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ESSAY

# Groundwater flow systems theory: research challenges beyond the specified-head top boundary condition

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The self-organisation of groundwater flow in nested systems as revealed and defined by Tóth (1963) is arguably one of the most fundamental properties of groundwater flow. Despite that, the theoretical characteristics of nested groundwater flow systems have mostly been studied under restricted modelling conditions. Overwhelmingly, from Tóth's (1963) original analysis till recent works (e.g. Wang et al. 2014; Zech et al. 2016), a specified-head top boundary condition has been used for representing the water table, often further assuming that the latter could be approximated by the land surface topography. While important insights can be gained using this undeniably convenient approach, the authors of this essay propose that specifying the hydraulic head along the top boundary can induce important errors in the flow solution, and that the water table would be better viewed as a variable function of the system's properties and stresses. It is argued that more research needs to be conducted on nested groundwater flow systems under conditions where the water table is not specified.

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## The water table as a specified-head boundary: rationale and shortcomings

In his seminal analysis, Tóth (1963) used an analytical solution that required the hydraulic head to be specified along the top boundary. This historical approach may partly explain why a specified-head condition has so often been used. Drastic simplifications were nevertheless required to obtain Tóth's solution: 2-D flow (cross-section), flat top boundary, homogeneous hydraulic conductivity, sinusoidal water table shape, and steady-state flow. Although more advanced analytical solutions have since been developed that allow for some of these assumptions to be relaxed (e.g. Craig 2008; Wang et al. 2011; Zlotnik et al. 2015), numerical solutions now exist that offer much greater flexibility. The use of numerical solutions for the study of nested flow systems has already been demonstrated by several authors (e.g. Cardenas and Jiang 2010; Goderniaux et al. 2013). Hence, should analytical solutions be thrown away? Obviously, the answer is 'no'. Even if they are approximate, analytical solutions can provide invaluable and rapid insights into the physics of the system, especially when they take the form of simple expressions; however and unfortunately, analytical solutions do not often have this attractive feature since in most cases they rely on the calculation of complicated infinite series. Furthermore, while analytical solutions exist for hydraulic head and velocity, many results of interest (e.g., geometry of nested flow systems,

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transport properties, etc.) still require numerical investigation of the velocity field (e.g. by particle tracking).

The topography has often been considered as a convenient approximation for the water table (e.g., Tóth 1963), contributing to the popularity of the specified-head approach. However, this assumption was shown to be unrealistic in many regions depending on climatic, geologic and topographic conditions (Haitjema and Mitchell-Bruker 2005; Gleeson et al. 2011). Using the topography instead of the water table implies an overestimation of the amplitude of the variations in hydraulic head, which in turn yields an overestimation of the fluxes through the water table, even in wet regions (Marklund and Wörman 2011). In reality, the water table outcrops only at a few locations such as along streams or other discharge features, thus implying that it mimics only the relatively large wavelengths of the topography. Zijl (1999) showed that, under homogeneous and isotropic assumptions, the penetration depth of a particular wavelength of the water table is of the same order as the wavelength itself. Therefore, at relatively small depth, groundwater fluxes are influenced by short water-table wavelengths that can significantly differ from the topography, and so using the topography in place of the water table will induce important errors. In contrast, at relatively large depth, the attenuation of short-wavelength signals might be such that groundwater fluxes could be assumed to be solely a function of topographic controls.

In nature, the water table obeys physical principles that give it particular shapes which cannot be easily reproduced by means of simple mathematical functions; therefore, specifying the water table (either from a pure analytical expression, from interpolated data, or from the topography) always implies a high risk of assigning a physically unrealistic boundary condition. The impacts on the simulated flow patterns would generally be unknown, but can be expected to be important given that the water table largely determines the flow patterns (Tóth 1963). Specifying the hydraulic head along the water table namely implies that recharge is an unconstrained result of the model (Sanford 2002), hence making this approach generally unsuitable for sustainability studies.

