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# A Linking Test to reduce the number of hydraulic parameters necessary to simulate groundwater recharge in unsaturated soils

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**Abstract**

In environmental studies, numerical simulation models are valuable tools for testing hypothesis about systems functioning and to perform sensitivity studies under scenarios of land use or climate changes. The simulations depend upon parameters which are not always measurable quantities and must be calibrated against observations, using for instance inverse modelling. Due to the scarcity of these observations, it has been found that parameter sets allowing a good matching between simulated and measured quantities are often non-unique, leading to the problem of equifinality. This can lead to non-physical values, erroneous fluxes and misleading sensitivity analysis. Therefore, a simple but robust inverse method coined the Linking Test is presented to determine if the parameters are linked. Linked parameters are then sub-divided into classes according to their impact on water fluxes. The Linking Test establishes the causes of non-uniqueness of parameter sets and the feasibility of the inverse modelling.

The Linking Test is applied to a one-dimensional soil-vegetation water flow model to predict groundwater recharge from the Richards' equation. Under the tested climates and by assuming the vegetation parameters constant, the Linking Test showed that only 2 parameters out of 6 Mualem–van Genuchten parameters are required to determine an accurate recharge for soils not reaching saturation. For a reference soil, the Linking Test enables to determine, all the different combinations of the parameters that give similar recharge. The parameter sets are obtained by optimising the parameters against time series of soil moisture profiles. The Linking Equations established for the reference soil have important implications for sensitivity analysis, upscaling and infiltration tests.


*Keywords:* Linking Test; Inverse modelling; Equifinality; Unsaturated flow; Groundwater recharge; Richards' equation; van Genuchten; Hydraulic parameters

## 1. Introduction

There is a growing need to determine the impact of deforestation/afforestation on *groundwater recharge* under climate change by using a reliable and cost-effective method. *Groundwater recharge*, i.e. soil water flux below the root zone, can be computed accurately by using physically based distributed models that solve the Richards'

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**Nomenclature**

| | |
|---|---|
| $E$ | actual evapotranspiration |
| $E_c$ | extension parameter |
| $E_p$ | potential evaporation |
| $\mathrm{FILE}_{\mathrm{sim}}$ | file that records OF, $Q_{\mathrm{sim}}$ and $\mathrm{PARAM}_{\mathrm{sim}}$ during optimisation |
| $g(h)$ | reduction of root water uptake at pressure head per cell |
| $h$ | matric potential |
| $h(\theta)$ | soil water retention curve |
| $h_{\mathrm{ae}}$ | air-entry matrix potential or bubbling pressure head |
| $h_{\mathrm{sv}}$ | matric potential at the onset of plant water stress |
| $h_{\mathrm{wp}}$ | matric potential at permanent wilting point |
| $K(\theta)$ | unsaturated hydraulic conductivity |
| $K_{\mathrm{s}}$ | saturated hydraulic conductivity |
| $L$ | shape factor |
| $m$ | shape parameter |
| $n$ | pore-size distribution |
| OF | objective function |
| $\mathrm{OF}_{\max}$ | greatest value of OF such that $\Delta Q = 5\%$ |
| $\mathrm{PARAM}_{\mathrm{feas}}$ | sets of feasible hydraulic parameters |
| $\mathrm{PARAM}_{\mathrm{ref}}$ | sets of reference hydraulic parameters |
| $\mathrm{PARAM}_{\mathrm{sim}}$ | sets of simulated hydraulic parameters |
| $P_{\mathrm{g}}$ | daily gross precipitation |
| $PTF(s)$ | pedo-transfer functions |
| $Q_{\mathrm{ref}}$ | reference cumulative groundwater recharge |
| $Q_{\mathrm{sim}}$ | simulated cumulative groundwater recharge |
| $z_{\mathrm{down}}$ | depth of bottom cell |
| $z_{\max}$ | root-zone depth |
| $z_{\mathrm{up}}$ | depth of top cell |
| $\Delta Q$ | discrepancy between $Q_{\mathrm{ref}}$ and $Q_{\mathrm{sim}}$ |
| $\Delta\mathrm{Rdf}_{\mathrm{i}}$ | vertical fraction of the roots density function per cell |
| $\beta$ | crop factor |
| $\theta_{\mathrm{e}}$ | normalised volumetric water content |
| $\theta_{\mathrm{final}}$ | final volumetric water content after the infiltration test |
| $\theta_{\mathrm{init}}$ | initial volumetric water content prior to infiltration test |
| $\theta_{\mathrm{r}}$ | residual water content or residual degree of saturation |
| $\theta_{\mathrm{ref}}$ | reference volumetric water content |
| $\theta_{\mathrm{s}}$ | saturated volumetric water content |
| $\theta_{\mathrm{sim}}$ | simulated volumetric water content |

equation [3,26,50]. Widely used models in this class include SHETRAN [17], SWIM [43], HYDRUS [47]; WAVES [58] and SOIL-SiSPAT [8]. A drawback of such physically based models is that they require a considerable number of *hydraulic* and *vegetation parameters* that need to be determined. Most of them are measured through a combination of costly and time-consuming laboratory and field methods. It is preferable to estimate these parameters indirectly *in situ* since measurements taken on samples poorly characterize field conditions.

*Groundwater recharge* is rarely measured. Therefore, in a research project, we tried to determine if *groundwater recharge* could be modelled using a water flow model, under various vegetation types. We tried to optimise simultaneously the *hydraulic* and the *vegetation* parameters of the soil water model. Optimisation was performed by matching solely observed and simulated time series of *soil moisture* profiles measured *in situ*. The soil water model used *precipitation* and *potential evaporation* as inputs. We found that a unique *groundwater recharge* value below the root zone could be obtained, but the optimised *hydraulic* and *vegetation* parameters were not unique [41]. Therefore, we investigate in this paper why the optimum *hydraulic parameters* are not unique. For simplification and demonstration purpose, we restrain the problem to soil *hydraulic parameters* only, assuming that vegetation parameters are known. We also use synthetic data sets to evaluate the potential of the methodology we propose.

The main problem is to determine if the optimised *hydraulic parameters* suffer from *equifinality*. This term has been, defined by Beven [5]. Equifinality occurs when more than one set of parameters give acceptable simulations relative to a given measure of goodness of fit between simulated and measured values [similar objective function values (OF)]. The *optimum parameter set* may not always provide a solution close to the "*true*" *soil parameter set*. This parameter set can be determined in the field or in the laboratory directly or indirectly. In our case study the "true" soil parameter sets are known as we used synthetic data. Solutions around the global optimum are kept as plausible solutions called *behavioural parameter set* [5]. Different categories of *behavioural parameter sets* identified by the authors may be recognized as

- *Inactive parameters*: parameters which values in the feasible parameter space, have little influence on OF, *water fluxes* and on the other parameters. This may be caused by the restrained range of the forcing data;
- *Sets of linked parameters*: when parameters are linked, there is an infinite combination of *sets of linked parameters* that produces OF values close to that obtained with the *optimum parameter set*;
- *Natural behavioural parameter set*: all parameters that are neither *inactive parameters* nor *linked parameters* are considered to be *natural behavioural parameter set*. There will always be sets of parameter causing *equifinality* due to inaccuracy in the data and in the model.