SIMULATION OF FRESHWATER-SEAWATER INTERFACE BY EMPLOYING CARTESIAN MESH ON THE FEM MODEL

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ABSTRACT: The increasing concentration of human settlements, agricultural development, and economics activities in coastal zone will impose the shortage of fresh groundwater. This may trigger a number of environmental problems, such as: groundwater decline, seawater intrusion, and land subsidence. In order to solve the negative impacts, the understanding of freshwater-seawater interface dynamics due to the human intervention become importance. Analysis by using numerical model needs a good representation of geological system leading to huge number of elements requirement, particularly for three-dimensional model. Now days, computer hardware allows to support this requirement. However, mesh generation for data input of the Finite Element Method (FEM) model is a time consuming task, and the implementation of the Mesh Free Method (MFM) requires special technique for imposing the essential boundary conditions. Therefore, this paper is addressed to develop a simple modeling technique by employing Cartesian mesh system on the FEM model. Verification of the model showed a good agreement with some other results for benchmark problem that is mainly used in seawater intrusion simulation. In addition, the model has been implemented to simulate the interface behavior at Semarang coastal aquifer. Simulation was performed by using the 2D and the 3D model with multi-layer aquifer approach. Comparing with field observation data, the simulation showed accurate and reasonable results.

Keywords: interface, coastal aquifer, multi layer, Cartesian mesh.

INTRODUCTION

Numerical modeling of Finite Element Method (FEM) is realized as the best method to analyze seawater intrusion phenomena. However, mesh generation for input data is well known as a formidable and time consuming task, therefore most of researchers simplify the complex of hydrogeological condition into a single layer of aquifer. This kind of simplification may give lack of accuracy such as shown by work of Frind (1980) and Rastogi et al (2002). Frind described the important influence of aquitard within a continuous system of aquifer-aquitard in controlling dynamics of the entire system, and Rastogi et al found that except dispersivity all other hydrogeological parameters produce significant effect to the seawater intrusion on multilayered-aquifers system.

Semarang aquifer is an extensive groundwater abstraction area in Indonesia, and it has been identified suffer from seawater intrusion. In order to understand the interface phenomena in this area, a new FEM model employing Cartesian Mesh is developed to overcome mesh generation problem. The code is used to simulate the impact of groundwater extraction from multilayered aquifers.

GOVERNING EQUATION

The interface of freshwater-seawater is analyzed by using variable density approach. The variable density problem requires solution of two partial differential equations representing fluid and solute mass balances. The fluid mass balance describes the groundwater flow at saturated-unsaturated medium, and the solute mass balance represents a mixing process on the freshwater-seawater interface.

Fluid Mass Balance

By assuming the contribution of solute dispersion to the mass average flux is negligible, the mass balance of fluid per unit aquifer volume at a point in the aquifer may be written as (Bear in Voss, 2002)

$$\left( \rho S_{op} \right) \frac{\partial \rho}{\partial t} + \rho \frac{\partial C}{\partial t} + \nabla \cdot \left( \rho \mathbf{v} \right) = Q_p$$

where \( \rho \) is fluid density (ML\(^{-3}\)), \( S_{op} \) is specific pressure storativity (ML\(^{-1}\)T\(^{-2}\)), \( \rho \) is the pressure(ML\(^{-1}\)T\(^{-2}\)), \( C \) the solute concentration of fluid as a mass fraction (M,M\(^{-1}\)), \( \varepsilon \) aquifer volumetric porosity (-), \( v \) fluid velocity (LT\(^{-1}\)), and \( Q_p \) a fluid mass source (ML\(^{-3}\)T\(^{-1}\)). In addition, the fluid velocity at any point in aquifer may be calculated through the application of Darcy’s law;

$$v = \left( \frac{k}{\varepsilon \mu} \right) (\nabla p - \rho \mathbf{g})$$

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k_0\) the permeability tensor \((L^2)\), \(\mu\) the fluid viscosity\((ML^{-1}T^{-1})\), \(\varepsilon\) the porosity\((-\)), and \(g\) the gravitational acceleration\((LT^{-2})\).

