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The stability of groundwater flow systems in unconfined sandy aquifers in the Netherlands

Marc J.M. Vissers, Marcel van der Perk *

Department of Physical Geography, Utrecht University, P.O. Box 80.115, 3508 TC Utrecht, The Netherlands

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Summary Groundwater flow is temporally variable and uncertain, due to climatologically or anthropogenically induced variation in boundary conditions that result in changes in the drainage network, and uncertainties in hydraulic model parameters used in the quantification of groundwater flow. The quantification and mapping of the variation and uncertainty in groundwater flow is especially essential in relatively flat areas where flow direction is sensitive to decimetre-scale head variations. In these areas, the variability and uncertainty of groundwater flow directions may therefore have important implications for the uncertainties in the spatial configuration of groundwater flow systems. In this study we aim to quantify and map the sensitivity of shallow groundwater flow systems to uncertainties in aquifer anisotropy and drainage resistance, and variations in drainage level and groundwater recharge for a sandy unconfined aquifer in the Salland region, the Netherlands. For this purpose, the most probable configuration of current groundwater flow systems was mapped using particle tracking and Monte Carlo analysis. Sensitivity was represented by the membership of each model cell to the defined groundwater flow systems given the uncertainties and variations in the hydraulic parameters and boundary conditions. In addition, the current configuration of groundwater flow systems was compared to the historical situation without artificial drainage. The average groundwater flow system size was found to be in the order of a few square kilometres, with a relatively stable configuration. In contrast to the intrinsic and temporally invariant hydraulic parameters, which were shown to have a minor influence on the spatial configuration of groundwater flow systems, natural variation in recharge and variations in drainage level management exert a large influence.

Introduction

In the past decade, there has been a growing interest in the information on groundwater flow for land use planning and

* Corresponding author. Tel.: +31 30 2535565; fax: +31 30 2531145.
E-mail address: m.vanderperk@geo.uu.nl (M. van der Perk).

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the conservation and management of ecosystems in addition to the traditional fields of groundwater sanitation and well-capture zone delineation (Van Buuren, 1991; Robinson and Reay, 2002; Batelaan et al., 2003). The analysis of groundwater flow systems (Tóth, 1963; Engelen and Kloosterman, 1996) provides valuable insight in the spatial patterns of groundwater flow, which, when combined with knowledge on contaminant input and geochemical processes, provides detailed insight in the spatio-temporal distribution of groundwater quality. The groundwater flow systems analysis provides an answer to an important water quality related issue, which is to relate observed water quality in streams, discharge areas, and wells at one moment in time to their recharge areas in terms of the past land use and water quality (Falkenmark and Allard, 1991).

Mapping groundwater flow systems is usually performed using particle tracking, as isohypses conceal most details of groundwater flow paths. In modelling capture zones of groundwater extraction wells, backward particle tracking analysis is frequently used (Bair et al., 1991; Frind et al., 2002), but also forward procedures are used to assess the probability of capture (Hunt et al., 2001; Van Leeuwen et al., 1999). In assessments of natural groundwater flow systems, forward tracking procedures are also used. Modica et al. (1997) used detailed forward particle tracking analysis to investigate the influence of streams in a generic aquifer, combined with parametric analysis of aquifer parameters. Buxton et al. (1991), and later Robinson and Reay (2002) and Batelaan et al. (2003) mapped groundwater residence times in a region or catchment using forward particle tracking. Vissers (2006) demonstrated that results from forward particle tracking analyses can be rendered into comprehensible two-dimensional maps of three-dimensional groundwater flow. These include map representations of groundwater flow systems combined with transit time, transit distance, travel distance at specified depths, net groundwater recharge, and piezometric heads.

However, the delineation of groundwater flow systems is not unambiguous, even in aquifers with relatively simple geometry (Frapporti et al., 1995). Zijl (1999) showed that the aquifer anisotropy and the 'wavelength' of the topography, which often corresponds to the distance between streams, are the critical parameters that determine the penetration depth of groundwater flow systems and thus their hierarchical configuration. However, uncertainties in hydraulic parameters that determine this anisotropy and wavelength, i.e. horizontal and vertical hydraulic conductivity and drainage level and resistance, give rise to uncertainties in the size and spatial configuration of the groundwater flow systems. Furthermore, the boundaries of flow systems may be unstable or move due to climatologically or anthropogenically induced changes in boundary conditions. Seasonal and inter-annual variations in groundwater recharge may lead to contraction and expansion of the stream network (De Vries, 1995), and thus in changes in the flow pattern. Human interventions in the drainage system, groundwater extraction, or artificial recharge can have substantial, but often unknown, effects on the spatial configuration of groundwater flow systems.

Up to date studies of uncertainties in groundwater flow modelling have largely been focused on the assessment of the influence of uncertainty and heterogeneity in model parameter values and boundary conditions on groundwater flow (e.g. Gomez-Hernandez and Gorelick, 1989; Varljen and Shafer, 1991; Vassolo et al., 1998) and the quantification of uncertainty of well-capture zones (e.g. Bair et al., 1991; Bhatt, 1993; Van Leeuwen et al., 1999; Wheater et al., 2000). Uncertainties in natural groundwater flow systems have rarely been quantified. These uncertainties and variations in groundwater flow pattern may impede the determination of past and future groundwater flow paths and, consequently, hamper the solution to the above stated water quality related issue. Therefore, quantification of the uncertainties and variations in groundwater flow systems is essential in the analysis and interpretation of spatial and temporal patterns in groundwater quality.

The aim of this study is to quantify and map the sensitivity of shallow groundwater flow systems in a relatively flat, sandy unconfined aquifer, to variations in anisotropy in hydraulic conductivity, drainage level, drainage resistance, and groundwater recharge. For this purpose, the Salland region, the Netherlands, was chosen as the study area, because this area is typical for sandy areas in the Netherlands with respect to topography and aquifer properties. A three-dimensional hydrological model was set up using MODFLOW (McDonald and Harbaugh, 1988) and calibrated against observed piezometric heads. Groundwater flow paths were computed using MODPATH (Pollock, 1989) and were used to map groundwater flow. A Monte Carlo analysis was performed to automatically map the spatial configuration of groundwater flow systems. To assess the stability of the flow systems the following steps were undertaken. First, the current spatial configuration of groundwater flow systems was compared to the natural pattern without artificial drainage. Second, a sensitivity analysis was performed to assess the hydraulic parameters and model boundary conditions to which the position of the groundwater flow system boundaries is most sensitive.

Study area

The study area comprises an area of 12 km × 18 km situated in the Salland region in the eastern part of the Netherlands (Fig. 1). The area stretches across a cover sand plain with undulating topography between 3 and 10 m above local ordnance datum (OD) in the western part of the study area towards the 'Holterberg' ice-pushed ridge (ice-displaced local deposits), which reaches +75 m OD, in the eastern part (Figs. 2 and 3). The cover sand (Boxtel Formation, Wierden Member; De Mulder et al., 2003) is a few meters thick and covers coarser fluvial sands (Kreftenheye Formation). These sandy deposits that were formed during the late Saalian, Eemian and Weichselian (~150,000–11,000 yr BP) comprise the studied aquifer with a base typically at −30 m OD. In the far west fine-grained floodbasin deposits locally occur within the Kreftenheye sands at approximately −10 m OD. The western half of the study area is underlain by impermeable fluvio-glacio-lacustrine clays (Kreftenheye Formation, Twello Member) (see Fig. 3).

Until the mid-19th century, there were hardly any streams present in the area and groundwater was discharged through evapotranspiration in groundwater-fed wetlands. In 1858 AD the Overijssels Canal crossing the mod-