Estimates of conservative contaminants vertical travel time throughout vadose zone in young glacial areas

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\section*{Motivation}
Estimation of contaminant travel time in the unsaturated zone is important for assessing aquifer vulnerability, delineating wellfield protection zones, planning monitoring and remediation, predicting the effects of land use and climate change on groundwater quality.

Travel time can be computed using several methods of varying complexity, based on either transient or steady flow assumption, but comparative studies are limited.

\section*{Objectives}
\begin{itemize}
  \item Comparison of numerical simulations of transient flow and advective-dispersive transport with simple methods based on the assumptions of steady state flow and advective transport
  \item Evaluating the role of the hydrodynamic dispersion and root zone influence on conservative contamination travel time
\end{itemize}

\section*{Soil profiles}

\begin{itemize}
  \item Clay Loam
  \item Clay loam
  \item Sand
  \item Sand with grass cover
\end{itemize}

\section*{Numerical modeling of transient flow and transport}

\begin{itemize}
  \item Implementation of Richards equation and advective-dispersive transport equation.
  \item Requires a large amount of data.
  \item Significant computational effort.
  \item Both recharge flux and travel time are obtained.
\end{itemize}

\section*{Analytical methods}

\begin{itemize}
  \item Transport only by advection (no dispersion).
  \item Steady downward flow.
  \item Recharge (R) taken from transient simulations
  \item a, b and c estimations based on literature data.
\end{itemize}

\section*{Results}

\begin{itemize}
  \item Profile I - bare sand
  \item Profile II - sand with grass cover
  \item Profile III - bare clay loam
  \item Profile IV - clay loam with grass cover
\end{itemize}

\begin{itemize}
  \item Volumetric water content profiles obtained from HYDRUS-1D simulations for profile I (bare sand), profile II (sand with grass cover), profile III (bare clay loam) and profile IV (clay loam with grass cover).
\end{itemize}

\begin{itemize}
  \item The average annual values of recharge (Tab. 2) computed by HYDRUS-1D show very significant influence of the vegetative cover, which reduces the recharge by a factor of about 2 for sand and about 4 for clay loam.
\end{itemize}

\begin{itemize}
  \item The early appearance of contaminant at the water table (\(c = 0.01 \text{ mg/cm}^2\)) is strongly influenced by the dispersion coefficient (Tab. 3), especially in sand where the travel time is 5 to 8 times shorter for large dispersion case compared to the small dispersion case. For clay loam the differences are smaller, but still very significant, with the difference in travel time by a factor of 2. On the other hand the in advance during the high infiltration (\(c = 0.01 \text{ mg/cm}^2\)) are much less significant and do not exceed 30%.
\end{itemize}

\begin{itemize}
  \item The hydrostatic profile assumption results in shorter travel times (Tab. 4), however the differences are not very big. The largest relative difference between the steady flow and hydrostatic profile occurs for bare sand, the smallest one for vegetation clay loam.
\end{itemize}

\begin{itemize}
  \item Travel times calculated with analytical methods vary greatly between the formulas (Tab. 5). For sand Eq (4) seems to be in a relatively good agreement with the results from transient simulations (small dispersion case). For clay loam the estimated travel time was significantly longer than the one obtained from HYDRUS-1D, especially in the case of vegetation. The method of Chowienczyk and Daniel (1993) gave travel times within the range predicted by Eq (4). In contrast, both Eq (6) and in all scenarios gave travel times much shorter than the ones computed from HYDRUS-1D and other methods. For sand Eq (6) leads to the shortest travel times, because the volumetric water content is smaller than the effective porosity used in Eq (7). For clay loam, if one uses small values of the effective porosity, as commonly reported in the literature, Eq. (7) predicts shorter time lag than Eq (6).
\end{itemize}

\section*{Conclusions}

\begin{itemize}
  \item Groundwater recharge flux strongly depends on the presence of root zone, for either sand or clay loam. Consequently, the travel time of pollutant also is affected by the presence of root zone.
  \item The assumed dispersion constant have significant influence on the arrival time of contaminant at the water table, which seems to be important in view of the widespread calculation of travel time based on the assumption of purely advective flow.
  \item The methods using steady flow approximation showed mixed performance, even though it was assumed that the exact value of average groundwater recharge is known for each soil profile. Care should be taken if simple analytical formulas are to be used to estimate unsaturated zone travel time. In view of the growing computer capacities and availability of simulation software and parameter data, it seems advisable that numerical simulations are used for at least partial comparisons with the analytical results.
\end{itemize}