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Delineating baseflow contribution areas for streams – A model and methods comparison

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ABSTRACT

This study addresses the delineation of areas that contribute baseflow to a stream reach, also known as stream capture zones. Such areas can be delineated using standard well capture zone delineation methods, with three important differences: (1) natural gradients are smaller compared to those produced by supply wells and are therefore subject to greater numerical errors, (2) stream discharge varies seasonally, and (3) stream discharge varies spatially. This study focuses on model-related uncertainties due to model characteristics, discretization schemes, delineation methods, and particle tracking algorithms. The methodology is applied to the Alder Creek watershed in southwestern Ontario. Four different model codes are compared: HydroGeoSphere, WATFLOW, MODFLOW, and FEFLOW. In addition, two delineation methods are compared: reverse particle tracking and reverse transport, where the latter considers local-scale parameter uncertainty by using a macrodispersion term to produce a capture probability plume. The results from this study indicate that different models can calibrate acceptably well to the same data and produce very similar distributions of hydraulic head, but can produce different capture zones. The stream capture zone is found to be highly sensitive to the particle tracking algorithm. It was also found that particle tracking by itself, if applied to complex systems such as the Alder Creek watershed, would require considerable subjective judgement in the delineation of stream capture zones. Reverse transport is an alternative and more reliable approach that provides probability intervals for the baseflow contribution areas, taking uncertainty into account. The two approaches can be used together to enhance the confidence in the final outcome.

1. Introduction

An environmentally sustainable stream depends on groundwater discharge for maintaining the steady baseflow and temperature needed to support a healthy aquatic ecosystem. Winter et al. (1998) illustrates the basic relationships for a typical multi-aquifer groundwater flow system containing a hierarchy of scales from local to regional, where the cycle from precipitation to discharge might range from days to millennia (Fig. 1). Water is lost by evapotranspiration and by discharge to wells and surface water.

Prevention of actual or potential threats to the quality and quantity of stream baseflow is critical to ensuring the environmental sustainability of streams. A major threat is land development for industrial, commercial, or residential purposes. Impervious surfaces such as roads, parking lots and roofs can impact groundwater recharge, promote storm runoff, and reduce aquifer storage. Development can also introduce contaminants such as road salt and increase the risk of chemical spills from point sources such as gas stations.

In order to manage these threats and find a balance between development and the protection of water resources, it is necessary to identify, with some confidence, the areas that contribute baseflow to sensitive streams or stream reaches. Appropriate protective measures can then be taken, and the potential economic cost can be assessed. The only practical approach to the delineation of these areas is through the use of simulation models.

Since an independent validation of model predictions is rarely possible, a critical issue is predictive uncertainty. This study focuses on one important source of uncertainty, namely the numerical uncertainty

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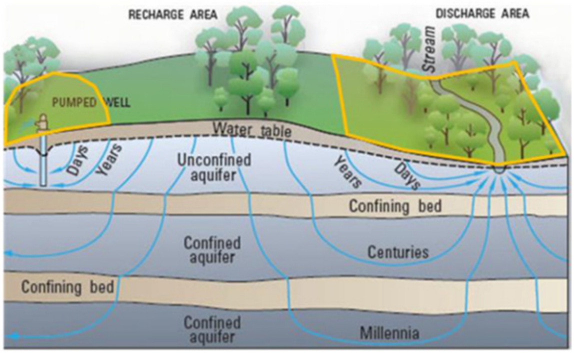

Fig. 1. Groundwater flow system: Well capture zone and stream capture zone are highlighted in orange.
(Source: adapted from Winter et al. (1998)).

based on model code selection. Other sources of uncertainty, as well as possible ways to control them, are briefly discussed in Section 7. Uncertainties due to alternative conceptual models in the context of wellhead protection are discussed by Sousa et al. (2013), as well as other authors.

In this paper we show that: (1) methodologies developed for well capture zone delineation can be applied to gaining stream reaches, (2) given the same model conceptualization, different groundwater models can produce different delineation results, and (3) results from different delineation methods can be combined to enhance the credibility of capture zone delineations.

A short version of this paper showing preliminary results has been presented at the GeoHydro conference in 2011 (Chow et al., 2011). Two models and an alternative delineation method have been added to this comparison. In addition, the models have been adjusted to isolate factors that cause differences in capture zone delineation.

