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# Efficient Mass Conservative Numerical Model for Solving Variably Saturated Groundwater Flow

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## Summary

A multi-dimensional mass conservative numerical method, particularly suitable for limited computational resources, is developed for solving transient variably saturated groundwater flow problems. The Richards equation is discretized spatially with a finite element method and temporally with an implicit Euler scheme, in which mass-conservative and mass-lumping techniques are used to keep the numerical simulation stable. In addition, the stiffness and mass matrices involved are approximated in a way to guarantee less computational effort. To confirm the accuracy and the efficiency of this code, we verified it using benchmark tests using one, two and three-dimensional problems. The present model is also applied to a real field case problem, where its superiority is clearly demonstrated. The code achieved reliable results for each problem.

## Keywords

Groundwater Flow, Finite Element, Modeling, Richards Equation, Variably Saturated Flow

## 23 1 Introduction

24 Flow in a variably saturated porous medium is governed by the Richards equation, a highly  
25 nonlinear PDE. Few analytical solutions using simplifying conditions or restrictive  
26 hypotheses were presented (Polubarinova, 1962; Teloglou et al, 2008; Moutsopoulos, 2013;  
27 Tracy, 1995, 2006, 2007; Hayek, 2015). Nevertheless, the most attempts to solve saturated-  
28 unsaturated flow problems are based on numerical techniques.

29 Several models, using the numerical approach of Celia et al. (1990), were developed (Clement  
30 et al, 1994; Van dam and Feddes, 2000; Kuznetsov et al, 2012; Herada, 2014). Belfort et al.  
31 (2013) presented a review of several estimations of the equivalent conductivity and analyzed  
32 the efficiency of the different averaging fashions when solving unsaturated flow. Fahs et al  
33 (2009) used the method of lines combined with the mixed finite element discretization to  
34 solve variably saturated flow in porous media. Younes et al (2013) studied the monotonicity  
35 of a finite volume-based method for solving flow in variably saturated and heterogeneous  
36 porous media. Hassane Maina and Ackerer (2017) discussed Newton-Raphson method and  
37 time-stepping strategies for solving the mixed form of Richards equation. Koohbor et al  
38 (2020) solved Richards equation in the context of fractured porous media. Zha et al. (2017)  
39 presented a modified Picard iteration scheme for overcoming drawbacks arising when  
40 simulating infiltration into dry soils. Farthing and Ogden (2018) and Zha et al (2019)  
41 presented a state-of-the-art review of the numerical solution of the Richards equation.  
42 Numerous aspects were discussed and challenges underlined related to equivalent hydraulic  
43 conductivity, computational efficiency or choice of primary variable among others.  
44 Other models were also developed (Thoms et al, 2006; Šimůnek et al, 2006) in view to solve  
45 3D flow in variably saturated porous media. These numerical models proceed by solving the  
46 resulting equations system subsequent to various approximation methods. However, these  
47 codes may be costing in CPU time when much finer temporal and spatial discretizations are

48 necessary, or in case of applications at the watershed scale, e. g., for climate change purposes  
49 when huge equations systems are to be solved. Drawbacks to the numerical resolution  
50 attempt of the Richards equation may be exacerbated, when computational resources are  
51 limited. Alternatives are proposed to avoid high CPU time costs of fully 3D numerical modes  
52 (Yakirevich et al, 1998; Paulus et al, 2013; Kuznetsov et al, 2012; Xu et al, 2012). These  
53 techniques act by lowering dimensions of the fully 3D Richards equation in both unsaturated  
54 and saturated domains or only in the unsaturated one when the saturated flow is modeled in its  
55 whole dimensionality. As a consequence the number of unknowns to be solved decrease  
56 significantly and the CPU time as well. However, doing so may constitute a source of  
57 inaccuracies that can affect the hydraulic heads as well as the fluxes in the separated domains.  
58 Indeed, as it is pointed out by Twarakavi et al. (2008), only solving the fully 3D Richards  
59 equation for the whole continuous flow domain is able to provide accurate solutions for  
60 hydraulic heads and subsequent fluxes in both unsaturated and saturated compartments.  
61 However, the most obstacle that limits the applicability of such models for regional scales is  
62 their computational demand and time cost.

63 In this paper, a multi-dimensional numerical model based on the mixed form of Richards  
64 equation, particularly suitable for limited computational resources, is developed to solve flow  
65 equation in both unsaturated and saturated zones under unsteady and steady regimes. The  
66 numerical model is Galerkin FE based and uses the Celia et al's (1990) first-order time  
67 integration method to solve the derived algebraic equations system. The use the Richrads  
68 equation may be inappropriate with coarse grids because of violation of the assumption of  
69 representative elementary volume which can result in loss of accuracy (Zha et al, 2019). The  
70 use of the fine grids, however, may complicate the resolution or simply make it infeasible due  
71 to high computational coast. In order to circumvent these difficulties, the proposed numerical

72 numerical scheme approximates the matrices involved in a newly fashion to guarantee less  
73 computational effort, when solving the involved PDE.

74 The paper is organized as follows: section 2 describes the flow model used to solve variably  
75 saturated porous media and reports the most used retention curves equations. Section 3 is  
76 dedicated to the numerical procedure adopted and the proposed approximation of the matrices  
77 obtained. In section 4 benchmark tests against analytical solutions show the present model  
78 capabilities to provide high level of accuracy. In addition, other tests available in the literature  
79 are also examined and the efficiency of the present model is demonstrated. Finally, section 5  
80 summarizes the concluding remarks.

## 81 2. Mathematical statement

82 The Richards equation can be expressed on three usual forms: the head-based form, the  
83 moisture-based form and under a mix form using the moisture and the head for the temporal  
84 and the spatial terms respectively. Discussion about these forms can be found in Fahs et al  
85 (2009), Farthing and Ogden (2018) and Zha et al (2019).

86 The mixed form of Richards' equation, modeling water flow in a variably saturated porous  
87 medium, is obtained by combining Darcy's law and continuity equation and is expressed as:

$$88 \quad \nabla \cdot (\mathbf{K}_s K_r(h) \nabla h) - q = \frac{\partial \theta}{\partial t} \quad (1)$$

89 Where  $\mathbf{K}_s$  is the saturated hydraulic conductivity tensor,  $K_r(h)$  is the relative conductivity,  $q$   
90 is the source/sink per volume of aquifer,  $\theta$  stands for the volumetric moisture content and  
91  $h$  is the hydraulic head.

92 Solving Richards' equation necessitates eliminating one of the two dependent variables, water  
93 content and the pressure head  $\psi = h - z$  (where  $z$  is elevation). This is often done by  
94 introducing constitutive equations, namely the water retention curves that express the water

95 content and the relative conductivity, as functions of the pressure head. Various formulations  
 96 can be found in the literature. In this work some of them will be used ranging from simplest to  
 97 very complex ones and are listed below.

