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Optimizing the configuration of streamflow stations based on coverage maximization: A case study of the Jinsha River Basin

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SUMMARY

Streamflow stations are typical hydrometric stations that serve as the basic components of hydrological monitoring networks. To effectively obtain information for predicting the magnitude and frequency of future floods and droughts, an optimal configuration of streamflow stations should be established to maximize the sensing capability with limited resources. In this paper, we propose a method to site streamflow stations in space to maximize the total area for streamflow monitoring. Considering the special regulations for deploying streamflow stations, a modified maximal covering location problem (MCLP) model is introduced. The effective coverage range of a streamflow station is determined based on the minimum density required and the site-specific terrain slope. The candidate sites are assumed to be continuously distributed along a river, and the river network is abstracted as a series of line-based river segments. The covering priority for each segment can be determined by the river length, the drainage area, or the level of flooding risk. The hydrometric network intersection point set (HNIPS) is proposed to identify finite candidate sites along a river. By narrowing the continuous search space to a discrete point set, this siting problem is solved using the MCLP-based model and HNIPS. The Jinsha River Basin is selected as a study area to test the proposed streamflow station siting method. Results show that the proposed method is effective in prescribing the optimal configuration of streamflow stations and the model solution achieves better coverage than that of the real-world deployment. The applicability of the proposed optimal siting method using HNIPS is analyzed. The criteria for candidate site selection and impacts of different weighting schemes applied to river segments are also discussed.

1. Introduction

Streamflow stations are the basic components of hydrological monitoring networks, and have been widely used to collect streamflow information in a river to support the analysis, forecasting, and early warning of disaster events, such as droughts and floods. To effectively obtain abundant streamflow observation data, a sufficient number of stations should be established along the main stems of large streams. However, deploying infinite stations is unrealistic in real-world applications because of the high costs involved in establishing and maintaining these stations and limited budgets available. Therefore, the configuration of stations needs to be efficiently designed to maximize the sensing capability of the monitoring network. The hydrological monitoring networks can be considered as reconfigurable and collaborative hydrological sensor web systems (Broring et al., 2011; Zheng et al., 2012), in which the streamflow stations serve as ground-based sensing node resources, and the node deployment must be optimized (Chen et al., 2013, 2014).

An optimal configuration of streamflow stations is essential to improve the resource utilization and increase cost savings in a hydrologic monitoring network. Because the development of a streamflow network is a long-term and gradual process, the optimization objective should be updated as the network is developed. Before evolving into a well-developed station deployment, a minimum streamflow network should be established preferentially, especially in the low-density watersheds. Such a network contains the least number of stations that is necessary to avoid serious deficiencies in streamflow monitoring and provides the basic framework for future expansion (Mishra and Coulibaly, 2009). Table 1 shows the minimum density of streamflow stations in specific zones that are recommended by the World Meteorological

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Table 1
Recommended minimum densities of streamflow stations.

Physiographic unit	Minimum network density/maximum control area (area in km^2 per station)
Coastal	2750
Mountains	1000
Interior plains	1875
Hilly/undulating areas	1875
Small islands	300
Polar areas	20,000

Organization (WMO) (WMO, 2008). The minimum network density represents the maximum control coverage per station in a stream-gauging network.

The density of streamflow stations in some watershed regions may be too low due to imbalanced regional development. According to the hydrological network census (Li et al., 2011), the average density of streamflow stations in the Yangtze River Basin in China is 2132 square km per station, which does not meet the WMO standard, particularly in the middle and upper reaches of the basin. To meet the increasing demand for streamflow monitoring, new stations must be added in the low-density watershed regions. Therefore, selecting the optimal locations for new streamflow stations presents a pressing need in watershed management.

The Jinsha River is located in the upper reaches of the Yangtze River with a total length of 3464 km. It crosses rugged mountain cliffs and two terrain steps in China and has an elevation difference of up to 5142 m, which accounts for 95% of the entire Yangtze River Basin (Du et al., 2013). The Jinsha River Basin can be divided into upper, middle, and lower sections. The lower section begins in Panzhihua City and ends in Yibin City, with a length of 733.4 km and a watershed area of 135,473 km^2. This section has attracted widespread attention because of its high annual streamflow of 149.8 billion cubic meters (Song et al., 2012). The streamflow monitoring in the lower reaches of the Jinsha River Basin is important for runoff forecasting in the upper reaches of the Yangtze River.

