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Entropy based groundwater monitoring network design considering spatial distribution of annual recharge

James M. Leach[a,*], Paulin Coulibaly[a,b], Yiping Guo[a]

[a] *Department of Civil Engineering, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L7, Canada*
[b] *School of Geography and Earth Sciences, McMaster University, 1280 Main Street West, Hamilton, ON L8S 4L7, Canada*

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ABSTRACT

This study explores the inclusion of a groundwater recharge based design objective and the impact it has on the design of optimum groundwater monitoring networks. The study was conducted in the Hamilton, Halton, and Credit Valley regions of Ontario, Canada, in which the existing Ontario Provincial Groundwater Monitoring Network was augmented with additional monitoring wells. The Dual Entropy-Multiobjective Optimization (DEMO) model was used in these analyses. The value of using this design objective is rooted in the information contained within the estimated recharge. Recharge requires knowledge of climate, geomorphology, and geology of the area, thus using this objective function can help account for these physical characteristics. Two sources of groundwater recharge data were examined and compared, the first was calculated using the Precipitation-Runoff Modeling System (PRMS), and the second was an aggregation of recharge found using both the PRMS and Hydrological Simulation Program-Fortran (HSP-F). The entropy functions are used to identify optimal trade-offs between the maximum information content and the minimum shared information between the monitoring wells. The recharge objective will help to quantify hydrological characteristics of the vadose zone, and thus provide more information to the optimization algorithm. Results show that by including recharge as a design objective, the spatial coverage of the monitoring network can be improved. The study also highlights the flexibility of DEMO and its ability to incorporate additional design objectives such as the groundwater recharge.

1. Introduction

The design of a hydrometric monitoring network that can provide the maximum amount of information for end users is essential due to the inherent importance of hydrometric data (Mishra and Coulibaly, 2009). Reliable and accurate hydrometric data are fundamental for the effective management of water resources which includes better optimization of water uses in both the public and private sectors. The goal of this research is to determine the benefits of including informative hydrological variables as additional objectives in the multi-objective optimization algorithm from (Samuel et al., 2013) for the optimal design and augmentation of a groundwater quantity monitoring well network. In particular, the research focus is on the optimal spatial locations of the monitoring wells and how they are influenced by the use of the additional objectives. The temporal frequency at which each well is monitored will not be addressed in this research as it is another aspect of optimal network design.

Hydrometric monitoring networks play an important role in water resources planning and management and have been around for many years. The Canadian Federal Hydrometric Network, which monitors water levels and streamflow, was developed in the 1890 s (Mishra and Coulibaly, 2009). In Ontario, the Provincial Groundwater Monitoring Network (PGMN), which provides both groundwater level data and water quality information, has been around since 2001 (Government of Ontario, 2013). Groundwater monitoring network design can be divided between quality monitoring and quantity monitoring. This does not mean that one network could not perform both tasks, just that the approaches used in the design of each vary based on the intended use of the network.

Approaches for groundwater quality monitoring network design were reviewed by (Loaiciga et al., 1992). The review suggests that to design a robust monitoring network, a combination of hydrogeological and statistical simulation, variance, or probability-based methods should be used. There has been a wide range of literature on the design of groundwater quality monitoring networks. These studies used a variety of data generation methods including Inverse Distance Weighting (IDW) (Li and Chan Hilton, 2005, 2007; Wu et al., 2005), Kriging methods (Wu et al., 2005, 2006;

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* Corresponding author.
E-mail address: leachjm@mcmaster.ca (J.M. Leach).

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Reed and Minsker, 2004; Kollat and Reed, 2006, 2007; Reed et al., 2007; Kollat et al., 2008; Dhar and Datta, 2009), physical models such as MODFLOW (Wu et al., 2005, 2006; Asefa et al., 2005; Alzraiee et al., 2013), Par Flow (Kollat et al., 2011; Reed and Kollat, 2012, 2013), and MT3MDS (Wu et al., 2005, 2006; Hudak et al., 1995). The optimization methods used in the groundwater network design literature include Branch and Bound (BB) (Hudak et al., 1995; Hudak and Loaiciga, 1993; Wagner, 1995), Simulated Annealing (SA) (Meyer et al., 1994; Nunes et al., 2004), Ant Colony Optimization (ACO) (Li and Chan Hilton, 2005, 2007), entropy theory (Nunes et al., 2004; Mogheir and Singh, 2002; Mogheir et al., 2009), Genetic Algorithms (GA) (Reed and Minsker, 2004; Kollat and Reed, 2006, 2007; Wu et al., 2006; Reed et al., 2007; Kollat et al., 2008; Alzraiee et al., 2013; Wagner, 1995; Cieniawski et al., 1995), machine learning (Asefa et al., 2005; Ammar et al., 2008), and Bayesian Optimization Algorithms (BOA) (Kollat et al., 2008, 2011; Reed and Kollat, 2012, 2013). These methods are ultimately used to design a monitoring network using a minimal amount of wells that have a higher chance of detecting contaminant plumes or for post remediation long-term monitoring (LTM). Despite the fact that several network design methods have been developed over the years for groundwater quality monitoring networks, few methods have been developed for the design of groundwater quantity monitoring networks (which is the focus of this study). Those that do focus on groundwater quantity monitoring are similar; including Kriging variance reduction methods in which monitoring wells are placed at high variance locations in the study area (Zhou et al., 2013; Yang et al., 2008; Prakash and Singh, 2000; Khan et al., 2008; Triki et al., 2013).

