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Scales and upscaling in groundwater flow and transport

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Fluid flow and solute transport in porous formations occur at a hierarchy of 4 fundamental scales: the pore scale O$(10^{-4}m)$, the laboratory or Darcy scale O$(10^{-2}m)$, the local formation three-dimensional scale O$(10^{0}m)$ and the regional two-dimensional scale O$(10^{2}m)$. At each scale the porous formation displays spatial variability of its properties and upscaling is carried out in space solely. The equations of flow and transport obeyed by the upscaled variables (pressure, flux, concentration) at each scale result from upscaling of the equations at the scale preceding it. The passage from Stokes equation at pore scale to Darcy's Law at the laboratory one (introducing the permeability K) and the subsequent passages to the upscaled Darcy's Law involving the effective permeability K_{ef} at formation and regional scales, are first discussed. Subsequently, a similar analysis is applied to upscaling of the transport equation. The selected upscaling approach is the stochastic one: the medium local properties are regarded as random space functions and upscaled variables, result of volume averaging, are also random. The main interest is in the ensmble mean values and the related effective properties appearing in the upscaled flow and transport equations. The presentation is focussed on a few issues of principle: what is the role of separation of scales? how restrictive is the requirement of statistical stationarity? what is the impact of nonergodic behavior? how are the theoretical results validated by field experiments?