., 2016) obtained by analyzing daily discharges. These above-mentioned statistics may be used to optimize the hydrometric network. The only statistics adopted here is the sample mean of annual discharges. We did not apply other statistics even though they would be a possible extension of the current work. The Runoff coefficient is another basin signature which can be adopted to solve the optimization of hydrological networks. The difficulty with basin runoff coefficient is that it involves the estimation of the basin average rainfall, which in turn is a "rainfall product" that needs interpolation tools in order to be evaluated. Another alternative is the use of digital models (based on a Geographic Information System) associated to soil, land use information and classification methods to find the most representative basins. The advantage of not adopting such an alternative is to limit the need of implementing digital models which themselves are to be verified using in situ data.

Thus, this work intends to extend the use of a specific river discharge, as a study variable to the hydrometric network optimization. One implicit assumption is that the geographic regions in the study are hydrologically homogeneous.

Many basin attributes may be included as a proxy for flood (and the specific discharge) estimation. They are often adopted in geo-regression approaches. The drainage area, the basin geology together with land use descriptors, soil characteristics, elevation data, and climate variables such as mean annual precipitation are often proposed as flood proxy or surrogates (Acreman and Sinclair, 1986). Wilson and Gallant (2000) noticed that steepness can be considered as a surrogate for overland and subsurface flow velocity and the runoff rate. Hundecha and Bardossy (2004) adopted basin size, slope and shape as characteristics for regionalizing Hydrologiska Byrans Vattenbalansavdelning (HBV) rainfall runoff model parameters. Kjeldsen and Jones (2007) adopted both the drainage area and the average annual rainfall together with an index of flood reduction attributable to reservoirs and lakes and a derived base flow index using the Hydrology of Soil Type classification.