Several methodological developments in hydrometric network design, particularly those for streamflow and precipitation monitoring networks, were reviewed in (Mishra and Coulibaly, 2009). That review found that the most efficient methods for hydrometric network evaluation and design are entropy (Husain, 1987, 1989; Krstanovic and Singh, 1992a, 1992b; Mishra and Coulibaly, 2010) and multi-objective optimization (Kollat et al., 2008, 2011) based methods. The entropy (information) theory itself has been used in groundwater monitoring network design studies previously (Nunes et al., 2004; Mogheir and Singh, 2002; Mogheir et al., 2009). The merit of entropy is that it both defines the information content of the data and is a measure of the uncertainty in the data, as the uncertainty increases, so does the potential information gain (Mogheir and Singh, 2002; Mishra and Coulibaly, 2010; Mogheir et al., 2006; Shannon, 1948). The use of entropy in hydrology and water resources practices was reviewed by (Singh, 1997). The most developed network design models involve a combination of entropy-based and optimization methods (Samuel et al., 2013; Nunes et al., 2004; Mogheir and Singh, 2002; Mogheir et al., 2009, Alfonso et al., 2010a, 2013, Yakirevich et al., 2013). Previous studies have proven entropy theory's applicability in network design (Samuel et al., 2013; Mogheir and Singh, 2002; Mogheir et al., 2009; Alfonso et al., 2010a, 2013) since it can provide a quantitative measure of the information content within a hydrometric network (Mishra and Coulibaly, 2010; Singh, 1997). In this study, the dual entropy multi-objective optimization (DEMO) approach was used to identify the optimal entropy function trade-offs between the maximum possible information content and the minimum shared information among the existing and potential monitoring stations using joint entropy and total correlation as objective functions respectively (Samuel et al., 2013; Alfonso et al., 2010a, 2013). Using binary decision variables within the optimization method, the model has the capability to seek the optimal trade-off between several entropy functions by systematically selecting values from within a set of all existing and potential stations.

Objectives of groundwater level monitoring include characterizing groundwater systems, analyzing groundwater quantity, identifying changes in groundwater recharge, storage, and discharge, detecting effects of climate change on groundwater resources, assessing impacts of groundwater development, calibrating groundwater flow models, and evaluating the effectiveness of groundwater management and protection measures (Zhou et al., 2013). This research will expand on the DEMO approach of (Samuel et al., 2013) by evaluating the impact and efficacy of including an additional hydrological/hydrogeological variable as an objective function. The additional objective functions will be used to help quantify the hydrologic behaviors in the study area. The inclusion of existing metrics such as vulnerability indices was considered since previous network evaluations have used them (Baalousha, 2010). However, an objective that considers the spatial distribution of groundwater recharge was ultimately chosen.

Recharge can be defined as the downward flow of water entering the saturated zone (de Vries and Simmers, 2002; Cherkauer, 2004; Scanlon et al., 2002). When choosing a model to estimate recharge in an area, the climate, geomorphology, and geology of that area need to be considered as they control the location and timing of recharge (Scanlon et al., 2002). The chosen study area is fairly humid, common characteristics of humid regions include shallow water tables and gaining streams (Scanlon et al., 2002). Diffuse recharge, the recharge derived from precipitation or irrigation that occurs over large areas, is dominant in humid regions (Scanlon et al., 2002). Additionally, recharge is higher in areas where annual crops and grasses are present and lower where trees and shrubs are present (Scanlon et al., 2002). Watershed models have been used in humid regions to estimate groundwater recharge (Scanlon et al., 2002; United States Geological Survey, 2013). The Precipitation-Runoff Modeling System (PRMS) is a physically based deterministic and distributed-parameter modeling system used to simulate streamflow responses to precipitation, although PRMS can be used to provide an estimate of groundwater recharge through its calibrated parameters (Cherkauer, 2004; Leavesley et al., 1983). The Hydrological Simulation Program – Fortran (HSP-F) is a continuous surface water model that can simulate all water balance components including groundwater recharge (Bicknell et al., 1996; AquaResources Inc., 2009). Other methods do exist to determine recharge, but will not be explored in this research (Scanlon et al., 2002; United States Geological Survey, 2013; Leavesley et al., 1983; Bicknell et al., 1996; Healy and Cook, 2002). A groundwater recharge based objective function was chosen to help quantify the hydrological characteristics of the vadose zone in the aquifer and thus provide more information for the optimization algorithm.

2. Study area and data

The study area is located in southern Ontario and consists of combined watersheds managed by three conservation authorities: Hamilton Conservation Authority, Conservation Halton, and Credit Valley Conservation. These combined watersheds have a surface area of approximately 2300 km^2 and contain approximately 80% agricultural and forested land as well as 20% urban land (Fig. 1) concentrated around the Lake Ontario shoreline. There are 26 Ontario PGMN monitoring wells within the study area. The soils are predominantly loam types, and the topography is generally flat to rolling hills with the exception of the Niagara Escarpment (Fig. 1). Within this study area are portions of several major Ontario aquifers including the Credit River, Oak Ridges Moraine, and Grand River Basin aquifers. Geologic mapping in the area indicates six geological formations, the Armabel Formation, Clinton Group, Georgian Bay Formation, Guelph Formation, Lockport Formation, and Queenston Formation (Fig. 1). The major rock types in the