Capture zone simulation for boreholes located in fractured dykes using the linesink concept

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Abstract

Delineation of capture zones for groundwater source protection is normally performed by using numerical codes which are based on the porous medium flow equation. However, boreholes are often sited in or along permeable dykes or single fracture zones through which aquifers are drained. It is very important to take into account dyke-influenced aquifers. This paper makes use of Linesink to simulate permeable dyke or fractured zones and utilises the pathline distribution to delineate the capture zones. Conditions when the influence of a fractured dyke can be considered negligible are also discussed through comparison with stagnation point in a uniform flow field. The approach may be sufficient to illustrate protection zoning requirements when dyke aquifers are considered.

Introduction

Studies on capture zones for simple flow conditions in uniform aquifers were performed by Todd (1980), Almendindger (1994) and others. For more complex flow situations where boundaries are considered, borehole capture zones or catchments may be delineated by using semi-analytical models (Nelson, 1978a,b; Keely and Tsang, 1983; Javandel and Tsang, 1986; Lerner, 1990 & 1992; Blandford and Huyakorn, 1991 and Kinzelbach et al., 1992).

The existing semi-analytical models provide a powerful tool to understand the capture zone concept and to acquire general ideas about borehole or wellhead protection zoning before embarking on a site-specific study of groundwater protection. However, these models do not account for the capture zone of a draining fracture. In South Africa, boreholes are often sited in highly fractured dykes for good water supplies. Strack (1989) and Haitjema (1995) presented the concept of the linesink which is utilised here to simulate a permeable dyke or fracture zone for delineating the capture zone in dyke aquifers.

A borehole protection area can be defined as the controlled area surrounding a production borehole (or wellfield). Demarcation of such controlled areas where certain activities of land use are prohibited would prevent contaminatants from reaching the borehole. It may consist of a capture zone as well as a borehole catchment. The latter, also referred to as the zone of contributing water (ZOC) (Todd, 1980; Reilly and Pollock, 1993), is the limiting case of the capture zone at t where $t \rightarrow \infty$. The borehole catchment may be interpreted as the projection on ground surface of a 3D aquifer volume which would contribute water to the borehole under steady-state flow and pumping conditions. Inside the catchment water would flow towards the borehole whereas water outside would flow away from the borehole. The delineation of the protection area is often based on assumption of the averaged steady-state flow. Assuming A (L^2) is the area of the catchment, P (LT^{-1}) a uniform rainfall recharge and Q (L^3T^{-1}) the averaged pumping rate from a borehole of interest, then the following relation holds:

$$AP = Q \qquad (1)$$

Eq. (1) tells us that the borehole catchment size A can be calculated if P and Q are known. However, Eq. (1) gives neither a physical location of the catchment with respect to the borehole, nor does it provide hydrogeological conditions like type of aquifer, etc. It merely provides a water balance with as many geometrical distributions as possible (illustrated in Fig. 1).

Under steady-state conditions, groundwater streamlines coincide with fluid pathlines. If dispersion is negligible, we may use pathline equations to track pollutant movements in aquifers. To demarcate either a capture zone or a borehole catchment under the steady-state, we utilise discharge potential to derive the pathline equations. Assuming that an aquifer thickness is more or less uniform, the pathline distribution under certain hydrogeological settings is investigated in an x, y plane.

Theory of capture zone simulation using linesink concept

For the sake of simplicity, we assume that the natural hydraulic gradient can be neglected. This is often encountered in aquifers interrupted by vertical dykes. If the gradient is assumed to be zero, a pumping borehole in a uniform aquifer will cause a circular shape of the cone of depression with radius r, which can be directly calculated from the formula: $r = \sqrt{(A/\pi)}$, where A is obtained from the water balance. However, the focus is on the following cases.

Discharge potential for fracture zone

Based on Strack (1989) and Haitjema (1995), a linesink can be defined as a mathematical sink line with a finite length. If a pumping hole is located in a fracture zone, the fracture can be regarded as an extension of the borehole. It is noticed that the behaviour of a pumping hole located in the fracture zone may be similar to that of a linesink. A fracture zone can be simulated by the linesink. Based on the complex potential for the linesink element with length L (Strack, 1989), the discharge potential may be written as follows:

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