Application of The Mixed Hybrid Finite Element Approximation to Water Transfers in Variably Saturated Porous Media with Time-Varying Infiltration

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Abstract:
In this study, a two-dimensional model for simulating water in homogeneous-heterogeneous, saturated-unsaturated porous media is presented. The model is based on the mixed-hybrid finite element method and the h-based form of the Richards equation is solved [16]. The time-varying infiltration is approximated by a number of piecewise linear elements of different lengths and slopes depending on the nature of the variation in infiltration rate. The unsaturated flow model (MHNS_2D) is applied to a variety of rigorous problem including transient flow in dry conditions and time-varying boundary conditions. It produces accurate predicted suction distribution in dry conditions compare to the analytical solution of J.R. Philip. It is also shown to provide good global water mass balance accuracy in simulations of vertical infiltration in spite of solving the h-based form of the Richards equation. MHNS_2D is used also to predict the water table fluctuation of an unconfined aquifer in response to time varying infiltration.

Keywords: unsaturated porous media; numerical model; mixed-hybrid finite element; time-varying infiltration.

1. INTRODUCTION
Transfer of water solutes under transient unsaturated conditions plays an important role in many branches of agriculture and environmental engineering. The unsaturated zone is prone to contamination from agriculture where many chemicals such as fertilizers, pesticides, as well as those naturally present in irrigation waters, are frequently applied to the field. When water is applied to the soil surface, either by rain or irrigation, it may transport chemical contaminants through the unsaturated zone to the underlying groundwater aquifer. Also the recharge of ground water by the natural precipitation, irrigation or artificial recharge may result into the rise of the water table closer to the ground surface. This causes many environmental disturbances as water logging, pollution of groundwater, increase in soil salinity. The latter is generally observed in irrigated land in arid and semi-arid zones. Sometimes, deep percolation of water induces an inescapable rise of the water table. Therefore, because of vulnerability of the unsaturated zone to contamination and its direct link to aquifers, a clear understanding of water transfers processes, vector of chemical transport, important for both agricultural and environmental engineers. An effective way to develop such an understanding is by means of computer simulation using numerical models. They play a significant role in the analysis of the movement of water and contaminants in porous media. That’s why they are also often employed in studies addressing the water and solute transfer in porous media. Numerical models of water flow in variably saturated porous media are commonly based upon the solution of the well-known Richards equation. Alternative forms of the Richards equation are derived by selection of the primary unknown are either pressure or suction head (h) or water or moisture content (θ). Nevertheless, serious mass balance and convergence problem can appear due to its non-linear nature.

Numerical models solving the h-based form have been reported to produce significant global mass balance
The objective of this paper is to develop an alternative numerical model that is able to produce accurate simulations of transient flow in 2-D unsaturated-saturated porous media. This model is based on h-based of Richard’s equation, and solved by mixed-hybrid finite element method. It has been quite successful for solving the flow equation in saturated porous media [10]. It provides separate approximation of the pressure head and the Darcy’s velocity. This property allows for a precise determination of flow lines and propagation of contaminants. We have also introduced in the model, a scheme of time-varying infiltration. The time-varying infiltration is approximated by a number of piecewise linear elements of different lengths and slopes depending on the nature of the variation in infiltration rate.

The accuracy of the proposed model is evaluated by comparing its results with analytical solution for unsaturated flow. We will also present the results of water table fluctuation characteristics due to change in the rate of infiltration.

2. FLOW EQUATION

The mathematical model used to describe fluid flow in partially saturated rigid porous media is obtained by combining the mass conservation equation with the generalized Darcy equation in the following form:

\[
\rho S_w (\alpha + \phi \beta + \phi(p - \rho g z)) \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_i} (\rho q) = 0
\]

