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Groundwater flow pattern and related environmental phenomena in complex geologic setting based on integrated model construction

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SUMMARY

Groundwater flow, driven, controlled and determined by topography, geology and climate, is responsible for several natural surface manifestations and affected by anthropogenic processes. Therefore, flowing groundwater can be regarded as an environmental agent. Numerical simulation of groundwater flow could reveal the flow pattern and explain the observed features. In complex geologic framework, where the geologic–hydrogeologic knowledge is limited, the groundwater flow model could not be constructed based solely on borehole data, but geophysical information could aid the model building. The integrated model construction was presented via the case study of the Tihany Peninsula, Hungary, with the aims of understanding the background and occurrence of groundwater-related environmental phenomena, such as wetlands, surface water–groundwater interaction, slope instability, and revealing the potential effect of anthropogenic activity and climate change. The hydrogeologic model was prepared on the basis of the compiled archive geophysical database and the results of recently performed geophysical measurements complemented with geologic–hydrogeologic data. Derivation of different electrostratigraphic units, revealing fracturing and detecting tectonic elements was achieved by systematically combined electromagnetic geophysical methods. The deduced information can be used as model input for groundwater flow simulation concerning hydrostratigraphy, geometry and boundary conditions. The results of numerical modelling were interpreted on the basis of gravity-driven regional groundwater flow concept and validated by field mapping of groundwater-related phenomena. The 3D model clarified the hydraulic behaviour of the formations, revealed the subsurface hydraulic connection between groundwater and wetlands and displayed the groundwater discharge pattern, as well. The position of wetlands, their vegetation type, discharge features and induced landslides were explained as environmental imprints of groundwater. The highly vulnerable wetlands and groundwater-dependent ecosystems have to be in the focus of water management and natural conservation policy.

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1. Introduction and aims

After the first analytical representation of the flow field in homogeneous and isotropic unit basins along a 2D cross section by Tóth (1962), a conceptual background has evolved for unravelling subsurface flow patterns and related environmental processes. In a theoretical small drainage basin, three different hydraulic regimes (recharge, through-flow and discharge) of local, intermediate and regional flow systems could develop (Tóth, 1962, 1963). The theory of regional groundwater flow – implying gravity-driven hierarchically nested groundwater flow in hydraulically continuous basin – (Tóth, 2009) could explain a variety of geologic processes. Since the first application of numerical flow models (Freeze and Witherspoon, 1966, 1967), many others have been constructed for understanding fluid flow in sedimentary basins (e.g. Garven, 1995), heat and solute transport (e.g. An et al., 2015), accumulation of petroleum and ore deposits (e.g. Person et al., 2012) as well as eco-hydrological conditions (e.g. Batelaan et al., 2003) and surface water–groundwater interaction (e.g. Winter et al., 1998). In recent years, significant advances and improvements can be seen in the analysis of flow systems by investigating the gravity-driven regional groundwater flow (GDRGF) in other environments such as thick confined and

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unconfined carbonates (e.g. Ben-Itzhak and Gvirtzman, 2005; Mádl-Szőnyi and Tóth, 2015), metamorphic and igneous, volcanic rocks (e.g. Mul et al., 2007; Herrera et al., 2016) and even in more complex rock framework (e.g. Pacheco, 2015); together with the application of 3D numerical models of groundwater flow (Zhou and Li, 2011).

Hydrogeologic models require diverse and large dataset with uniform spatial coverage. In most cases these requirements are not completely fulfilled. Geophysical measurements can provide continuous information. Furthermore, coupling them with geologic (boreholes, profiles, sections, maps) and hydrogeologic data (water levels, pumping tests, laboratory measurements), and mapping the groundwater flow-related surface phenomena, the connected numerical models could represent the geologic structure, even its complexity, and explain the observed features. Utility and effectiveness of application of geophysical methods to hydrogeologic problems have already been highlighted by many studies (e.g. Rubin and Hubbard, 2005; Kirsch, 2009).

It has been revealed that the undulation of topography (provides the gravitational energy), the geology (controls the amount of stored groundwater, the geometry and rate of flow, chemical composition, and temperature) and the climate (determines the water supply and its distribution) have the major effect on the evolving groundwater flow systems. These agents constitute the conceptual system of hydrogeologic environment (Tóth, 1970). Thus, groundwater flow is controlled by the interaction of hydrosphere, lithosphere and atmosphere, and due to this interaction, typical environmental manifestations occur, which are attributed to the flowing groundwater. These natural phenomena and conditions are: (1) water-level fluctuation, regionally varying moisture content, discharging springs, base-flow of streams and springs; (2) water salinity and soil salinization, diagenesis, weathering, dissolution; (3) wetlands and vegetation type; (4) positive or negative geothermal anomaly; (5) soil and rock mechanical weakness failures, i.e. liquefaction, instability, landslides, slumping; (6) geomorphic features, i.e. gullying, erosion, karstification; and (7) transport and accumulation of heat, hydrocarbon, ores and contaminants (Fig. 1) (Tóth, 2009).

