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Assessing the flow regime in a contaminated fractured and karstic dolostone aquifer supplying municipal water

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SUMMARY

The Silurian dolostone bedrock in Ontario, Canada, is a broad 400 km long swath northward from Niagara Falls through the Bruce Peninsula that represents an important water source for municipal, industrial, and agricultural uses. Where the Quaternary overburden is thin or absent, karst is common. This study concerns an urban area where the dolostone aquifer is 100 m thick beneath up to 50 m thick Quaternary deposits and where karst features identified by borehole information are common. Hydraulic tests show moderate to large bulk rock hydraulic conductivity and rock core tests indicate much smaller matrix hydraulic conductivity than the bulk rock values. Therefore, the aquifer is essentially a dual permeability, fully saturated system in which conduits occur within a network of ubiquitous extensive, horizontally- and vertically-interconnected fractures. Karst features are concentrated in a thin zone at the top-of-rock, likely representing former epikarst, and also in a thicker zone in the middle of the aquifer. Some pumping test results and large yields of some municipal wells are consistent with conduit occurrences. However, atmospheric tritium, distributed-source contamination (Cl^-, NO_3^-), and a point-source pesticide plume (metolachlor) show detailed concentration distributions lacking influence of flow in conduits. Detailed hydraulic head profiles also show no influence of conduit flow. This study shows that when designing monitoring networks for groundwater quality and source water protection in similar contexts, locating conduits is not necessary because contaminant distributions are governed by the combined influences of the rock matrix, fractures and conduits, the hydraulic boundary conditions, and the interconnected fracture network with only minimal conduit effects. Prior to glaciations, an integrated karstic aquifer could develop with flow controlled by conduits; however, this original, converging flow system became non-functional when the Quaternary sediments drastically modified the boundary hydrologic conditions and the head distribution.

1. Introduction

In the Province of Ontario, Canada, the middle Silurian rocks of the Amabel, Lockport, and Guelph Formations overlain by discontinuous Quaternary deposits constitute an extensive high yield aquifer system commonly referred to as the dolostone aquifer. This aquifer extends as a belt northward from Niagara 300 km to Owen Sound (Fig. 1) and further north to the tip of the Bruce Peninsula. Singer et al. (2003) indicate that this is one of the most important aquifers in Ontario, as it provides drinking water to more than half a million people in cities, towns, and farms. In the literature concerning this aquifer, two very different conceptualizations of the hydrological conditions are used – karst and non-karst – and the choice of model predominantly depends on the end purpose of the analysis. Generally, the karst model is used in geomorphological studies (e.g., Cowell and Ford, 1983), wherein conduit flow governs the hydrological system. The non-karst model is used when the focus is an assessment of the aquifer for municipal water supply or groundwater contamination (e.g., Zanini et al., 2000). In the non-karst model, groundwater flow occurs in a network of ubiquitous interconnected fractures with various lengths and apertures with inconsequential influence of conduits. In the heavily urbanized area of Cambridge, Ontario, the dolostone aquifer is covered by thick Quaternary deposits and no springs are present. The groundwater flow system is controlled by pumping from numerous municipal wells and aquifer contamination is extensive. Because of the importance of the aquifer for drinking water supply, numerous boreholes have been drilled that provide many types of subsurface data over several decades. This has resulted in an exceptionally large and diverse database for assessing the applicability of the two conceptual models in this area of most intensive groundwater extraction.

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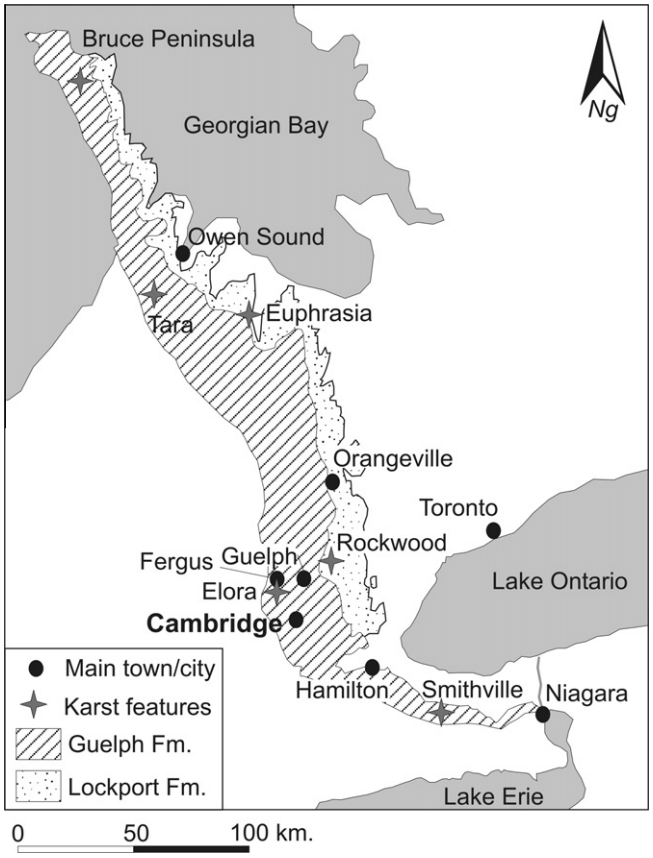

Fig. 1. Simplified regional map showing the extent of the Guelph and Lockport Formations across south-western Ontario.