Where \(\rho\) is the mass density (M L\(^{-3}\)); \(S_w(h)\) degree of water saturation (0 < \(S_w \leq 1\), \(S_w = 1\) if the medium is saturated) (L\(^3\) L\(^{-3}\)); \(x_i\) (i = 1, 2) the spatial coordinates (L); \(\alpha\) is the coefficient of skeleton compressibility (M\(^{-1}\)L\(^2\)); \(\beta\) is the fluid compressibility (M\(^{-1}\)L\(^2\)); \(\phi\) is the porosity (L\(^3\) L\(^{-3}\)); \(p = \rho g h\) is the pressure (ML\(^{-1}\)T\(^{-2}\)); \(q\) Darcy’s velocity (LT\(^{-1}\)) and \(h\) pressure head (L) linked to \(H\) (L) piezometric head by the classical relation \(H = h + z\) where \(z\) is the vertical coordinate positive upward (h ≥ 0 in saturated medium and h < 0 in unsaturated medium). If \(\alpha = 0\) then the porosity is not a function of the pressure, if \(\beta = 0\), then the mass density is not a function of the pressure. If the mass density is constant then the equation (1) leads to:

\[
\left( \phi \frac{\partial S_w}{\partial \rho} \right) \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (q) = 0
\]

(2)

By the use of the volumetric water define as \(\theta = \phi S_w\) (L\(^3\) L\(^{-3}\)), equation (2) becomes:

\[
\frac{\partial \theta}{\partial t} + \frac{\partial}{\partial x_i} (q) = 0
\]

(3)

The water flow in saturated porous media can be represented by the generalized Darcy’s law given by:

\[
\vec{q} = -K(h)\vec{\nabla}H
\]

(4)

in which \(K(h)\) is hydraulic conductivity in unsaturated domain (LT\(^{-1}\)) with \(K(h, x, z) = K_s = (x, z) K_r(h, x, z), K_s\) (x, z) is the hydraulic conductivity at saturation and \(K_r(h, x, z)\) the relative hydraulic conductivity of the soil.

The mass conservation law can be written as it follows:

\[
C(h) \frac{\partial H}{\partial t} + \nabla \cdot \vec{q} = f
\]

(5)

\(C(h)=d\theta / dh\) is the capillary capacity (L\(^{-1}\)), \(h\) is the pressure (L), \(f\) represents the volumetric flow rate via sources or sinks per unit volume of the medium (T\(^{-1}\)). Combining equations (4) and (5) leads to the h-based form of the Richards’ equation given as:

\[
C(h) \frac{\partial h}{\partial t} - \frac{\partial}{\partial x_i} \left[ K(h) \left( \frac{\partial h}{\partial x_i} + u_i \right) \right] = f
\]

(6)

Where \(u_i\) is the unit vector in the direction of the \(x_i\) coordinate.
Richards’s equation can be written in different form by using either the pressure head (h) as a principal variable (h-based form) or the water content (θ) as a principal variable (θ-based form).

If equation (6) is applied to a planar flow in a vertical cross section then \( x_1 = x \) represents the horizontal coordinate and \( x_2 = z \) the vertical coordinate, the latter taken to be positive upward. Any initial condition in terms of pressure head or water content can be invoked. Dirichlet (pressure head) or Neumann (flux) boundary conditions at the top or bottom of the profile must be associated to the partial differential equations.

3. MIXED HYBRID APPROXIMATION

We would like to approximate the piezometric head \( H(L) \) in the domain \( \Omega \). This domain will be discretize by triangular elements \( E \). We are looking for a way which permits an approximation of the piezometric head \( H(L) \) and its associated velocity field \( q(L/T) \).

3.1 The mixed formulation

The mixed formulation gives a separate approximation of the piezometric head \( H[L] \) and the Darcy’s velocity \( q[L/T] \) [15].

Let us consider a triangular element \( E \) with edges \( F_i, i = 1,2,3 \). In the mixed-hybrid formulation of the mixed approximation, \( H \) and \( q \) are approximated over each element \( E \) by:

- The mean value of \( H \) over the element \( E \): denoted by \( H_E \)
- The mean value of \( H \) over edge \( F_i, i = 1,2,3 \): denoted by \( TH_{E,i} \)
- Approximation of \( \nabla \cdot q = -K(h) \nabla H \) over element \( E \) denoted by \( q_E \) having the following properties over \( E \) [3]:
  - The scalar product \( q_E \cdot n_{Ei} \) is constant over edge \( F_i \) of \( E \) where \( n_{Ei} \) is the outer vector normal to \( F_i \).
  - \( q_E \) is determined by the knowledge of its flux \( Q_{Ei} \) through the edge \( F_i, i = 1,2,3 \).