Accordingly, this paper presents a methodological scheme of how geophysical methods could aid obtaining geologic information for hydrogeologic flow modelling purposes if the a priori knowledge is quite restricted and/or in geologically complex areas. The study area is the Tihany Peninsula, Hungary, which is characterised by complex volcanic, siliciclastic and carbonate geologic structure and it is a natural conservation area. The peninsula is also a main touristic destination because of its natural and cultural heritage and pleasant milieu, so artificial influences are also present. In spite of its important and protected status, fluid flow model of the area, which could support water management and natural protection policy (Singh, 2014; Kløve et al., 2011), had not been constructed previously. Therefore, the aims of the study are: (1) constructing integrated groundwater flow model for a geologically complex area; (2) depicting hierarchical flow and discharge pattern; (3) understanding the background and occurrence of environmental phenomena, such as wetlands and groundwater-dependent ecosystems, surface water–groundwater interaction, discharge-related slope instability; (4) determining anthropogenic activity-related issues on groundwater flow; and (5) diagnosing the potential effect of climate change.

2. Hydrogeologic setting of the study area

The Tihany Peninsula, situated in the Bakony–Balaton Highland Volcanic Field, is surrounded by the Lake Balaton, Hungary (Fig. 2a). The preservation of environment and biodiversity is an important issue in this Natura 2000 area, with special emphasis on three minor wetlands. It has been presumed that they are recharged exclusively from precipitation. However, based on field observations, historical documents (Csizmazia, 2010) and

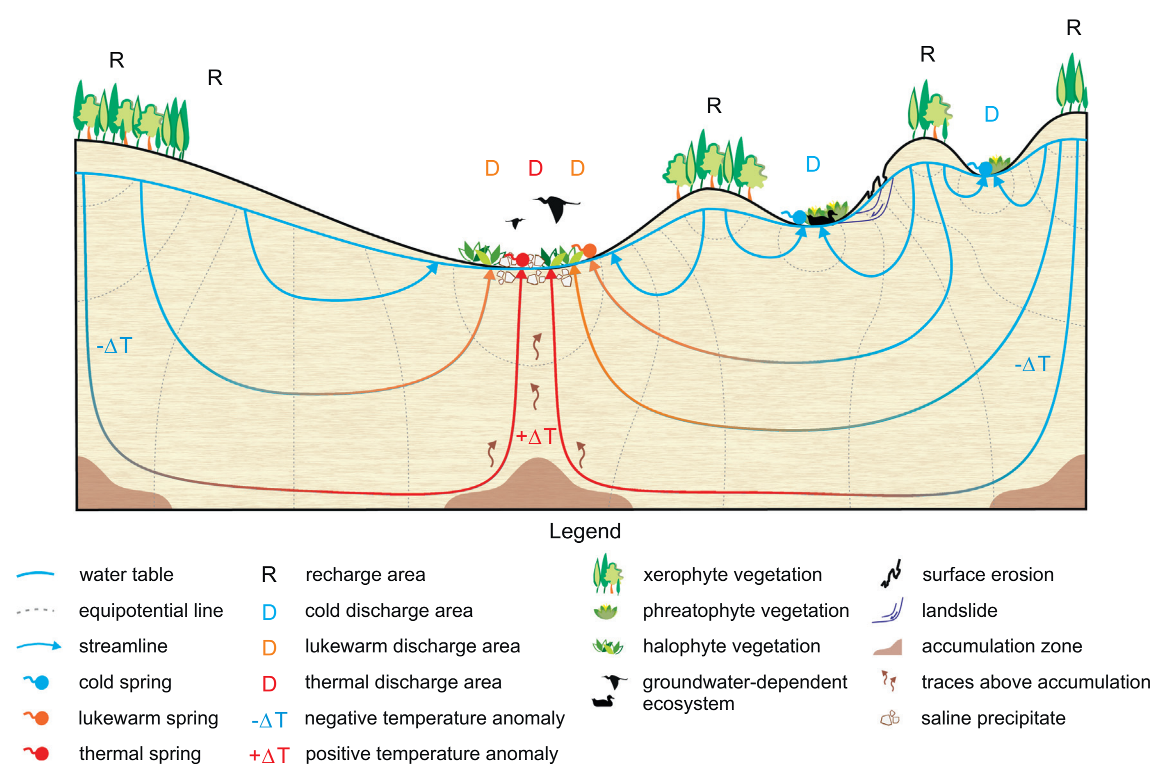

Fig. 1. Natural conditions and phenomena due to environmental agency of flowing groundwater in drainage basin (modified after Tóth, 1999).

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