OPTIMIZING ENVIRONMENTAL MONITORING NETWORKS WITH DIRECTION-DEPENDENT DISTANCE THRESHOLDS

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Abstract. In the direction-dependent approach to location modeling developed herein, the distance within which a point of demand can find service from a facility depends on direction of measurement. The approach is effective for environmental location problems in which an underlying process with a prevailing gradient (e.g., wind or water flow) influences the interaction between sites in a modeled field. The utility of the approach is illustrated through an application to groundwater remediation.

1. Introduction

Over the last three decades there has been widespread application of location-based optimization methods to the problem of siting service facilities. Many applications seek to optimize coverage within a field of demand. In conventional applications of location-covering models, the distance threshold within which a point of demand can find service is independent of direction of measurement. This paper introduces the concept of the direction-dependent, or anisotropic distance threshold and illustrates its utility to environmental monitoring with an application to groundwater remediation.

Groundwater contamination problems are commonly remediated by pumping water from a network of extraction wells located within a contaminant plume. For a given application, the success of this type of remediation strategy is highly dependent on the effective location of extraction wells within the field of contamination. Location models modified with direction-dependent distance thresholds can be used to determine optimal extraction well configurations.

The location set covering model (Toregas et al., 1971; Toregas and ReVelle, 1972) and the maximal covering location model (Church and ReVelle, 1974) are classic examples of location-covering models. The former finds the locations of the minimum number of facilities which will ensure that each point of demand on a network will find service (i.e., coverage) within a specified threshold (commonly expressed as a distance); and the latter finds the locations of a specified number of facilities that will maximize coverage within a service threshold. As conventionally applied, the distance threshold is independent of the direction of measurement from a point of demand (i.e., the threshold is isotropic). The isotropic threshold implies that the effective radius of influence \( r \) of a facility is constant. If the radius of influence of a facility varies with direction, an anisotropic distance threshold is appropriate. Figure 1(a) shows a hypothetical facility and its anisotropic radius of influence. Figure 1(b) shows an arbitrary demand node and the sites at which a
facility (with a radius of influence as defined above) could service the demand node. The distance within which the point of demand could be covered by a facility is direction-dependent, or anisotropic. The formulations for the location set covering model and maximal covering location model, modified by the inclusion of an anisotropic distance threshold, are developed in Appendix 1.

2. Application

The modified location-covering models were applied to determine optimal remediation strategies for the hypothetical groundwater contamination problem illustrated in Figure 2. In this problem, an elliptical contaminant plume measuring 305 m in width and 610 m in length resides within a 15-m thick unconsolidated sand aquifer. The aquifer is characterized by a hydraulic conductivity ($K$) of 1.5 m/day, a horizontal hydraulic gradient ($I$) of 0.005, and an effective porosity of 0.25. The specific discharge ($q$), defined as the product of $K$ and $I$, is equal to 0.0075 m/day. Hypothetical field tests indicate that an extraction well penetrating the aquifer can sustain a pumping rate of 55 m$^3$/day. Two different problems are to be addressed: (1) determine the locations of the minimum number of pumping wells and associated