It is defined over the whole domain by:

\[
\vec{q} = \sum_{i=1}^{3} Q_{E,j} \vec{w}_i
\]

Where \( \vec{w}_i \) (1, 2, 3) being the basis vectorial functions defined by:

\[
\int_{F_j} W_i \cdot n_{Ej} = \delta_{ij}, \quad i,j = 1,2,3
\]

\( \delta_{ij} \) is the Kronecker delta.

The basic vectorial function \( \vec{w}_i \) corresponds to a vector having its flux equal to 1 through the edge \( F_i \) and zero through the others satisfying the following condition:

\[
\sum_{j=1}^{3} \int_{E} W_i \cdot n_{Ej} = 1
\]

This condition imply an exact local mass balance and the continuity of the normal component of the velocity vector between two adjacent elements. The mixed formulation consists on writing a numerical development of the Darcy’s law and the flow equation.

3.2 Numerical development of the Darcy’s law

We rewrite the Darcy’s law (eq. 2) in the following form:

\[
K^{-1}(h) q = -\nabla H
\]

Multiplying scalarly each member of the equation with a test function \( s \), integrating over \( E \) element and using the Green formula, we obtain the following relation:
\[
\begin{align*}
\int_E \left( K^{-1}(h_E) \hat{q} \right) \cdot s_E &= -\int_E \nabla H \cdot s_E = \int_E H \nabla s_E \\
\forall s_E \in H(\text{div}, E)
\end{align*}
\] (11)

Substituting H and \( \hat{q} \) by their approximations over E element in equation (11), we obtain the following elemental equation linking \( \text{H}_E, \text{TH}_{E,i} (i = 1, 2, 3) \) and \( \hat{q}_E \):

\[
\begin{align*}
\int_E \left( K^{-1}(h_E) \hat{q}_E \right) \cdot \hat{w}_i &= \text{H}_E \int_E \nabla \cdot \hat{w}_i \\
- \sum_{j=1}^{3} \int_{F_j} \text{TH}_{E,j} \hat{w}_i \cdot n_{Ej} &\quad \forall i = 1, \ldots, 3
\end{align*}
\] (12)

Considering the three-basic function \( \hat{w}_i \) of the Raviart-Thomas space, \( \text{H}_E \) remaining constant over E and \( \text{TH}_{E,i} \) also constant over \( F_j \), we obtain from equation (12):

\[
\begin{align*}
\int_E \left( K^{-1}(h_E) \hat{q}_E \right) \cdot \hat{w}_i &= \text{H}_E \int_E \nabla \cdot \hat{w}_i \\
- \sum_{j=1}^{3} \text{TH}_{E,j} \int_{F_j} \hat{w}_i \cdot n_{Ej} &\quad \forall i = 1, \ldots, 3
\end{align*}
\] (13)

Using conditions (7) and (9) into equation (13) gives:

\[
\begin{align*}
\sum_{j=1}^{3} Q_{E,j} \left( \left( K^{-1}(h_E) \hat{q}_E \right) \cdot \hat{w}_j \right) \cdot \hat{w}_i = \text{H}_E \int_E \nabla \cdot \hat{w}_i \\
- \sum_{j=1}^{3} \text{TH}_{E,j} \int_{F_j} \hat{w}_i \cdot n_{Ej} &\quad \forall i = 1, \ldots, 3
\end{align*}
\] (14)

Now we define the \( 3 \times 3 \) symmetric matrix \( B_E \) associate to E element:

\[
B_E = [B_{i,j}]
\] (15)

in which

\[
B_{ij} = \int_E \left( \left( K^{-1}(h_E) \hat{q}_E \right) \cdot \hat{w}_j \right) \cdot \hat{w}_i
\]

\( K_E \) remains constant over E element.

By using this notation \( B_j \) into equation (14), the numerical development of Darcy’s law can be written as:

\[
\sum_{j=1}^{3} Q_{E,j} B_{ij} = \text{H}_E - \text{TH}_{E,i} \quad \forall i = 1, \ldots, 3
\] (16)

Using a matrix notation we have the following form:

\[
B_E Q_E = \text{H}_E \text{DIV}^T_E - \text{TH}_E
\] (17a)

Where,

\[
\text{DIV}_E^T = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, \quad Q_E = \begin{bmatrix} Q_{E,1} \\ Q_{E,2} \\ Q_{E,3} \end{bmatrix}
\]

\( \text{DIV}_E^T \) is the transposed elemental divergence matrix.