98 Based on the model of Irmay (1954), the moisture content, as in Tracy (2006), is expressed  
 99 as:

$$100 \quad \theta = \begin{cases} \theta_r + (\theta_s - \theta_r) e^{\alpha\psi} & \psi < 0 \\ \theta_s & \psi \geq 0 \end{cases} \quad (2)$$

101 Where  $\theta_s$  and  $\theta_r$  are saturated and residual moisture content respectively.

102 Gardner (1958) expressed the relative conductivity as an exponential function of the pressure  
 103 head:

$$104 \quad k_r(\psi) = \begin{cases} e^{\alpha\psi} & \psi < 0 \\ 1 & \psi \geq 0 \end{cases} \quad (3)$$

105 The moisture content and the relative conductivity formulated by Van Genuchten (1980) are  
 106 very popular and are written as:

$$107 \quad \theta = \begin{cases} \frac{(\theta_s - \theta_r)}{\left(1 + (\alpha|\psi|)^n\right)^m} + \theta_r & \psi < 0 \\ \theta_s & \psi \geq 0 \end{cases} \quad (4)$$

$$108 \quad k_r(\psi) = \begin{cases} \Theta^{\frac{1}{2}} \left(1 - \left(1 - \Theta^{\frac{1}{m}}\right)\right)^2 & \psi < 0 \\ 1 & \psi \geq 0 \end{cases} \quad (5)$$

109 Where  $\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$  expresses the effective saturation and  $\alpha$ ,  $n$  and  $m = \frac{n-1}{n}$  are constants  
 110 depending upon the soil properties.

111 Brooks and Corey (1964) provided also equations describing hydraulic properties of soils,  
 112 expressed originally as functions of the moisture content  $\theta$ :

113 
$$\psi = \psi_s \left( \frac{\theta - \theta_r}{\theta - \theta_s} \right)^{-\frac{1}{\lambda}} \quad (6)$$

114 
$$k_r(\theta) = \left( \frac{\theta - \theta_r}{\theta - \theta_s} \right)^{\frac{2+3\lambda}{\lambda}} \quad (7)$$

115 Where  $\psi_s = \psi(\theta_s)$ , is the pressure head at saturation,  $\theta_r$  is the residual water moisture  
 116 content and  $\lambda$  is a parameter describing the pore-size distribution index of the medium.

117 Other relationships, linking moisture content and relative conductivity to the pressure head,  
 118 are presented by Haverkamp et al. (1977):

119 
$$\theta = \begin{cases} \frac{A(\theta_s - \theta_r)}{1 + (100|\psi|)^B} + \theta_r & \psi < 0 \\ \theta_s & \psi \geq 0 \end{cases} \quad (8)$$

120 
$$k_r(\psi) = \begin{cases} \frac{C}{C + (100|\psi|)^D} & \psi < 0 \\ 1 & \psi \geq 0 \end{cases} \quad (9)$$

121 Where A, B, C and D are constants to be determined experimentally for the soil type.

## 122 3. Numerical solution

### 123 3.1. Finite element model

124 To solve the flow equation (1), the finite element Galerkin method with linear basis functions  
 125 is used to discretize the whole domain of flow (saturated and unsaturated), along with an  
 126 implicit finite difference scheme for time. Linear, rectangular and hexahedral elements are  
 127 used in the codes for 1D, 2D and 3D features. Discretization leads to the following system of  
 128 nonlinear equations:

129 
$$\mathbf{G}(\mathbf{h}^{k+1})\mathbf{h}^{k+1} + \mathbf{M}(\mathbf{h}^{k+1}) - \mathbf{q}(t^{k+1}) = 0 \quad (10)$$

130 where  $\mathbf{h}^{k+1}$  is the vector of nodal head values at time  $t^{k+1}$ ,  $k$  is a time step index.  $\mathbf{G}$  is the  
 131 conductance (stiffness) matrix,  $\mathbf{M}$  is a vector containing the moisture content derivative with  
 132 respect to time and  $\mathbf{q}$  is a vector containing the boundary conditions and flow rates pumped  
 133 or injected.

### 134 3.2. Linearization technique

135 Applied to (10), the Picard scheme, where the soil moisture at the current iteration level is  
 136 approximated as a truncated expansion of Taylor series about the pressure head at the last  
 137 iteration level (Celia et al, 1990), gives the following system of linear equations to be solved  
 138 for  $\mathbf{h}^{k+1,m+1}$ , the vector of nodal hydraulic heads at the current iteration level; superscript  $m$  is  
 139 the iteration index:

$$140 \quad \mathbf{G}(\mathbf{h}^{k+1,m})\mathbf{h}^{k+1,m+1} + \mathbf{C}(\mathbf{h}^{k+1,m})\frac{\mathbf{h}^{k+1,m+1} - \mathbf{h}^{k+1,m}}{\Delta t^{k+1}} + \mathbf{M}(\mathbf{h}^{k+1,m}) - \mathbf{q}(t^{k+1}) = 0 \quad (11)$$

141 Stiffness matrix  $\mathbf{G}$ , mass matrix  $\mathbf{C}$  and vector  $\mathbf{M}$  depend upon the hydraulic head.

142 The entries of these matrices and the elements of the vector are defined as follows:

$$143 \quad G_{IJ} = \sum_e \int_{V^e} k_r \nabla b_i \mathbf{K}_s \nabla b_j dx dy dz \quad (12)$$

$$144 \quad C_{IJ} = \sum_e \int_{V^e} S_g(\psi) b_i b_j dx dy dz \quad (13)$$

$$145 \quad C_{II} = \sum_e \int_{V^e} S_g(\psi) b_i dx dy dz \quad (14)$$

146 Where  $S_g(\psi) = \frac{\theta}{\theta_s} S_s + \frac{d\theta}{d\psi}$  indicates the general storage coefficient and  $S_s$  stands for the  
 147 specific storage coefficient.

148 Equation (14) gives the coefficients of the mass matrix  $\mathbf{C}$  if mass lumping technique is used.

149 
$$M_I = \sum_e \int_{V^e} \frac{d\theta}{dt} b_i dx dy dz \quad (15)$$

150 Chord slope is used to perform the moisture content derivative with respect to time as  
 151 follows:

152 
$$\frac{d\theta}{dt} = \frac{\theta^{k+1,m} - \theta^k}{\Delta t^{k+1}} \quad (16)$$

153  $I$  and  $J$  represent the global nodes, while  $b_i$  and  $b_j$  are basis functions related, respectively, to  
 154 local nodes  $i$  and  $j$  belonging to the element  $e$ . Gaussian quadrature rule is applied to perform  
 155 the integrals.

156 3.3. Solution procedure

157 To solve iteratively the equation (11), the matrices involved have to be updated at each  
 158 iteration level, making the solution process very costly on a CPU time basis, particularly for  
 159 large scale problems. To make the procedure fast, approximations are proposed for the matrix  
 160 coefficients (Aharmouch and Amaziane, 2012). The idea is to split the coefficients into to  
 161 quantities, one constant, computed once and stored, and the other varying with iteration,  
 162 needing to be updated. The authors applied the method to solve 3D steady state groundwater  
 163 flow problems only in the saturated zone and neglect the flow in the unsaturated region.  
 164 However, the flow modeling in the vadose zone constitutes an important issue in hydrology  
 165 and plays a key role for sustainable groundwater use, particularly in dry regions, by  
 166 evaluating the water transfer rates to the water table during recharge and also by assessing the  
 167 water losses during dry periods. For these purposes, retention curves equations have to be  
 168 used to characterize the unsaturated medium.

169 In the present work, the stiffness entries are approximated as in the work of Aharmouch and  
 170 Amaziane (2012), but with incorporating the retention curves equations, aforementioned, to  
 171 solve correctly the flow in the vadose zone as well as for the saturated one.

