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Emergence of dynamic effective properties in periodic flow through heterogeneous aquifers

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Periodic transient flow of groundwater due to time dependent boundary conditions occurs in a few circumstances (e.g.rainfall seasonal, tidal diurnal and high frequency oscillatory well tomography, variations). Solving the flow equations (Darcy's Law, mass conservation) requires knowledge of hydraulic conductivity K and storativity s. In case of heterogeneous aquifers of random spatial variations of K and s, it is common to derive the mean flow variables (heads, fluxes) by adopting constant effective properties in the flow equations. The usual approach is the quasi-steady one, which adopts the well known steady state K_{efst} and the arithmetic mean s_A values, supposedly applying to sufficiently low frequency ω. We derive the effective conductivity K_{ef} of heterogeneous aquifers of lognormal conductivity distribution for arbitrary ω. It leads for the first time to the new effect of emergence of dynamic K_{ef}, which is complex. This implies a phase difference between the average flux and head gradient in the upscaled Darcy's Law, in contrast with the local Darcy's Law for which K_{ef} is real. The dependence of both the amplitude and phase of K_{ef} upon ω and the logconductivity variance are illustrated graphically, with delimitation of the parameters values for which the quasi-steady approximation applies. The results are illustrated for a few realistic values of aquifer properties, for which the quasi-steady approximation generally applies, with the exception of formations of very low mean conductivity. The results can be used for more complex time variations by superimposing harmonics of different ω.