\( B_E \) is an invertible matrix. We can write equation (17a) in the following form:

\[
Q_E = B_E^{-1} \left( \text{H}_E \text{DIV}_E^T - \text{TH}_E \right)
\] (17b)

Or in another form,

\[
Q_{E,F} = \text{H}_E a_{EF} - \sum_{F \subset \partial E} B^{-1}_{EF,F} \text{TH}_{EF}
\]

where \( a_{EF} = \sum_{F \subset \partial E} B^{-1}_{EF,F} \) (18)

\( \partial E \) represent the boundaries of E element (the three E edges).
Equation (18) represents a relation among the flux on the edges \( (Q_{E,F}) \), the mean value of the piezometric head over \( E \) element \( (H_E) \) and the mean value of the piezometric head over each edge of \( E \) element \( (TH_{EF}) \). Knowing the mean value of the piezometric head over the element and its edges, the flux are then perfectly determinate.

### 3.3 Numerical development of the flow equation

We start discretization of time in intervals. Each interval has a duration \( \Delta t \). The flow equation (5) can be written in the following form:

\[
C(h) \frac{\partial H}{\partial t} + \nabla \cdot q = f
\]  

(19)

This equation must be integrated over each element \( E \) of the domain. This is achieved by multiplying each member of equation (19) with a test function \( s \in L^2(E) \) and integrating over \( E \) in order to obtain a formulation like finite volume type of the equation over \( E \).

\[
\int_E C_E \left( \frac{\partial H}{\partial t} \right) s + \int_E s \nabla \cdot \tilde{q} = \int_E fs \quad \forall \ s \in L^2(E)
\]  

(20)

Substituting approximation of \( H \) and \( \tilde{q} \) over \( E \) element in (20), and taking into account that the approximations \( H_E \) and \( \tilde{q}_E \) satisfy the following conditions:

- \( H_E \) is constant over \( E \) and
- \( \nabla \cdot \tilde{q}_E = \frac{1}{|E|} \sum_{i=1}^{3} Q_{E,i} \) is constant over \( E \), where \( |E| \) represent the area of \( E \) element. We obtain from (20):

\[
\int_E C_E \frac{H_E^n - H_E^{n-1}}{\Delta t} s_E + \int_E s_E \nabla \cdot \tilde{q}_E^n = 0
\]

\[\int_E f^n s_E \quad \forall s_E \in \text{Raviart–Thomas space} \]

in which \( s_E \) is constant over \( E \) and \( C_E \) is the capillary capacity over \( E \) and is considered to be constant over \( E \). After dividing each member of equation (21) by \( s_E \), we obtain a new equation in the following form:

\[|E| C_E \frac{H_E^n - H_E^{n-1}}{\Delta t} + \sum_{i=1}^{3} Q_{E,i}^n = F_E^n\]

(22)

Where \( F_E^n \) is the approximation of \( \int_E f^n \), constant over \( E \).

Using a matrix notation, the flow equation (22) can be written as:

\[|E| C_E \frac{H_E^n - H_E^{n-1}}{\Delta t} + \text{DIV}_E Q_E^n = F_E^n \quad \forall \ E \in \Omega\]

(23)

### 3.4. The mixed hybrid formulation

The mixed-hybrid approach consists of using the piezometric head on the edges \( TH_{E_i} \) as principal unknowns. The other unknowns \( (Q_{E,F} \) and \( H_E \)) are eliminated \cite{Mosé et al., 1994}. The numerical development of the Darcy’s law, of the flow equation and the continuity of the fluxes between two adjacent elements

\( \text{i.e. } Q_{E,F} + Q_{E,F} = 0 \) for every edge \( F \), \( E \) and \( E' \) being adjacent,

are the three equations used to reduce the number of unknowns to the mean value of the piezometric head of the edges.

Dirichlet conditions are achieved by an equality of the head over edges and Neumann conditions by a flux equality. The mixed approximation takes
account of Neumann conditions in a very specific way by prescribed fluxes on element edges whereas the sink/source terms are averaged over the element. Initial conditions are given with the knowledge of $TH_{i0}$.

After solving the system of equations on trace of $H$, we use local equations over each element $E$ in order to compute the flux through the edges and the mean value of the piezometric head over the element.