172 The stiffness entries (equation 12) are approximated for 1D, 2D and 3D features as:

$$173 \quad G_{II} \cong k^* \sum_e \int_{-1}^1 {}^t \nabla b_i \mathbf{K}_s b_j d\xi \quad (17)$$

$$174 \quad G_{II} \cong k^* \sum_e \int_{-1}^1 \int_{-1}^1 {}^t \nabla b_i \mathbf{K}_s b_j d\xi d\eta \quad (18)$$

$$175 \quad G_{II} \cong k^* \sum_e \int_{-1}^1 \int_{-1}^1 \int_{-1}^1 {}^t \nabla b_i \mathbf{K}_s \nabla b_j d\xi d\eta d\zeta \quad (19)$$

$$176 \quad k^* = \frac{1}{N_G \cdot n_{eS}} \sum_{e=1}^{n_{eS}} \sum_{n_g=1}^{N_G} k_r(e, n_g) \cdot \det[\mathbf{J}](e, n_g) \quad (20)$$

177 The mass matrix entries for the distributed form (equation 13) can be readily approximated as  
 178 for the stiffness coefficients with making the necessary change. However, the lumped form  
 179 (equation 14) is used only, because of its property to guarantee non oscillatory solution as it  
 180 was demonstrated by Celia et al. (1990).

181 The mass matrix entries using mass lumping technique (equation 14) are approximated for  
 182 1D, 2D and 3D features as:

$$183 \quad C_{II} \cong S_g^* \sum_e \int_{-1}^1 b_i d\xi \quad (21)$$

$$184 \quad C_{II} \cong S_g^* \sum_e \int_{-1}^1 \int_{-1}^1 b_i d\xi d\eta \quad (22)$$

$$185 \quad C_{II} \cong S_g^* \sum_e \int_{-1}^1 \int_{-1}^1 \int_{-1}^1 b_i d\xi d\eta d\zeta \quad (23)$$

$$S_g^* = \frac{1}{N_G \cdot n_{eS}} \sum_{e=1}^{n_{eS}} \sum_{n_g=1}^{N_G} S_g(e, n_g) \cdot \det[\mathbf{J}](e, n_g) \quad (24)$$

187  $\xi$ ,  $\eta$  and  $\zeta$  are local coordinates,  $n_{eS}$  is the number of elements sharing the nodes  $I$  and  $J$ ,  
 188  $n_g$  indicates Gauss integration points,  $N_G (= 2, 4, 8)$  stands for their numbers, depending on  
 189 the dimensionality of the problem and  $\det[\mathbf{J}](e, n_g)$  is the Jacobian matrix determinant related  
 190 to Gauss integration point  $n_g$  and element  $e$ .

191 As it was pointed out in the work of Aharmouch and Amaziane (2012),  $k^*$  expresses the  
 192 arithmetic mean of the term  $k_r \cdot \det[\mathbf{J}]$  over the integration points involved in the elements that  
 193 share the nodes  $I$  and  $J$ . Similarly, it can be seen that  $S_g^*$  is the arithmetic mean of the term  
 194  $S_g \cdot \det[\mathbf{J}]$  over the integration points involved in the elements that share the nodes  $I$  and  $J$ .  
 195 Only the hydraulic properties (relative conductivity and general storage coefficient) have to  
 196 be updated during the iteration process, which guarantees gain in CPU time.

197 Time stepping is performed as in the work of Paniconi and Putti (1994). Time step sizes  
 198 during transient simulations are dynamically recalculated depending on the convergence  
 199 behavior of the nonlinear procedure. The simulations start with a certain time step  $\Delta t_0$  which  
 200 can be augmented, by a magnificence factor  $\Delta_{\text{mag}}$ , to a certain  $\Delta t_{\text{max}}$ , or reduced, using a  
 201 reduction coefficient  $\Delta_{\text{red}}$  to a minimum value,  $\Delta t_{\text{min}}$ , depending on the number of iterations  
 202 allowed in each nonlinear iteration and according to some performance criteria. If the  
 203 convergence is achieved in less than  $\text{maxit}_1$  iterations, the time step is increased and remains  
 204 unchanged if the number of iterations is within  $\text{maxit}_1$  and  $\text{maxit}_2$  iterations and reduced if  
 205 convergence iterations needed are more than  $\text{maxit}_2$ . The solution can also be recomputed at  
 206 the current time, if convergence is not accomplished among the specified criteria, when  $\text{maxit}$   
 207 limit is exceeded, by reducing the time step and going back to the old status (“back  
 208 stepping”).

209 The infinity norm ( $l_\infty$ ) of the convergence error is adopted as stopping criterion of the  
 210 nonlinear iterative process, thus the convergence is achieved when  $\|\mathbf{h}^{k+1,m+1} - \mathbf{h}^{k+1,m}\|_\infty < tol$  is  
 211 satisfied. In the field case example, the convergence is checked using a relative norm based  
 212 stopping criterion. The convergence is, therefore, achieved when  $\frac{\|\mathbf{h}^{k+1,m+1} - \mathbf{h}^{k+1,m}\|_2}{\|\mathbf{h}^{k+1,m}\|_2} < tol$  is  
 213 satisfied, where  $\|\cdot\|_2$  expresses the ( $l_2$ ) norm (the square root of the sum of squares of a vector  
 214 components).

215 Owing to that the systems of linear equations obtained with the Picard finite element  
 216 approximation are sparse and symmetric, conjugate gradient solvers are particularly indicated  
 217 in such situation. In this work preconditioned conjugate gradient method with incomplete  
 218 Cholesky decomposition preconditioner (ICCG) is used to solve the resulting linear systems  
 219 for 2D and 3D problems, whereas tridiagonal direct algorithm is used for solving those  
 220 obtained for 1D configuration.

#### 221 4. Numerical tests and model assessment

222 For validation purposes, numerical examples are treated to verify the proposed model  
 223 described in section 3 either (equations 17—24), designated as "M<sub>1</sub>" or equations (14 and  
 224 17—20), designated as "M<sub>2</sub>". The obtained results are then checked against some available  
 225 solutions measured or analytical to account for the model accuracy. Numerous examples are  
 226 considered including 1D, 2D and 3D flow features and dealing with the most encountered  
 227 problems of groundwater in variably saturated porous media, ranging from infiltration-  
 228 evaporation in a soil column, recharge-drainage of a free surface 2D aquifer and free surface  
 229 3D aquifer response to recharge and pumping. Special attention is paid to flow in unsaturated  
 230 flow in porous media.

231 The efficiency of the proposed numerical model is demonstrated against the standard model,  
232 labeled "Stand", where stiffness and mass matrices entries are expressed normally (equations  
233 12 and 14).

234 Comparisons between the two models were focused on the following criteria:

- 235 — The number of time steps, Nts,
- 236 — The number of back steps, Nbs
- 237 — The total computation time, CPU,
- 238 — The total number of nonlinear iterations, Nnlit,
- 239 — The mass balance error, MBE, computed as in Yeh (1981).

240 All the simulations were performed on a 3.00 GHz Pentium Dual-Core E5700  
241 microcomputer.

#### 242 4.1. Transient flow in a soil column under infiltration

##### 243 4.1.1. Description

244 This example was chosen to verify the presented model when dealing with infiltration. The  
245 experimental results have been reported by Haverkamp et al. (1977). Later, Clement et al.  
246 (1994) presented a 2-dimensional numerical study of the same case and checked the obtained  
247 results to those observed by Haverkamp et al. (1977). In the present study, the flow domain is  
248 a one-dimensional sand column of 0.7 m length, where a constant pressure head of  $\psi = -0.615$   
249 m is specified at the outlet and a constant flux of 3.29 m/day is imposed at the inlet.

250 The soil properties are taken as in Clement et al. (1994). The saturated hydraulic conductivity  
251 is  $K_S = 8.16$  m/day, the porosity (saturated water content) is  $\theta_s = 0.287$  and the residual water  
252 content is  $\theta_r = 0.075$ . The values of the soil properties used to parameterize the retention  
253 curve (equation 8) are  $A = 1.61 \times 10^6$  and  $B = 3.96$  and those for the relative conductivity  
254 expression (equation 9) are  $C = 1.18 \times 10^6$  and  $D = 4.74$ .