## Beyond the specified-head boundary condition

In most common groundwater models, the water table is in fact part of the solution. This has been the case since the first approaches to groundwater flow modelling (Dupuit 1863) and reflects the facts that: (1) the water table can be significantly different to the topography; (2) water-table data are generally too sparse to allow for a suitable characterisation; (3) modelling is very often undertaken to study the response of the system to stresses (e.g., climate change, groundwater extraction) that induce changes in water-table levels that need to be predicted; and (4) water-table dynamics have a key role in the inter-relationships between groundwater, the land surface, vegetation and the atmosphere (Levine and Salvucci 1999; Cohen et al. 2006; Maxwell and Kollet 2008). Therefore, in most practical models, the water table is a variable that adapts to the system's properties and stresses. A large number of physical formulations of the upper boundary condition and corresponding mathematical solutions have been developed over recent decades, including—specified-flux on a fixed boundary (e.g. Nield et al. 1994), specified-flux on a free-surface boundary with adaptive seepage area (e.g. Batelaan and De Smedt 2004; Harbaugh 2005; Bresciani et al. 2012), double-constraint (head and flux; e.g. El-Rawy et al. 2015), and variably-saturated flow (e.g. Freeze 1971; Simunek 2006). These approaches further offer the opportunity to couple the groundwater flow process to a variety of external processes that impact the water table such as overland flow, evaporation and transpiration (e.g. Therrien et al. 2004; Maxwell et al. 2007).

Despite the long existence of such modelling tools, little research has been done to elucidate the general properties of nested groundwater flow systems within these more advanced physical frameworks. Groundwater-surface water interactions around a single surface-water body might constitute an exception (e.g. Anderson and Munter 1981; Winter 1983; Nield et al. 1994), but in these studies the topography beyond the surface water body does not take part. Only a few studies have analysed the complex, non-linear interactions of the water table with the topography, including Forster and Smith (1988) and Bresciani et al. (2014), who dealt with cases of sloping cross-sections. Studies that considered the effect of topographic undulations include Liang et al. (2013), who emphasised the joint role of recharge and hydraulic conductivity on the development of nested flow systems; Gleeson and Manning (2008), who studied topographic and hydrogeologic controls on groundwater flow in a synthetic three-dimensional setting; Goderniaux et al. (2013), who developed a partitioning technique based on transit times to estimate the relative proportion of shallow versus deep flow; and Condon and Maxwell (2015), who evaluated the relationships between topography and the water table at continental scales using a fully-integrated model.

Additional research is needed to explore a wider range of physical processes and to derive scaling laws for the occurrence and characteristics of nested groundwater flow systems in typical settings. Studies should not only investigate cross-sectional configurations but also tackle the problem in three dimensions, for which Tóth's (1963) concept of flow systems has not been rigorously examined. The effects of the spatial distribution of recharge, the interaction with surface water and vegetation, the fractal characteristics of topography (Wörman et al. 2007), and subsurface heterogeneities all must be investigated. The impact of groundwater pumping on the hierarchical organisation of flow systems is obviously critical, and hence deserves more attention. What are the nature and the magnitude of these effects? What is the characteristic response time of the induced changes? Similar questions hold about the impacts of climate change on groundwater flow organisation and the feedbacks of groundwater on the climate (Green et al. 2011). This research is needed not only to gain a better fundamental understanding of hydrological systems, but also to drive intuition in real-world problems. When developing specific groundwater flow and transport models, conceptual choices have to be made. These choices are important and govern the outcomes of subsequent modelling efforts. Further research on groundwater flow systems, including their characterization as a function of recharge and external processes, is necessary to enhance system conceptualization and to improve qualitative and quantitative understanding of groundwater flow. While technical difficulties may have hampered advances on this topic in the past, a myriad of methods and computing power are now available to make this research possible – let us do it!

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