4. INTRODUCING TIME-VARYING INFLTRATION

We have considered that the rate of infiltration depends on time and this is more close to the reality particularly in case of natural infiltration. The infiltration can have any flux (rate of infiltration) entering the soil through its surface.

The sum of the infiltration during time $iT(\bar{x},t)$ from all sources of infiltration, can be represented by the relation given below [9]-[13]:

$$I(\bar{x},t) = \begin{cases} \sum_{i=1}^{N} q_i(t) & \text{for } x_{i1} \leq x \leq x_{i2} \\ 0 & \text{elswhere} \end{cases}$$

(24)

$x_{i1}$ and $x_{i2}$ being the boundaries of the “$i$” infiltration site.

$N$ represent the total number of infiltration zone, $q_i(t)$ is the rate of infiltration and is approximated by using a series of linear elements in the following form:

$$q_i(t) = \begin{cases} m_{ij} t + c_{ij} & t_j \leq t \leq t_{j+1} \\ c_{ik} & t > t_k \end{cases}$$

(25)

Where $m_{ij}$ and $c_{ij}$ are the slope and intercept of the $j$th linear element of the $i$th infiltration zone. Advantage of this type of approximation is that any complex nature of variation of infiltration rate for any number of infiltration cycle can be approximated with more accuracy.

5. EXAMPLES

To demonstrate the performance of our model, a variety of example are considered. The hydrodynamics properties are represented by Mualem (1976) and Van Genuchten’s equation [21]:

$$S = \frac{\theta - \theta_s}{\theta_s - \theta_r} = \frac{1}{1 + (\alpha |h|)^{1-n}}$$

with $h < 0$

(26)

$$S = 1$$

with $h \geq 0$

And

$$K = K_s \sqrt{S} \left[1 - \left(1 - S^{\left(\frac{n-1}{n}\right)}\right)^{(1-(1/n))}\right]^2$$

with $n > 1$

(27)

Where $\theta_s$ (L$^3$) and $\theta_r$ (L$^3$) are the saturated and residual water content, respectively, $S$ is relative saturation, $K_s$ (L T$^{-1}$) is the saturated hydraulic conductivity, and $\alpha$ (L$^{-1}$) and $n$ (-) are empirical constants determining the shape of the functions.

The hydraulics properties of the soil we have used are:

$\theta_s = 0.102$, $\theta_r = 0.368$, $K_s = 796.61$ cm/d (and we have used 8m/d in the simulations), $\alpha = 0.335$ cm$^{-1}$ and $n = 2$.

5.1 Example 1
In this case, we compare the results of the model with those obtained by using the J.R Philip’s analytical solution [12]. We simulate water infiltration in 30-cm column of homogenenous soil under constant surface pounding [14]. Specifically, the pressure head at the boundaries is such that:

\[ h = -75 \text{ cm} \]
\[ \text{at } z = 30 \text{ cm (top)} \]

\[ h = -1000 \text{ cm} \]
\[ \text{at } z = 0 \text{ (bottom)} \]

Initially, the pressure is uniform throughout the column, that is,

\[ h = -1000 \text{ cm at } t = 0, \quad 0 \leq z \leq 30 \text{ cm} \]

This problem considers infiltration into a soil with initial water content close to residual. Results for 0.25 cm grid size and 0.1 cm grid size are compared in Figure 1 and Figure 2, respectively with the results obtained from semi analytical solution of J.R. Philip.

Figure 1 shows some discrepancy between the results of numerical solution and the analytical solution, but the trends are the same. Looking at these results, we refine the grid in order to have a good agreement between numerical and analytical solutions. Results of this operation are presented in Figure 2 for grid size equal to 0.1 cm.