#### 255 4.1.2. Results and discussion

256 The domain of study is discretized in 71 nodes with a constant spacing of 0.01 m. Transient  
257 simulations are performed during a period of 0.8 hours using a varying time step technique,  
258  $\Delta t_0 = 0.1 \times 10^{-2}$  hr,  $\Delta t_{\min} = 0.1 \times 10^{-5}$  hr,  $\Delta t_{\max} = 0.1 \times 10^{-1}$  hr,  $\Delta t_{\text{mag}} = 1.2$ ,  $\Delta t_{\text{red}} = 0.5$ , along with  
259  $\text{maxit}_1 = 10$ ,  $\text{maxit}_2 = 20$  and  $\text{maxit} = 30$ . A tolerance of  $10^{-3} m$  is fixed for non linear  
260 iterations. The linear system of equations is solved directly using tridiagonal algorithm.  
261 Transient solutions are then computed at each 0.1 hours during a total time simulation of 0.8  
262 hours, both with the present model and the standard one. Simulation details are summarized in  
263 Table 1.

264 Simulated and measured water content are shown in Fig.1. The numerical water content  
265 profiles are identical for the standard formulation and the new model. Both are in good  
266 agreement with the experimental results. Numerically, the two models perform quite similarly  
267 as it can be seen in Table 1. For every time simulation, the time steps number, the nonlinear  
268 iterations number, the CPU times are almost the same, as well as the mass balance error. The  
269 new model (version  $M_1$ ) performs similarly, but takes 2 or 3 iterations more to converge to  
270 the same solution.

#### 271 4.2. Two-dimensional, transient variably saturated water-table recharge

##### 272 4.2.1. Description

273 This test case is taken from Vauclin et al. (1979) and involves a transient flow through a  
274 homogeneous and isotropic rectangular soil embankment of 6.00 length and 2.00 m height.  
275 The soil surface is recharged with a constant flux of  $q = 3.55$  m/day, applied over a strip of  
276 1.00 m width, located at the center of the domain. The remaining surface is covered to avoid  
277 evaporation. Because of symmetry, only one part of the whole domain is to be modeled (for  
278 instance, the right one). The subsequent domain is of 3.00 m by 2.00 m and the recharge flux

279 is then applied over a 0.5 m wide strip. The remaining soil surface is subject to no-flow  
280 condition as well as the bottom and the left side of the resulting domain. Fixed head boundary  
281 is used at the wetting zone of the right side of the domain by maintaining the water level at  
282 0.65 m, whereas a no-flow condition is set to the remaining zone (Clement et al, 1994).

283 The soil properties are those of Vauclin et al. (1979). The saturated hydraulic conductivity is  
284  $K_s = 8.40$  m/day, the porosity (saturated water content) is  $\theta_s = 0.30$  and the residual water  
285 content is  $\theta_r = 0.30$ . The values of the soil properties used to fit Van Genuchten's (1980)  
286 retention curve model (equations 4 and 5) are  $\alpha = 3.3 \text{ m}^{-1}$  and  $n = 4.1$  (Clement et al, 1994;  
287 Kuznetsov et al, 2012). Specific storage is set to zero (Clement et al, 1994).

#### 288 4.2.2. Results and discussion

289 Two grids are used, one coarse, with nodal distance of  $\Delta x = 0.1$  m along the horizontal axis,  
290 and  $\Delta z = 0.05$  m with respect to the vertical axis. For the fine grid, nodal distances are taken  
291 to be the half of those of the coarse grid. For the initial conditions, the water level is fixed to  
292 0.65 m throughout the whole domain. Transient simulations are performed during a period of  
293 8 hours using a varying time step technique,  $\Delta t_0 = 0.1 \times 10^{-2}$  hr,  $\Delta t_{\min} = 0.1 \times 10^{-6}$  hr,  $\Delta t_{\max} = 0.1$   
294 hr,  $\Delta t_{\text{mag}} = 1.2$ ,  $\Delta t_{\text{red}} = 0.5$ , with  $\text{maxit}_1 = 10$ ,  $\text{maxit}_2 = 10$  and  $\text{maxit} = 30$ . A tolerance of  
295  $10^{-3} \text{ m}$  is fixed for non linear iterations and  $10^{-12}$  for inner ICCG iteration. Transient solutions  
296 are then computed at 2, 3, 4 and 8 hr elapsed time, using the present model and the standard  
297 one. Simulation details, related to the coarse grid, are exhibited in the Table 2.

298 Simulated water-table positions for different periods independently of the model are in good  
299 agreement with the measured data of Vauclin et al. (1979), as it can be seen in Fig.2.

300 However, the solutions obtained with the fine grid are more close to the experimental data.

301 The proposed model ( $M_1$  and  $M_2$ ) and the standard one provide identical solution. The two

302 versions of the present model, in all cases, converge in less CPU time when compared to the

303 standard model. Overall, the standard model takes more CPU time to achieve the convergence  
304 to the fixed level of accuracy. The best performance is recorded by the version M<sub>2</sub> of the  
305 proposed model. As an example, during the 2 hours duration of the first period, the  
306 convergence of the version M<sub>2</sub> is accomplished in 6401 iterations for 436 s whereas the  
307 version M<sub>1</sub> converges in 9552 iterations for 617 s and the standard one converges in 7839  
308 iterations for 993 s. However, on a per-non linear iteration basis, the versions M<sub>1</sub> and M<sub>2</sub> of  
309 the present model and the standard one needed respectively an average CPU time of 0.0645 s,  
310 0.0681 s and 0.1266 to converge. In addition, the version M<sub>1</sub>, the standard model and, in a  
311 lesser extent, the version M<sub>2</sub>, experience difficulties during the iterative process which is  
312 reflected by the number of the needing back steps, 6 for the version M<sub>1</sub>, 5 for the standard  
313 model and only 2 for the version M<sub>2</sub>. The mass balance errors are of  $0.215 \times 10^{-1} \%$  and  
314  $0.208 \times 10^{-1} \%$ , for the standard and the version M<sub>2</sub>, respectively, and of 0.398 % for the  
315 version M<sub>1</sub>. The same performances of the competing models can be observed at the end of  
316 the other periods of simulation. The overall CPU time required for the version M<sub>2</sub> to attain the  
317 solution is about 2.3 times lesser than that needed by the standard model.

318 For the fine grid, the same outcome is observed regarding the rate of convergence and the  
319 efficiency of the 3 models, with, however, the CPU time needed for model M<sub>2</sub> about 2.5 times  
320 lesser than that necessitated by the standard model.

#### 321 4.3.1. Description

322 This test deals with three-dimensional flow in an unsaturated porous media. The flow domain  
323 is taken as a very dry cubic block of soil of length  $a = 15$  m and is discretized with hexahedral  
324 elements of size  $0.25 \times 0.25 \times 0.25$  m<sup>3</sup>. Because of the symmetry of the problem, only the half  
325 of the domain is discretized, resulting in 58621 nodes and 54000 elements. On the top and the  
326 bottom of the cubic domain, the pressure head is given by:

327  $\psi(x, y, z, t) = \frac{1}{\alpha} \ln \left( e^{\alpha\psi_r} + (1 - e^{\alpha\psi_r}) \sin \frac{\pi x}{a} \sin \frac{\pi y}{a} \right)$  and  $\psi = \psi_r$  respectively, where as a non-  
328 flux condition is assigned to the vertical sides. To complete the problem the following initial  
329 conditions are taken,  $h(x, y, z, 0) = \psi_r + z$ , where  $z$  indicates elevation. The relative  
330 conductivity is modeled as  $k_r = e^{\alpha\psi}$  . and he moisture content as  $\theta = \theta_r + (\theta_s - \theta_r) e^{\alpha\psi}$  , where  
331  $\theta_s$  is the saturated moisture content and  $\theta_r$  is the residual content. Parameters of the problem  
332 are :  $\alpha = 0.25$ ,  $\theta_s = 0.45$ ,  $\theta_r = 0.15$ ,  $\psi_r = -15$  m and the saturated hydraulic conductivity is  
333 taken  $K_s = 0.15$  m/day.