This paper has two goals. The first is to examine the borehole data for evidence of karst features and, based on this, develop a conceptual model for the nature and origin of karst in the dolostone aquifer where karst geomorphological features cannot be seen due to the cover by Quaternary deposits. The second goal is to determine the degree to which, if any, conduit flow must be invoked to account for the borehole observations concerning groundwater flow and the distribution of contaminants. In the approach currently used by hydrogeologists in the parts of Ontario where thick Quaternary deposits cover the dolostone, well field management is increasingly based on numerical models (e.g., MODFLOW, FEFLOW) in which conduit flow is not represented. Also, for estimation of source water protection zones pertaining to municipal wells, velocities typical of conduit flow are generally not used for calculation of contaminant arrival time estimates. Therefore, important practical implications are associated with the assessment of the two conceptual models in these contexts.

Substantial literature on this dolostone aquifer concerns regional occurrences of karst geomorphological features, such as sinkholes, karstic springs, and caves, where the Quaternary deposits are thin or absent (Fig. 1): the Bruce Peninsula (e.g., Cowell and Ford, 1983), Euphrasia Township and near the town of Tara (Chapman and Putnam, 1984), and the Rockport area (Kunert et al., 1998). The Ontario Geological Survey has launched a karst inventory project to describe the degree of karstification in the various bedrock units in southern Ontario (Brunton et al., 2005, 2006). There is clear evidence of the widespread occurrence of karst features in dolostone outcrops and below thin Quaternary deposits; however, the distribution and hydrological importance of karst in dolostone areas covered extensively with Quaternary deposits is little known. For example, Novakowski and Lapcevic (1988) report on a detailed subsurface hydrogeological study of the dolostone in the Niagara Falls area without mention of the occurrence or influence of solution conduits; they describe this dolostone as fractured with variable hydraulic conductivity with depth.

In several areas in the dolostone belt, groundwater contamination has prompted intensive subsurface investigations of groundwater flow and contaminant transport and fate in the dolostone aquifer. One is near the town of Smithville (Fig. 1) in the southern part of the dolostone belt, where contamination by polychlorinated biphenyls (PCBs), chlorobenzenes, and trichloroethylene occurs in the upper part of the dolostone aquifer. McIelwain et al. (1989) and Zanini et al. (2000) reported on investigations of contaminant distributions and groundwater flow inferred from hydrogeological and geochemical measurements, respectively, without noting any apparent influence of solution conduits. They attribute the active groundwater flow in the dolostone to the substantial bulk hydraulic conductivity provided mainly by extensive horizontal bedding plain fractures. Worthington (2002) proposed an alternative conceptual model for groundwater flow in the dolostone in the Smithville area dominated by the influence of conduits. This alternative model is based on observations such as a trough in the potentiometric surface, the presence of higher hydraulic conductivity at depth, rapid water level and hydrochemical responses to recharge events, and the existence of a sinkhole and underground stream near the site. Worthington and Ford (2009) tested the two hypotheses (conduit networks versus fracture networks with no conduits) based on sixteen tracer tests in a contaminated area where pumping wells capture contamination and six tracer tests between a sinking stream and a spring to the south of the contaminated area. From the very rapid tracer velocities obtained, solution conduits evidently connect the sinking stream and the spring; however, whether or not conduits govern the much slower tracer test results in the shallow contaminated part of the rock, rather than just interconnecting mostly bedding parallel fractures, is a separate issue.

The regional study area considered in this paper encompasses the City of Cambridge and surrounding urban and agricultural terrain (Fig. 2). Although many active municipal wells are in the study area and contamination is an important issue, only one groundwater assessment of a contaminated site has been published, (Carter et al., 1995), with no mention of conduit influences. The information examined in the present study includes that obtained by consultants for government organizations over past decades and more recent information obtained by researchers at the University of Waterloo who have applied a suite of conventional and new methods in boreholes in the dolostone.

2. Geological and hydrogeological setting

The regional study area (Fig. 2) is located on the Algonquin arch that separated the Michigan and Appalachian sedimentary basins during the Paleozoic era (Telford, 1978). In this paper, the terminology of the Appalachian basin is used. The relevant units are Silurian in age and include the dolostone of the Albemarle group (Lockport and Guelph Formations), having a total thickness of 100–110 m, which constitute the dolostone aquifer. These rocks are diagenetically-dolomitized limestone (Coniglio et al., 2003) with well preserved primary limestone structures, such as bedding planes and fossils. These formations are underlain by the shale confining unit of the Clinton group (Cabot Head and Rochester Formations) and overlain by deposits of the Late Wisconsinan glaciation that form a sequence of sandy and silt–clay units. The total thickness of these Quaternary deposits varies between 0 and 50 m (Bajc and Newton, 2007; Brunton, 2008) (Fig. 3).

The permeability of the intact dolostone rock matrix is extremely small, averaging 2.5×10^{-10} cm^2 as measured using core