The geographic location of the study area and the distribution of the existing streamflow stations are shown in Fig. 1. Prior to 2000, 39 streamflow stations existed, and the network density was 3386.83 km^2 per station. After 2000, 10 new stations were deployed, and the density became 2709.46 km^2 per station. The physiographic units in the Jinsha River Basin mainly include mountains and interior plains, so the WMO standard for the control area of a streamflow station in the region is 1000 km^2 per station (in mountain areas) or 1875 km^2 per station (in plain areas). Obviously, the density of the streamflow stations in the study area does not meet the minimum density standard.

The deployment of streamflow stations is often a slow and evolutionary process that begins with a minimum number of stations and increases gradually until a "best" configuration is reached. Given the importance of a stream-gauging network, valuable research has been conducted on methods to achieve the optimal deployment of hydrological stations. Chang and Makkeasorn (2010) developed an optimal site selection strategy by integrating satellite images with grey integer programming. Vivekan and Jagtap (2012) presented a method for optimizing a hydrometric network using spatial regression. Baltas and Mimikou (2009) suggested several important criteria for selecting appropriate sites, including the terrain slope, easy access and proximity to settlements. Do et al. (2011, 2012) proposed optimal procedures to design nutrient monitoring points based on an export coefficient model and identified river water quality sampling locations based on human activities. The principal component analysis and geostatistical variance-reduction methods have also been used to determine the optimal sites for precipitation stations (Basalirwa et al., 1993; Eulogio, 1998). In addition, entropy-based approaches have been applied to optimize network designs (Karamouz et al., 2009; Yoo et al., 2011; Awadallah, 2012; Su and You, 2014).

However, these optimization methods primarily focus on the siting regulations, ignoring the maximum area that can be effectively monitored given a fixed number of stations. In this study, the optimal configuration of streamflow stations and the associated location decisions are considered as a facility location problem. Each streamflow station serves as a facility that provides the "service" of observing streamflow information. The potential sites for streamflow stations can be located anywhere along a river. The associated demand objects are the river streams of interest that requires monitoring. Considering the limited amount of observation resources, the optimization objective is to deploy a certain number of stations in a watershed to achieve the maximum covered demands and the highest monitoring efficiency. In this

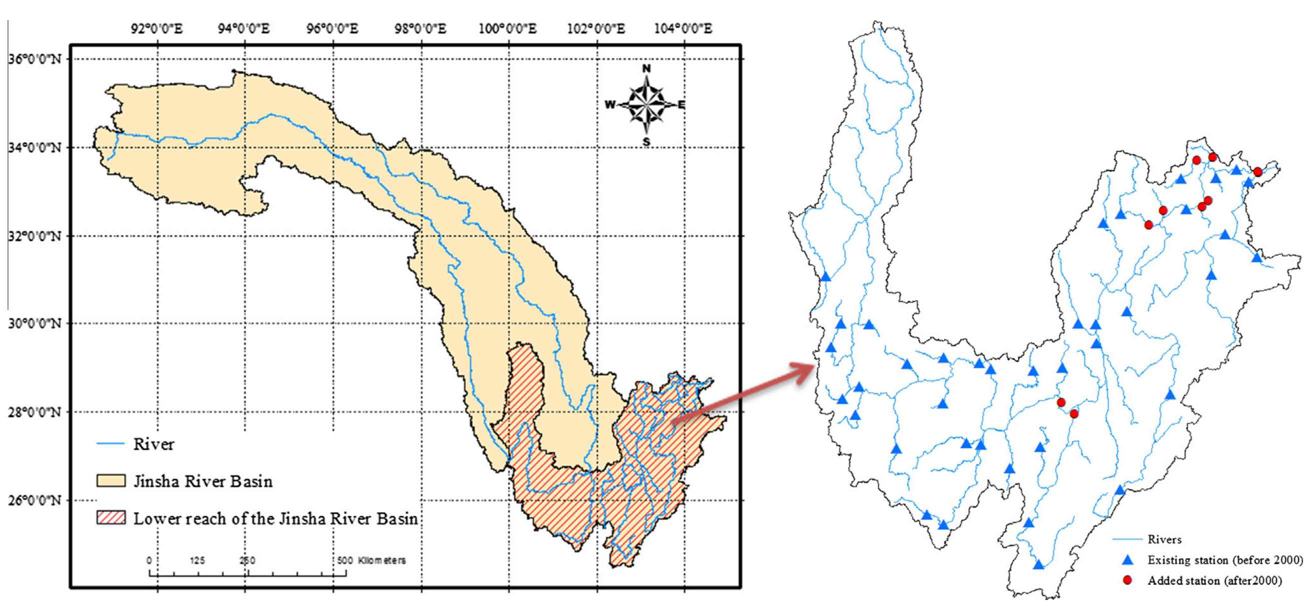

Fig. 1. Location of the study area and distribution of existing streamflow stations.