#### 334 4.3.2. Results and discussion

335 Transient simulations are conducted during a period of 15 days using a varying time step  
336 technique,  $\Delta t_0 = 0.01$  day,  $\Delta t_{\min} = 0.001$  day,  $\Delta t_{\max} = 0.025$  day, with  $\text{maxit}_1 = 10$ ,  $\text{maxit}_2 = 10$   
337 and  $\text{maxit} = 30$ . Transient solutions are then computed at 2.5, 5, 10, and 15 days elapsed time,  
338 using the present model and the standard one. Simulation details are listed in Table 3.

339 Fig. 3 shows the pressure head contours at different times obtained with the present numerical  
340 model (versions M<sub>1</sub> and M<sub>2</sub>) and the standard one, together with those obtained with the  
341 analytical solution (Tracy, 2006). Very good agreement can be noted between the solutions.

342 As for the precedent cases, the present model performs better than the standard one for all  
343 time simulations. In addition, the version M<sub>1</sub> ensures its superiority when compared to the  
344 version M<sub>2</sub>. On a per-non linear iteration basis, for all the time simulations, the versions M<sub>1</sub>  
345 and M<sub>2</sub> of the present model needed an average of 8.23 s and 8.96 s of CPU time,  
346 respectively, to converge, whereas an average time of 25.83 s is required for the standard  
347 model, which represent more than 3 times the time needed by the present model, in the case  
348 of the version M<sub>1</sub>, and slightly less than 3 for the other version. Overall, with respect to the  
349 total CPU time, the standard model takes about 3.11 times and 2.88 times the CPU time

350 needed for the versions  $M_1$  and  $M_2$ , respectively, to converge. The standard model is very  
351 costly in terms of CPU time. As an example, during the 15 days period of simulation, the  
352 CPU time needed for the standard model to attain the solution is 9 hr 51 min 40 s, whereas 3  
353 hr 10 min and 3 hr 25 min were recorded for the versions  $M_1$  and  $M_2$ , respectively. Again the  
354 version  $M_1$  of the presented model shows its highest efficiency.

355 Regarding the rate of convergence, the three models show practically the same number of  
356 iterations for every time simulation, despite a little advantage of the standard model and the  
357 version  $M_2$  against the version  $M_1$ , which takes 7 more iterations to accomplish the  
358 convergence to the same solution. None of the 3 models had experienced difficulties to  
359 converge during all the periods of simulation, thus any back step was noticed. Finally, the  
360 Present model and the standard one show very satisfactory mass balance. The absolute values  
361 of the mass balance errors for almost all simulations are less than  $10^{-3}$  %.

#### 362 4.4. Three-dimensional transient variably saturated infiltration and pumping

##### 363 4.4.1. Description

364 Two tests are involved and are taken from Kuznetsov et al. (2012), both deals with three-  
365 dimensional flow in a variably saturated porous media. Recharge from the top is considered  
366 first and pumping is studied afterwards, separately. The flow domain is a rectangular  
367 parallelepiped of 1000 m in both lateral directions and of 10 m height. The domain is  
368 discretized with hexahedral elements of size  $10 \times 10 \times 1$  m<sup>3</sup> resulting in 112211 nodes and  
369 100000 elements. For the infiltration case, the boundaries of the domain are subject to no flow  
370 condition except the top, which receives a recharging flux of 0.01 m /day from a square area  
371 of 100 m $\times$ 100 m, located at the centre of the surface domain, whereas the remainder part is  
372 taken to be impervious. For the pumping case, the boundaries of the domain are subject to no  
373 flow condition and a fully penetrating vertical well is situated in the centre of the domain and

374 screened over 2 m from the bottom, with constant pumping rate 50 m<sup>3</sup>/day, during 150 days.  
375 For the both cases, the initial water table height is of 5 m from the bottom of the domain.  
376 Parameters of the soil properties used along with the Van Genuchten's (1980) retention curve  
377 model are  $\alpha = 0.145 \text{ m}^{-1}$  and  $n = 2.68$  (Kuznetsov et al, 2012) and the saturated hydraulic  
378 conductivity is taken  $K_s = 5 \text{ m/day}$ .

#### 379 4.4.2. Results and discussion

380 Transient simulations are conducted during a period of 150 days using a varying time step  
381 technique,  $\Delta t_0 = 0.1 \text{ day}$ ,  $\Delta t_{\min} = 0.001 \text{ day}$ ,  $\Delta t_{\max} = 1 \text{ day}$ , with  $\text{maxit}_1 = 10$ ,  $\text{maxit}_2 = 10$  and  
382  $\text{maxit} = 30$ . A tolerance of  $10^{-3} m$  is fixed for non linear iterations and  $10^{-12}$  for inner PCG  
383 iteration. Transient solutions are then computed at 50, 100, and 150 days elapsed time, using  
384 the present model and the standard one. Tables 4 and 5 summarize simulation results and  
385 simulated water-table positions obtained are shown in Fig.4.

386 As can be expected, the present model performs better than the standard one for all time  
387 simulations. Also, the version M<sub>1</sub> shows again its relative superiority when compared to the  
388 version M<sub>2</sub>. On a per-non linear iteration basis, for all the time simulations, the versions M<sub>1</sub> of  
389 the present model necessitated an average of 24.20 s to converge and the version M<sub>2</sub> needed  
390 an average of 25.44 s of CPU time to achieve the convergence, while the standard model  
391 required an average time of 93.24 s to accomplish the convergence to the same level of  
392 accuracy. For the pumping case the performances are of 24.10 s, 25.39 s and 90.68 s of CPU  
393 time, respectively. Consequently, the versions M<sub>1</sub> and M<sub>2</sub> of the present model are more than  
394 3 times and half faster than the standard model. Globally, with respect to the total CPU time,  
395 the standard model takes about 3.85 times and 3.66 times the CPU time needed, respectively,  
396 for the versions M<sub>1</sub> and M<sub>2</sub> to converge when dealing with infiltration and about 3.95 times  
397 and 3.74 times the CPU time needed in case of pumping. This demonstrates the high

398 computational cost of the standard model and the highest efficiency of the version  $M_1$  of the  
399 present model.

400 Concerning the rate of convergence, the three models show exactly the same number of  
401 iterations for every time simulation. No resize was necessary for the time step already fixed,  
402 depending on the convergence history, during all the time simulations. Finally, the two  
403 versions of the present model show very satisfactory mass balance, contrarily to the standard  
404 model. Indeed, for all the simulations, the mass balance errors are under  $10^{-2}$  % for the present  
405 model and are more than 5% for the standard model, in the infiltration case and are under 0.1  
406 % for the present model and more than 10.0% for the standard model, when dealing with  
407 pumping.

408 As a comparison with an already published work, Kuznetsov et al. (2012) studied the same  
409 test (medium scale) and reported that their Quasi-3D model performs almost as a standard  
410 full-3D model. The CPU time needed for the standard full-3D is almost about 1.16 times  
411 superior to the CPU time needed for the Quasi-3D model.

