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Hydraulic heterogeneity and its impact on kinematic porosity in Swedish coastal terrains

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ABSTRACT

Hydrogeology in crystalline rock aquifers is often problematic due to the heterogeneity and anisotropy in the fracture network. Kinematic porosity of the host rock is exceedingly important for municipal decision makers in assessing sustainably extractable water supply volumes and assessing contaminant transport behavior within the matrix. This study explores heteroscedasticity in the hydrogeological characteristics of the fracture network and estimation of kinematic porosity from superficial fracture measurements. Estimates were based on the geometrical properties of the fractures including: fracture frequency, aperture and orientation. The estimates were adjusted for aperture changes with depth, connectivity of the fracture network, fracture continuity and measurement orientation bias. The results were compared with well archive data and correlations were found to be significant with more than 95% confidence. Erratic behaviour of well data relative to fracture measurements indicates that well orientation with respect to the fracture network gives incomplete hydrogeological data. Spatial heterogeneity of the bedrock was examined using spatial statistics and geographic information systems. The results from the spatial statistical analyses of well data showed that the heterogeneity within the bedrock is sufficiently high that spatial correlations cease to exist in nearly all investigated rock types at distances greater than 500 m, and in some rocks, particularly sedimentary gneisses, no spatial correlations were observed. Arbitrarily grouped samples with similar geology and topography showed evidence of non-stationary variance. Results indicate that regional generalizations based on sparse point measurements are highly error prone and potential exists in complementary field-based estimates.

1. Introduction

An important factor in both water-supply oriented hydrogeology and contaminant transport hydrogeology is kinematic or effective porosity, meaning the porosity which contributes to the flow network. Often associated with specific yield, which includes drainable, dead-end zones (Stephens et al., 1998), or total porosity, which includes zones not accessible to fluid transport, kinematic porosity is often estimated from literature, core samples or tracer tests, but is seldom well defined in hard rock aquifers (Snow, 1969; Zimmerman and Bodvarsson, 1996; Singhal and Gupta, 1999). Fractured matrices often behave as a dual-porosity system (Cherubini et al., 2010). Due to the relatively impermeable nature of the rock matrix compared with the fracture network, the assumption is often made that significant flow only occurs in the fractures and that the matrix flow is negligible (Singhal and Gupta, 1999; Cesano et al., 2003; Surrette et al., 2008; Voeckler and Allen, 2012).

Estimating porosity from core samples (Penttinen et al., 2006; Savukoski, 2007) will often lead to overestimations, as additional flow paths are created from the act of obtaining the core or underestimated since large fractures may be missed entirely (Tullborg and Larson, 2006). Tracer tests may also be used to estimate porosity values, but are time consuming and costly (Li, 1995; Li et al., 1996), limiting their applications in municipal water supply investigations in peri-urban areas. Additionally, uncertainty in estimates may be dependent on the selected transport model (Stephens et al., 1998). Heterogeneity in fracturing makes regional estimates based on point data error-prone, indicating that the use of zones demarcated by geological structures and which have independent hydrogeological properties may be advantageous (Surrette et al., 2008; Chesnaux et al., 2009). Spatial correlations are often very weak in crystalline rock, indicating that heterogeneity exists between groups with similar geological and topographical characteristics (Wladis and Gustafson, 1999; Earon et al., 2015). Methods which rely on physical or chemical indicators such as in Dethlefsen et al. (2017) may not be sufficient to characterize the reservoir. Geophysical characterization based on Archie's Law (Arétouyap et al.,

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2017) is sensitive to lateral geological heterogeneity, and in regions with intrusive crystalline rocks surrounded by water uncertainty in estimates would be extremely high.

Volumes of water available for local water supplies are limited by kinematic porosity rather than specific yield as closed pores in the fracture network which would be drainable become air-filled after repeated recharge-discharge cycles due to use and seasonal variation. Specific yield may overestimate the fraction of the medium which may contribute to water supplies. Thus, kinematic porosity is essential in determining the actual volumes of water which are sustainably extractable in order to avoid problems such as saline water intrusion or groundwater reservoir depletion as well mitigating possible effects of groundwater level variations induced by climate change (Hrkal et al., 2009). Many Swedish municipalities are undergoing a shift to an increased level of permanent residency from seasonal residency as seen in Tyresö Municipality (2017) which puts a strain on local groundwater resources due to typically increasing water use. As many municipalities lack the technical background or resources for comprehensive hydrogeological investigations involving more complex models, simple estimates can aid in planning and managing resources in a sustainable way.

Important factors which affect the effective porosity of a hard rock aquifer are: fracture frequency (or spacing), aperture width, length, degree of roughness or contact and connectivity between the fractures. The physical nature of these factors is governed by the geological history of the rock and complex factors such as mineral precipitation or dissolution, stress, shearing, roughness, and fracture genesis may influence kinematic porosity. Frequency can refer to the number of fractures per distance unit, or the frequency between a particular, predominant fracture set (Liu et al., 1999). The former use is advantageous as interpretation of a single predominant fracture orientation may be error-prone and inherently assumes that surface measurements will represent bulk of the rock mass, at least at shallow depths. However, it is often the case that the more weathered surface is quite often more fractured (Seeburger and Zoback, 1982; Mortimer et al., 2011), and thus the second methodology can provide a means to remove the non-representative measurements from the data, particularly in foliated rock masses (gneisses) which often have fracture orientations following the foliation of the host rock. Bedding fractures which may arise from a release of overburden stress (Skinner and Porter, 1995) can also disrupt accurate frequency estimations as they may be missed due to the measurements usually being taken on surfaces parallel to such fractures. These fractures, however, are vital to the connectivity of a fracture system.