2. The stream capture zone concept

In principle, the area that provides water to a stream encompasses the watershed or catchment area. However, it may not be practical to protect an entire watershed. The alternative is to identify the portion of the watershed that contributes baseflow for a specific reach of an environmentally sensitive stream. Veale et al. (2014) demonstrated this approach by means of a limited particle tracking analysis.

Conceptually, an area contributing to a stream reach should obey the same principles that govern a well capture zone. Fig. 1 shows the similarities between well and stream capture zones. On this basis, much of the well-established methodology for delineating capture zones for drinking water wells should apply to streams. In the following sections, we will use the term "stream capture zone" to mean "baseflow contribution area for streams". Section 2.1 describes the conceptual differences between well and stream capture zones, followed by Section 2.2 which describes the expected uncertainties associated with delineating a stream capture zone.

2.1. Differences between well and stream capture zones

There are several critical conceptual differences between delineating a stream capture zone as opposed to a well capture zone. Three fundamental differences are:

1. *The Nature of the Gradients*. Natural gradients near a stream will generally be much smaller than gradients induced by pumping at a well and therefore will be subject to greater relative numerical errors (Chow et al., 2011). In this study, the near-subsurface has been finely discretized vertically in order to reduce the numerical errors from natural gradients (Section 4.1).
2. *The Nature of the Source/Sink Function*. A well is a fixed-rate point source/sink, while a stream is a line source/sink variably distributed over the length of the stream. Where and how much groundwater a stream is gaining is generally not known. This study uses a fully integrated state-of-the-art surface water-groundwater model to obtain the spatial distribution and rates of groundwater exchange at streams (Section 4.2).
3. *The Significance of Transient Flow*. Stream discharge is more variable in time than water pumped from a well. For a water supply well, the pumping rate is generally constant for longer periods. Conversely, flow for a stream is strongly influenced by precipitation events and seasonal conditions. The purpose of a capture zone is to designate an area where the planned land use will provide a certain measure of protection. This area cannot change over the seasons or from year to year. Transients can play a role in the delineation, but in the end, the delineated area must be fixed. Accordingly, this study assumes a steady-state flow system and that transient effects originating at the ground surface generally dampen out over a long period of time. The issue of transience is discussed further in Section 7.

2.2. Structural and numerical uncertainties

Present standard practice in wellhead protection is to calibrate a model to available data and then to use the calibrated model predictively for capture zone delineation. This procedure neglects structural and numerical uncertainty due to model-related differences such as the discretization scheme and the computational algorithm.

Pinder and Frind (1972) have shown that, with increased grid refinement, both finite element and finite difference model types converge to the same answer. However, run times increase with the discretization, and in practice, the time available for model runs is often limited. Therefore, groundwater models are often not optimally discretized. Discretization aspects specific to this study are discussed in Section 4.1.

The computational method used for the capture zone delineation can also have a major effect on the delineation. Section 5 compares two well-known methods, particle tracking and reverse transport. Section 6 extends the comparison to different particle tracking algorithms and shows how it can be combined with reverse transport.

In this study, four well-known model codes are used to delineate capture zones for two gaining stream reaches in the Alder Creek watershed in southern Ontario.

3. Model codes considered and comparison approach

The following four models were chosen for this study:

HydroGeoSphere (HGS): This advanced control-volume finite element model (Aquanty Inc., 2013) integrates saturated/unsaturated groundwater flow (modified Richards' equation; Richards, 1931) with surface water flow (Diffusion-wave equation). As such, it is well suited for the stream capture zone study because it can generate its own water courses. It currently does not have a particle tracking routine, but is compatible with WATRAC (Frind and Molson, 2004) for particle tracking and with the Waterloo Transport Code (WTC) (Molson and Frind, 2004) for reverse transport.

WATFLOW: The well-proven finite element flow model WATFLOW (Molson et al., 2002) has been used extensively in previous studies of the Waterloo Moraine (Martin and Frind, 1998; Frind et al., 2014). WATFLOW has an integrated automatic calibration algorithm (Beckers and Frind, 2001), a particle tracking code, WATRAC (Frind and Molson, 2004), and a transport code, WTC (Molson and Frind, 2004). WATRAC is based on the Pollock Method (Pollock, 1988), adapted for triangular prismatic elements.

MODFLOW 2000 (VERSION 1.19.01): The finite difference model MODFLOW (McDonald and Harbaugh, 1988) is the most widely used groundwater code worldwide. It is linked to the particle tracking code MODPATH (Pollock, 1988). The original FORTRAN version is freely available through the U.S. Geological Survey, and several graphical user