#### 412 4.5.1. Description

413 This example deals with a hypothetical large scale groundwater flow problem in a semi-arid  
414 context that is described by Prudic et al. (2004). The flow domain is a closed alluvial basin in  
415 which recharge is tributary to interactions between the aquifer and the rivers that cross it,  
416 broadly, from northwest to southeast and from east to west. The aquifer is constituted of  
417 unconsolidated deposits of mostly sand and gravel overlying a substratum that is many times  
418 less permeable than the filling material of the valley, which thickness increase toward the  
419 centre. A three dimensional structured mesh of this hypothetical aquifer is generated and  
420 adjusted to fit aquifer geometry and wells location. Maps of the aquifer top and bottom are  
421 presented in Fig.5 below. The studied domain is discretized into non uniform finite

422 hexahedral elements by a 51×54×11 mesh, respectively in x-, y- and z-direction, resulting in  
423 30294 nodes and 26500 elements.

424 The boundaries of the domain are subject to no flow condition except the top where  
425 evaporation occurs, mostly in the vicinity of the streams network, as described in Prudic et al.  
426 (2004), when the depth of the free surface is less than a certain value (6.5 m for the present  
427 simulations) and with variable rates, to a maximum of 0.0021 m/d. The streambed thickness is  
428 of 0.915 m and the corresponding leakance is globally constant of 0.864 d<sup>-1</sup>, but can reach  
429 locally 1.728 d<sup>-1</sup> in the blue river (Prudic et al, 2004). The elevation of the water in different  
430 streams (sum of the streambed thickness and the stream depth) is taken constant and equal to  
431 1.25 m.

432 For the retention curve model, Brooks and Corey's model (1964) is chosen (equations 6 and  
433 7) with the sets of values of Herrada et al. (2014) and which are used as follows: in the  
434 vicinity of the channels ( $\theta_s = 0.396$ ,  $\theta_r = 0.$ ,  $\psi_s = -0.131$  m and  $\lambda=0.127$ ) and ( $\theta_s = 0.477$ ,  $\theta_r =$   
435  $0.1$ ,  $\psi_s = -0.45$  m and  $\lambda=1.20$ ) for the sediments in the remainder part of the valley. The  
436 hydraulic conductivity is taken as in Prudic et al. (2004): 52.8 m/d in the vicinity of the  
437 streams and 10.7 m/d elsewhere. Ten pumping wells are considered; from each one, an  
438 amount of 40000 m<sup>3</sup>/d is extracted during a period of 50 years. The initial conditions are  
439 provided as a result of a steady-state simulation of the model without pumping.

#### 440 4.8.2. Results and discussion

441 Two simulations were conducted to provide the results presented in the framework of this  
442 study. First, a steady-state simulation without pumping, but taking into account leakage and  
443 evaporation, was conducted to provide initial conditions inputs necessary to the transient  
444 simulation. For this purpose, a constant guess water head of 320.25 m was used for all the  
445 nodes. A tolerance of 10<sup>-4</sup>, using the relative norm, is fixed for non linear iterations together

446 with a tolerance of  $10^{-12}$  for inner PCG iteration. The steady-state simulation, performed with  
447 the present model, required 18 iterations to converge to the specified criteria with an error  
448 mass balance of 0.211%. The CPU time needed for the model to converge in steady-state  
449 regime is 44.3 s. The standard model, however, fails to converge to the same level of solution  
450 mentioned above. The convergence of the standard method is also examined with alleviated  
451 criteria and did not converge even with non linear tolerance reduced to  $10^{-2}$ . Indeed, the inner  
452 iterations (i, e), the PCG iterations, fail to converge when the inner tolerance is still  $10^{-12}$ .  
453 With less drastic conditions (non linear tolerance of  $10^{-2}$  and inner tolerance of  $10^{-5}$ ) the  
454 standard method reaches convergence in 17 iterations within 125 s of CPU time and with a  
455 mass balance error of 34.6%, whereas, the present new model converges in 2 iterations within  
456 only 11.8 s of CPU time and with a mass balance error of 0.866%. Fig.6 (left) shows steady-  
457 state water-table contours.

458 Transient simulations are conducted during a period of 50 years using a varying time step  
459 technique,  $\Delta t_0 = 15$  day,  $\Delta t_{\min} = 5$  day,  $\Delta t_{\max} = 365$  day, with  $\text{maxit}_1 = 10$ ,  $\text{maxit}_2 = 10$  and  
460  $\text{maxit} = 30$ . A tolerance of  $10^{-4}$  is fixed for non linear iterations and  $10^{-12}$  for inner PCG  
461 iteration. Transient solutions are then computed at 50 years elapsed time, using the present  
462 model and the standard one. Table 6 displays obtained simulation results.

463 Fig.6 (right) exhibits water level contours obtained with the version  $M_1$  of the present model  
464 after 50 years of pumping.

465 For this mimicking real world groundwater flow problem, the present model shows its  
466 absolute superiority compared to the standard model. The versions  $M_1$  and  $M_2$  of the present  
467 model achieve the convergence in 167 and 301 iterations with CPU times, respectively, of  
468 584 s and 1040 s, whereas, for the standard model, the convergence is achieved in 450  
469 iterations within 5680 s. On a per-iteration basis, standard model, version  $M_1$  and version  $M_2$

470 of the present model need, respectively, 12.62 s, 3.45 sand 3.5 s CPU time. Thus, the present  
471 model (versions  $M_1$  and  $M_2$ ) is about 3.6 times faster than the standard one. In addition,  
472 regarding the total CPU time, the version  $M_1$  of the present model is almost 10 times faster  
473 than the standard model and almost 2 times faster than the version  $M_2$  of the present model,  
474 which demonstrates the high convergence rate of the version  $M_1$  compared to the standard  
475 model and the version  $M_2$  of the present model. This is confirmed by the iterations numbers  
476 needed for convergence which are of 167, 301 and 450, respectively for the versions  $M_1$  and  
477  $M_2$  of the present model and the standard one. As it can be seen, particularly for this real  
478 world test, the version  $M_1$  of the present model shows the highest numerical efficiency to  
479 solve large and complex groundwater flow problems.

480 Regarding the mass balance analysis, the versions  $M_1$  and  $M_2$  provide satisfactory mass  
481 balance, 0.144% and -0.633%, contrarily to the standard model which shows an excessively  
482 high mass balance error of 131%. Thus, the standard model (equations 12 and 14) may be  
483 inadequate to solve complex groundwater flow problems, in addition to its high numerical  
484 cost. Fig.7 shows the solutions obtained with the version  $M_1$  and  $M_2$  of the present model  
485 together with the solution obtained with the standard one.

## 486 5. Conclusions

487 An efficient transient numerical mass-conservative model is constructed to solve variably  
488 saturated groundwater flow problems. A Galerkin linear finite element mesh is used to  
489 discretize the entire domain, saturated and unsaturated compartments. Picard iteration  
490 technique, together with the fully implicit Euler method, is used to solve the obtained  
491 discretized equations system. The present model is particularly suitable for limited  
492 computational resources when 3D groundwater flow problems are tackled. The stiffness and  
493 mass matrices involved are approximated in a way that only hydraulic properties are updated  
494 during the iterative process to guarantee less computational effort, when solving the PDE. The

495 geometric part of the matrices remains unchanged, so computed once and stored, which  
496 ensures important savings in CPU time. The new model is presented with or without  
497 approximate mass matrix (versions  $M_1$  and  $M_2$ ). Both are tested and compared to a standard  
498 numerical model obtained with non altered matrices.