5.2. Example 2

In this case we have considered a vertical cross section of the soil in rectangular form with 1000 m dimension in \( x \)-direction and 10 m deep in \( z \)-direction. It receives infiltration from a canal of 4 m width and an unconfined aquifer below. The canal is located in the center. Two cycles of infiltration are considered. In this case we want to compare the aquifer response owing a constant infiltration rate and a time-varying infiltration rate. The pattern of constant infiltration rate and the time-varying infiltration are shown in Figure 3 (a) and Figure 3 (b). The infiltration operation consists of two wet periods separated by a dry one, each of 5 days duration.
Initial conditions are given firstly by considering the water table at 3 m height from the base of the aquifer and the zone above is considered as an unsaturated zone with a uniform pressure distribution of -2 m. We have done simulation without infiltration in order to obtain a steady state pressure distribution in the whole domain before the onset of the infiltration. After first simulation the water level is found at 2.6 m height from the base of the aquifer. Because of the symmetry, we have considered only one half of the domain. The domain is discretized into 6160 triangular elements with 3255 nodes and 9414 edges. Five different size of grid are used for discretization of the domain, fine grid of 0.5 m x 0.5 m size around the infiltration zone, a second large size of grid with 1 m x 0.5 m dimension size, a third large size grid of 2 m x 0.5 m dimension, a fourth large size grid of 3 m x 0.5 m dimension and the mast fifth rank, until the limit of the domain 5 m x 0.5 grid size. Numbering of nodes and elements start at the lowest left corner to the top, vertical axis is positive upward. Results of these simulations are shown below through Figure 4.

Figure 4 shows the differences in the fluctuation of zero pressure head in response to periodically applied constant infiltration rate and time varying infiltration. The difference is due to variation in the nature of infiltration rate. The magnitude of variation is maximum below the center of canal and decrease with distance away from the canal.

5.3 Example 3

In this example two cycles infiltration each 20 days duration separated by a dry period of 20 days as
shown in Figure 5. The purpose is to compare the
nature of distribution of zero pressure head due to
both cycle of infiltration. This pattern of infiltration
is taken from Manglik and Rai (2000) and Rai and
Manglik (2000)[9]-[13].

Figure 5: Time varying infiltration rate applied at
the canal

Figure 6 shows some discrepancies between the
distribution of zero pressure head in response to the
first and the second cycle of infiltration at different
times. This is principally due to the fact than the
water table after 20 days of dry period has not
reach its initial position as shown in Figure 7.

Figure 6: Comparison of profiles of zero pressure
head distribution in response to time varying
infiltration at: (a) 4days, (b) 10 days and (c) 20
days after the onset of both cycles of infiltration.

Figure 7: Distribution of zero pressure head, (d) 10
days and (e) 20 days after the onset of dry period.

The maximum growth of the water table after 10
days is 3.40 m below the infiltration site during the
first cycle of infiltration and 4.2 m during the
second cycle. But we note that, contrary to the case
of second example, the influence of the infiltration
on the water table movement is negligible after
only 250 m as against 100 m for the case of the
second example. This is because of the long
duration of the infiltration period. These results
indicate that the model is able to predict pressure
head distribution in unsaturated porous media in
the presence of constant or time varying
infiltration. The knowledge of zero pressure head
distribution in response to natural or artificial
infiltration is very important to maintain the
regional water balance in order to prevent
environmental problems like water logging, soil
salinity, etc.

CONCLUSION

In this work, we present a 2-dimensional model for
the simulation of water flow in unsaturated porous
media based on the mixed hybrid finite element
theory. This model solves the h-based Richards
equation and provides good results compared to the
analytic solution of J.R. Philip [12]. It provides also
a good water mass balance (less than 1%), which
represents a good improvement compare to those
obtained by Rathfelder and Abriola (1994) using
traditional finite element method (9.5%) with the
same temporal and spatial discretization of the flow
domain. This improvement is due to the continuity
of flux imposed at the interface of two adjacent
elements as well as the local mass balance which is
one of the properties of the mixed hybrid method.
We have also introduced a scheme of
approximation of time-varying infiltration
(Manglik and Rai, 2000; Rai and Manglik, 2000).
Results show the difference between zero pressure
head distribution due to periodically applied
constant and time varying infiltration. This sheme
of approximation of time varying infiltration is
more close to the reality particularly for natural
infiltration.
Nevertheless, the weakness of the mixed hybrid approximation lies in the computational cost involved. This, because the number of unknowns is more in mixed hybrid approximation than in standard finite element or finite difference schemes. On the other hand the separate approximation of the pressure head and the Darcy’s velocity in mixed hybrid approach allows for a precise determination of flow lines and propagation of contaminants. Therefore, if a good precision of pressure distribution and the velocity field is needed in any simulation case, the use of the mixed-hybrid finite element approach becomes a necessity.

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