Hydraulic aperture, or the width of the fracture through which fluid can readily flow, is an avidly discussed subject (Zimmerman and Bodvarsson, 1996; Olsson and Barton, 2001; Klimczak et al., 2010; Cao et al., 2016). Average aperture sizes of fractures visible on the surface of the host rock can often be misleading, as the aperture may be widened due to weathering. Additional factors such as closure due to stress can also complicate meaningful approximations (Carlsson and Olsson, 1993; Mortimer et al., 2011). Roughness adds additional complications when estimating kinematic porosity, as flow within fractures often only occurs through a portion of the fracture (Carlsson and Olsson, 1993; Gustafson, 2009). Often, flow occurs through as little as 25% of the individual fracture (Carlsson and Olsson, 1993; Gustafson, 2009), due to tortuosity and channel effects, and can be completely discontinued if contact area within a fracture approaches 50% (Zimmerman and Bodvarsson, 1996; Gustafson, 2009).

Connectivity between fractures adds another uncertainty to the estimation of kinematic porosity (Illman, 2006). If all fracture planes within a bedrock mass lie in parallel orientations without any connecting fractures, then the kinematic porosity would be negligible unless connected by a hydraulic pathway, such as a well, manually. Carlsson and Olsson (1993) attempted to quantify this feature through the addition of a coefficient varying theoretically from 1 to 3 which represents degree of connectivity. This approach could be improved in practice, as fractures occur at varying orientations with respect to the measurement surface and it is often very difficult to ascertain with certainty if a fracture is water conducting or not from the ground surface.

The aim of this work is to present a simple model for estimation of kinematic porosity based on fracture characteristics measured on exposed rock surfaces and assess it within the context of regional hydraulic heterogeneity. The purpose of this model is for use in sustainable groundwater resources management, particularly in regions with extremely high levels of spatial heterogeneity where small numbers of point estimates are insufficient to estimate hydrogeological parameters. Surficial fracture measurements will be used to estimate regional kinematic porosity, which will then be compared to measured well capacity data as a means to support the methodology.

2. Methodology

2.1. Study locations and well archive

Tyresö Municipality is located 20 km southeast of Stockholm (Fig. 1), Sweden, and is expected to have a population of roughly 60,000 by 2035 (Tyresö Municipality, 2017). Roughly 200 to 250 buildings are constructed yearly, with an additional 50 to 100 per year by 2030, and increases in population of 450 people per year, following a trend of increasing permanent residency and subsequent increased sanitation and water supply demands. The eastern peninsula, Brevik, is mostly surrounded by brackish water from the Baltic Sea, a potential source of salt water intrusion. The area was also glaciated until the last 10,000 years, and subsequently was submerged under saline and brackish water during periods after the last glaciation. Thus, at lower depths there are likely large volumes of fossil salt water not yet flushed by meteoric water (Olofsson, 1994).

Based on the Geological Survey of Sweden's (SGU) 1:50000 geological maps, the bedrock in the Tyresö area (Fig. 1) is comprised mostly of sedimentary gneiss, with periodic intrusive granite regions (1.86–1.96 GA) which typically is concordant with the foliation of the gneiss. The area has a great deal of bedrock outcroppings and topography in the region can vary as much as 0 to +85 m.a.s.l.. The eastern peninsula is part of a large-scale, steeply dipping geological fold, indicating potentially strong and difficult to predict in-situ stresses during previous geological eras. Due to several glaciations during the Quaternary period, the top soils consist of till deposited from the ice, covered in depressions by silt and clay sediments. Since the ice depressed the crust to 150 m below recent seawater levels and due to the on-going isostatic land upheaval the topographically higher-located sediments have been re-deposited due to wave action in the valleys leaving a high frequency of polished rock outcrops at high altitudes. Towards the western edge of Tyresö, there is an esker (glaciofluvial sand-gravel deposition) stretching in the north-south orientation.

Vallentuna and Österåker Municipalities are located roughly 20 km north of Stockholm, and have populations of roughly 30,000 and 40,000 people. The bedrock geology in Vallentuna and Österåker (Fig. 1) is comprised primarily of younger granitic rock types (1.88 to 1.74 GA), whereas Österåker's geology contains older granitic rock types, with large areas of ultra-basic to intermediate rock types, such as gabbro or granodiorites (SGU, 2012). The topography of Vallentuna and Österåker varies between 0 and 78 m.a.s.l.. The frequency of outcrops is lower and the spacing between outcrops is greater in Vallentuna compared to Österåker and Tyresö. A minor area, Blackeberg/Nockeby, which is located close to Stockholm City was also selected due to local differences seen in the well archive. This area is comprised of a mix of younger and older granitic as well as older sedimentary gneissic bedrock. The area is comprised of mostly clay and till filled valleys with regular hard rock outcrops. All Blackeberg/Nockeby measurements were carried out on the younger granitic bedrock. Blidö is an island located Norrtälje municipality northeast of Österåker, and was selected