499 The proposed model capabilities are tested and compared to the standard model across  
500 benchmark tests for which analytical solutions or experimental results are available. A “real  
501 world” groundwater flow problem is also solved to examine the performance of the  
502 competing numerical tools. Different soil water curve models, conferring variable non  
503 linearity degrees to the Richards equation, are also implemented. Emphasis is made when  
504 reproducing these examples on two major aspects, that are accuracy and efficiency assessed,  
505 respectively, by the mass balance error and the CPU time to achieve convergence.

506 Along with the studied examples, the developed new model shows its superiority to solve  
507 variably saturated flow problems in 1D, 2D and 3D configurations. The developed new model  
508 exhibits high computational performance regarding time cost and solution accuracy. These  
509 outcomes are clearly revealed with high dimensionality problems. In effect, the present model  
510 and the standard one perform almost similarly when dealing with 1D flow problems, may be,  
511 because of the relatively small number of nodes and elements. The numerical water content  
512 curves are identical and the CPU times are very close as well as the mass balance errors.

513 Since the dimensionality increases, the present model ( $M_1$  and  $M_2$ ) performs increasingly  
514 better than the standard model. The latter is computationally intensive due to the fact that the  
515 involved matrices should be, totally rebuilt, at every nonlinear iteration, contrarily to the  
516 proposed new model, where only the hydraulic parts are to be updated; the geometric parts are  
517 computed once and stored. As a consequence, the CPU time needed to attain the convergence  
518 becomes dramatically highest for the standard model. It is clear that the required CPU time  
519 increases with high dimensionality and the total number of elements and nodes.

520 For the 2D recharge test, the CPU time needed by the standard model is about 2.3–2.5 times  
521 higher than the CPU time needed for the present model, whereas the mass balance errors are  
522 satisfactory for the competing models. When dealing with the 3D flow examples the CPU  
523 time needed by the standard model to achieve convergence is about 3.66–3.95 times greater  
524 than that needed by the present model to converge to the same level of accuracy. On the other  
525 hand, the mass balance error is very satisfactory for the present model, less than 0.01% for the  
526 recharge test and less than 0.1% for test of pumping, whereas for the standard model, these  
527 mass balance errors are more than 5% and more than 10% for the two tests mentioned,  
528 respectively. It is to notice that the mass balance error provided by the two competing model  
529 are very satisfactory (less than 0.001%), when dealing with the totally unsaturated flow  
530 example. Indeed, the numerical solutions obtained with the two models (present and standard)  
531 match very well. However, the CPU time needed by the standard model to converge under the  
532 same constraints is globally about 3 times greater than that needed for the present model.

533 For the hypothetical real word test, the present model shows its absolute superiority when  
534 compared to the standard model. Also, the version  $M_1$  confirms its superiority when  
535 compared to the version  $M_2$ . Globally, with respect to CPU time, the standard model takes  
536 almost 10 times and more than 5 times the CPU time needed respectively by the versions  $M_1$   
537 and  $M_2$  of the present model to converge. This, clearly, shows the highest efficiency of the  
538 version  $M_1$  of the present model. The version  $M_2$  take about 2 times the CPU time needed to  
539 the version  $M_1$  to converge, indeed. Regarding the mass balance analysis, the versions  $M_1$  and  
540  $M_2$  provide satisfactory mass balance, 0.144% and -0.633%, contrarily to the standard model  
541 which shows an excessively high mass balance error of 131%.

542 As it can be seen, particularly for this real world test, the version  $M_1$  of the present model  
543 shows the highest numerical efficiency to solve large and complex groundwater flow  
544 problems. Consequently, the use of the standard model to solve groundwater flow problems

545 may be difficult and almost prohibitive to perform more complicated and repetitive operations  
546 as the calibration, for instance, or to solve coupled groundwater flow and solute transport  
547 problems, particularly with poor or insufficient computational resources. The present model,  
548 however, particularly the version  $M_1$ , is shown to be suitable for solving large and complex  
549 groundwater flow problems and, probably, to be used usefully for the anticipated related  
550 issues.

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657 Table 1. Simulation results for the transient flow in a soil column under infiltration

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| Model | $\Delta z$ | Time | Nts | Nbs | CPU | Nnlit | MBE (%) |
|-------|------------|------|-----|-----|-----|-------|---------|
|-------|------------|------|-----|-----|-----|-------|---------|

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|                     | (m)  | (hr) |    |   | (s)  |     |           |  |
|---------------------|------|------|----|---|------|-----|-----------|--|
| New, M <sub>2</sub> | 0.01 | 0.1  | 19 | 0 | 2.31 | 82  | -0.261E-3 |  |
| Stand               | 0.01 | 0.1  | 19 | 0 | 2.36 | 82  | -0.165E-3 |  |
| New, M <sub>2</sub> | 0.01 | 0.2  | 29 | 0 | 3.52 | 126 | 0.583E-3  |  |
| Stand               | 0.01 | 0.2  | 29 | 0 | 3.51 | 126 | 0.927E-3  |  |
| New, M <sub>2</sub> | 0.01 | 0.3  | 39 | 0 | 4.56 | 166 | 0.103E-2  |  |
| Stand               | 0.01 | 0.3  | 39 | 0 | 4.62 | 166 | 0.162E-2  |  |
| New, M <sub>2</sub> | 0.01 | 0.4  | 49 | 0 | 5.66 | 206 | 0.940E-3  |  |
| Stand               | 0.01 | 0.4  | 49 | 0 | 5.72 | 206 | 0.192E-2  |  |
| New, M <sub>2</sub> | 0.01 | 0.5  | 59 | 0 | 6.70 | 246 | 0.912E-3  |  |
| Stand               | 0.01 | 0.5  | 59 | 0 | 6.76 | 246 | 0.212E-2  |  |
| New, M <sub>2</sub> | 0.01 | 0.6  | 69 | 0 | 7.80 | 286 | 0.924E-3  |  |
| Stand               | 0.01 | 0.6  | 69 | 0 | 7.85 | 286 | 0.224E-2  |  |
| New, M <sub>2</sub> | 0.01 | 0.7  | 79 | 0 | 8.84 | 326 | 0.894E-3  |  |
| Stand               | 0.01 | 0.7  | 79 | 0 | 8.96 | 326 | 0.228E-2  |  |
| New, M <sub>2</sub> | 0.01 | 0.8  | 89 | 0 | 9.94 | 366 | 0.525E-3  |  |
| Stand               | 0.01 | 0.8  | 89 | 0 | 10   | 366 | 0.204E-2  |  |

