

# GroundwaterDupuitPercolator: A Landlab component for groundwater flow

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DOI: [10.21105/joss.01935](https://doi.org/10.21105/joss.01935)

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Submitted: 03 December 2019

Published: 10 February 2020

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## Summary

A large portion of the water that enters a catchment as precipitation percolates through soil and rock before exiting to water bodies or returning to the atmosphere as evapotranspiration. In many places, the discharge of water stored in the subsurface is a primary source of streamflow, and thus controls the ways in which catchments respond to stochastic variations in precipitation and climate (Beck et al., 2013; Jasechko et al., 2014). Previous studies have shown the importance of groundwater for a diverse range of processes, from transpiration to solute export (Maxwell & Condon, 2016; Verseveld, McDonnell, & Lajtha, 2009), and across diverse timescales, from rainfall-runoff response to landscape evolution (Huang & Niemann, 2006; Sklash, Farvolden, & Farvolden, 1979). Of particular relevance to landscape evolution, groundwater can be an important control on the occurrence of overland flow, as the interaction of the water table with the ground surface controls the spatial extent of saturation and groundwater return flow (Dunne & Black, 1970). Variably-saturated groundwater flow is often assumed to be governed by the Richards equation, which describes how water content and/or total energy potential evolve in an idealized porous medium due to fluxes of water driven by gradients in total potential. Numerical solutions to the Richards equation are computationally expensive (e.g. Kirkland, Hills, & Wierenga, 1992), often limiting their applications. For computational efficiency, we use the widely applied Dupuit-Forcheimer approximation, which simplifies the Richards equation when aquifers are laterally extensive in comparison to their thickness, and the capillary fringe above the water table is relatively thin (e.g. Childs, 1971; Troch, Paniconi, & Van Loon, 2003). In this case, the water table is modeled as a free surface with groundwater flow driven by gradients in water table elevation. This formulation is known as the Boussinesq model of an unconfined aquifer. When the model assumptions are valid, this greatly reduces the model complexity while still producing water table elevations and discharges comparable to Richards equation solutions (Hilberts, Van Loon, Troch, & Paniconi, 2004).

Groundwater models of varying complexity are available for different purposes. Fully coupled groundwater and surface water models such as PARFLOW (Kollet & Maxwell, 2006), CATHY (Camporese, Paniconi, Putti, & Orlandini, 2010), and PIHM (Qu & Duffy, 2007) solve the three-dimensional Richards equation for variably saturated flow, and couple this with precipitation and runoff components. MODFLOW (Langevin et al., 2019) also solves the three dimensional Richards equation, and may be coupled to precipitation and runoff models, as in GSFLOW (Regan, Niswonger, Markstrom, Maples, & Barlow, 2018). More parsimonious models (with fewer necessary parameters and calculations) are also available, such as those that solve the hillslope storage Boussinesq equation for one-dimensional groundwater

flow in hillslopes of non-constant width (Marçais, Dreuzy, & Erhel, 2017, pp. @broda\_low-dimensional\_2012). Two-dimensional implementations of the Boussinesq model are common, but do not appear to be widely available as open source packages. The simplicity and computational efficiency of this method is advantageous for capturing the first-order effects of groundwater flow on other Earth surface processes. More sophisticated groundwater models may be necessary depending on the hydrological features that the user intends to capture.

Implementations of the Boussinesq model often encounter numerical instabilities where the water table intersects the surface and groundwater return flow occurs through a seepage face. This is due to the presence of a discontinuity in the energy gradient from inside the hillslope (where it is determined by the water table) to the seepage face (where it is determined by the topography). Marçais et al. (2017) introduced a regularization that smooths the transition between subsurface flow and surface flow. Although introduced for numerical stability and not based on physical principles, this smoothing may reproduce the effect of subgrid heterogeneity where saturation within a grid cell is unlikely to be homogenous or well-reproduced by a binary condition (saturated vs unsaturated).

The `GroundwaterDupuitPercolator` solves the governing groundwater flow equations with an explicit, forward in time finite volume method, using the Marçais et al. (2017) regularization at seepage faces. While the explicit method limits the maximum timestep that can be used without jeopardizing stability, the model includes an adaptive timestep solver that subdivides the user-provided timestep in order to satisfy a Courant–Friedrichs–Lewy stability criterion.

The `GroundwaterDupuitPercolator` can be implemented on both regular (e.g. rectangular and hexagonal) and irregular grids determined by the user. Recharge, hydraulic conductivity, and porosity may be specified as single values uniform over the model domain, or as vectors on the nodes (recharge, porosity) or links (hydraulic conductivity) of the grid. Link hydraulic conductivity can also be specified from a two-dimensional hydraulic conductivity tensor using an included function. For mass balance calculations, the model includes methods to determine the total groundwater storage on the grid domain, the total recharge flux in, and total groundwater and surface water fluxes leaving through the boundaries.

The `GroundwaterDupuitPercolator` is implemented in Landlab, a Python-based open source Earth surface modeling toolkit (Hobley et al., 2017). Landlab has a modular framework, which allows for easy coupling of different process components to meet the needs of the modeler. For example, the surface water flux from the `GroundwaterDupuitPercolator` can be passed to the `FlowAccumulator` module to route overland flow and calculate discharge at nodes. A summary of links to the documentation and example Jupyter notebooks is provided by the submodule [README](#). A diverse array of components are available, yielding many possibilities for model coupling that have not yet been explored. Given the importance of groundwater for many Earth surface processes, this component is an important contribution to the Landlab environment.

## Acknowledgements

D. Litwin was supported in part by a Horton Research Award from the American Geophysical Union. K. Barnhart was supported by NSF EAR Postdoctoral Fellowship (NSF 1725774).

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