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664 Table 2. Simulation results for the transient two-dimensional water-table recharge

| Model | $\Delta x$ | $\Delta z$ | Time | Nts | Nbs | CPU | Nnlit | MBE (%) |
|-------|------------|------------|------|-----|-----|-----|-------|---------|
|-------|------------|------------|------|-----|-----|-----|-------|---------|

|                     | (m) | (m)  | (hr) |     |   | (s)  |       |          |
|---------------------|-----|------|------|-----|---|------|-------|----------|
| New, M <sub>1</sub> | 0.1 | 0.05 | 2    | 779 | 6 | 617  | 9552  | 0.398    |
| New, M <sub>2</sub> | 0.1 | 0.05 | 2    | 541 | 2 | 436  | 6401  | 0.208E-1 |
| Stand               | 0.1 | 0.05 | 2    | 685 | 5 | 993  | 7839  | 0.215E-1 |
| New, M <sub>1</sub> | 0.1 | 0.05 | 3    | 810 | 6 | 636  | 9873  | 0.287    |
| New, M <sub>2</sub> | 0.1 | 0.05 | 3    | 555 | 2 | 445  | 6540  | 0.142E-1 |
| Stand               | 0.1 | 0.05 | 3    | 707 | 5 | 1020 | 8061  | 0.201E-1 |
| New, M <sub>1</sub> | 0.1 | 0.05 | 4    | 834 | 6 | 651  | 10106 | 0.240    |
| New, M <sub>2</sub> | 0.1 | 0.05 | 4    | 565 | 2 | 453  | 6636  | 0.111E-1 |
| Stand               | 0.1 | 0.05 | 4    | 718 | 5 | 1030 | 8170  | 0.201E-1 |
| New, M <sub>1</sub> | 0.1 | 0.05 | 8    | 875 | 6 | 676  | 10478 | 0.186    |
| New, M <sub>2</sub> | 0.1 | 0.05 | 8    | 605 | 2 | 473  | 6937  | 0.622E-2 |
| Stand               | 0.1 | 0.05 | 8    | 758 | 5 | 1080 | 8517  | 0.350E-1 |

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674 Table 3. Simulation results for the transient, three-dimensional unsaturated flow

| Model               | $\Delta x$ | $\Delta y$ | $\Delta z$ | Time   | Nts | Nbs | CPU   | Nnlit | MBE (%)   |
|---------------------|------------|------------|------------|--------|-----|-----|-------|-------|-----------|
|                     | (m)        | (m)        | (m)        | (days) |     |     | (s)   |       |           |
| New, M <sub>1</sub> | 0.25       | 0.25       | 0.25       | 2.5    | 103 | 0   | 2660  | 352   | -0.232E-3 |
| New, M <sub>2</sub> | 0.25       | 0.25       | 0.25       | 2.5    | 103 | 0   | 2850  | 345   | -0.210E-3 |
| Stand               | 0.25       | 0.25       | 0.25       | 2.5    | 103 | 0   | 8150  | 345   | -0.449E-3 |
| New, M <sub>1</sub> | 0.25       | 0.25       | 0.25       | 5      | 203 | 0   | 4420  | 552   | -0.867E-3 |
| New, M <sub>2</sub> | 0.25       | 0.25       | 0.25       | 5      | 203 | 0   | 4790  | 545   | -0.106E-2 |
| Stand               | 0.25       | 0.25       | 0.25       | 5      | 203 | 0   | 13600 | 545   | -0.159E-2 |
| New, M <sub>1</sub> | 0.25       | 0.25       | 0.25       | 10     | 403 | 0   | 7930  | 952   | -0.444E-3 |
| New, M <sub>2</sub> | 0.25       | 0.25       | 0.25       | 10     | 403 | 0   | 8570  | 945   | -0.660E-3 |
| Stand               | 0.25       | 0.25       | 0.25       | 10     | 403 | 0   | 24600 | 945   | -0.174E-2 |
| New, M <sub>1</sub> | 0.25       | 0.25       | 0.25       | 15     | 603 | 0   | 11400 | 1352  | -0.231E-3 |
| New, M <sub>2</sub> | 0.25       | 0.25       | 0.25       | 15     | 603 | 0   | 12300 | 1345  | -0.401E-3 |
| Stand               | 0.25       | 0.25       | 0.25       | 15     | 603 | 0   | 35800 | 1345  | -0.200E-2 |

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686 Table 4. Simulation results for the transient, three-dimensional water-table recharge.

| Model               | $\Delta x$ | $\Delta y$ | $\Delta z$ | Time   | Nts | Nbs | CPU   | Nnlit | MBE (%)  |
|---------------------|------------|------------|------------|--------|-----|-----|-------|-------|----------|
|                     | (m)        | (m)        | (m)        | (days) |     |     | (s)   |       |          |
| New, M <sub>1</sub> | 10.0       | 10.0       | 1.0        | 50     | 59  | 0   | 2860  | 117   | 0.880E-2 |
| New, M <sub>2</sub> | 100        | 10.0       | 1.0        | 50     | 59  | 0   | 3010  | 117   | 0.470E-2 |
| Stand               | 10.0       | 10.0       | 1.0        | 50     | 59  | 0   | 10600 | 117   | 5.40     |
| New, M <sub>1</sub> | 10.0       | 10.0       | 1.0        | 100    | 109 | 0   | 5310  | 217   | 0.508E-2 |
| New, M <sub>2</sub> | 10.0       | 10.0       | 1.0        | 100    | 109 | 0   | 5530  | 217   | 0.403E-2 |
| Stand               | 10.0       | 10.0       | 1.0        | 100    | 109 | 0   | 19500 | 217   | 5.46     |
| New, M <sub>1</sub> | 10.0       | 10.0       | 1.0        | 150    | 159 | 0   | 7580  | 317   | 0.385E-2 |
| New, M <sub>2</sub> | 10.0       | 10.0       | 1.0        | 150    | 159 | 0   | 8020  | 317   | 0.374E-2 |
| Stand               | 10.0       | 10.0       | 1.0        | 150    | 159 | 0   | 30600 | 317   | 5.53     |

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700 Table 5. Simulation results for the transient, three-dimensional water-table with pumping.

| Model               | $\Delta x$ | $\Delta y$ | $\Delta z$ | Time   | Nts | Nbs | CPU   | Nnlit | MBE (%)   |
|---------------------|------------|------------|------------|--------|-----|-----|-------|-------|-----------|
|                     | (m)        | (m)        | (m)        | (days) |     |     | (s)   |       |           |
| New, M <sub>1</sub> | 10.0       | 10.0       | 1.0        | 50     | 59  | 0   | 3060  | 130   | -0.255E-1 |
| New, M <sub>2</sub> | 10.0       | 10.0       | 1.0        | 50     | 59  | 0   | 3230  | 131   | -0.237E-1 |
| Stand               | 10.0       | 10.0       | 1.0        | 50     | 59  | 0   | 12500 | 132   | -12.8     |
| New, M <sub>1</sub> | 10.0       | 10.0       | 1.0        | 100    | 109 | 0   | 5440  | 230   | -0.291E-1 |
| New, M <sub>2</sub> | 10.0       | 10.0       | 1.0        | 100    | 109 | 0   | 5750  | 231   | -0.323E-1 |
| Stand               | 10.0       | 10.0       | 1.0        | 100    | 109 | 0   | 20700 | 232   | -12.8     |
| New, M <sub>1</sub> | 10.0       | 10.0       | 1.0        | 150    | 159 | 0   | 7360  | 298   | -0.265E-1 |
| New, M <sub>2</sub> | 10.0       | 10.0       | 1.0        | 150    | 159 | 0   | 7780  | 298   | -0.343E-1 |
| Stand               | 10.0       | 10.0       | 1.0        | 150    | 159 | 0   | 29100 | 323   | -12.7     |

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715 Table 6. Simulation results for the transient, hypothetical river-connected aquifer.

| Model               | $\Delta x$ | $\Delta y$ | $\Delta z$ | Time    | Nts | Nbs | CPU  | Nnlit | MBE (%) |
|---------------------|------------|------------|------------|---------|-----|-----|------|-------|---------|
|                     | (m)        | (m)        | (m)        | (years) |     |     | (s)  |       |         |
| New, M <sub>1</sub> | -          | -          | -          | 50      | 64  | 0   | 584  | 167   | 0.144   |
| New, M <sub>2</sub> | -          | -          | -          | 50      | 70  | 0   | 1040 | 301   | -0.633  |
| Stand               | -          | -          | -          | 50      | 84  | 7   | 5680 | 450   | 131     |

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