**Solute Mass Balance**

The solute mass balance equation including advective and dispersive spreading mechanisms is described mathematically by Bear (Voss, 2002) as:

\[
\rho_0 \frac{\partial C}{\partial t} + \rho_0 \nabla \cdot (D \nabla C) = \frac{\partial}{\partial x_j} \left[ \left( \frac{\partial D}{\partial x_j} \right) \nabla C \right] - \nabla \cdot (\rho_0 v C) + \nabla \cdot (g C) + \nabla \cdot (Q C) + \Phi \nabla \cdot D C
\]

where \(C\) is solute concentration as a mass fraction \((M/M^1)\), \(D\) is apparent molecular diffusivity of solute in solution in a porous medium including tortuosity effects \((L^2T^{-1})\), \(I\) is identity tensor (ones on diagonal, zero elsewhere), \(D\) is dispersion tensor \((L^2T^{-1})\), and \(C^*\) is solute concentration of fluid sources \((M/M^1)\).

Relation between density and concentration is given as a linear function:

\[
\rho = \rho_0 + \frac{\partial \rho}{\partial c}(c - c_0)
\]

Where \(\rho_0\) is fluid density at base solute concentration \((ML^3)\), and \(\partial \rho/\partial c\) is constant of proportionality for each solute.

**NUMERICAL MODEL**

**Mesh Generation**

Mesh generation code for 2D and 3D numerical model by employing the Cartesian grid system developed in this paper are integrated with numerical model by a loose coupling system. As a loose coupling technique, the codes organize output files according to structure of data required by the numerical code. The 2D and 3D mesh are visualized with GL-View software, and structural contour maps of geological material layers in 3D-model with Model Viewer software.

By using the Cartesian system, the grid can be generated in a very short time and has simple arithmetic operation. Yet, its disadvantage is incorrect treatment of the geometry shape in a computational domain (Ono K et al, 1999). The Cartesian grid locates node points on a uniform grid, and the grid elements are rectangles in two dimensions and blocks in three dimensions. The Cartesian mesh is not body fitted. There is no embedding meshes and it is frequently used a “stair-cased” description of any geometry.

This mesh generation codes were designed under some considerations such easy and simple in implementation, building and representing volumes from surfaces, distributing nodes within a volume, defining a connectivity of nodes that is compatible with the computational tools being utilized for modeling. It is also provided additional information of initial condition and nodes for assigning boundary conditions. There are some steps include in the mesh generation code:

a. **Defining of background mesh** to cover all modeling area and to define size of mesh, element connectivity, satellite nodes for each node, and node within an element.

b. **Surface map generation** through interpolating borehole data by using surface fitting employing the Moving Least Square Method.

c. **Assignment of hydrogeological parameters** as data input into space discretization with three different approaches; node-wise, cell-wise, and element-wise.

d. **Eliminating of in-active elements** (mesh) to reduce memory demand in simulation.

e. **Fixing of satellite nodes, element connectivity, and nodes information** by re-numbering nodes and elements, element connectivity, and satellite nodes of elements after elimination in-active mesh.

f. **Preparing of information of boundary nodes** to avoid difficulties in identifying boundary nodes to impose the essential boundary condition.

**Numerical Code**

Numerical code used SUTRA2D3D software as a basis code development. The code employed finite element and finite difference method to approximate the governing equations. The hybridization of both methods gain advantages in which it is naturally mass lumping, in contrast to common formulation of the finite element method, which requires mass lumping to avoid oscillatory solutions. In addition, the hybrid finite element and finite difference methods has all the ability of finite element method to handle irregular geometries and complex boundary conditions (Voss, 2003).

In this paper, the original code of SUTRA2D3D has been modified with four considerations:

1. Problem to be solved has been simplified for groundwater flow and solute transport only.
2. Ability to perform simulation with the Cartesian grid system or the FEM mesh.
3. Efficiency of memory demand by recognizing parameter values for elements based on material type identity;
4. Numerical solver for approximation of governing equation uses Pre-Conditioned Bi-Conjugate gradient method.

**Model Verifications**

**The 2D-Model Verification**

The Henry problem is the one of the analytical solution for density dependent groundwater flow in combination with hydrodynamic dispersion for 2D-
model. This analytical solution is rather controversial because so far no numerical model has been able to produce closely his result, but is always used as benchmark of variable density models (Simpson, et al, 2003). Therefore, verification is mainly done to against other numerical results

The Henry’s problem is used to study seawater intrusion in a cross section under steady state. Geometry of the problem was formulated for seawater intrusion in a homogeneous, isotropic, confined, and rectangular aquifer with dimensions of height (d) = 100 cm by length (l) = 200 cm. The top and bottom boundaries are impermeable, with a constant freshwater flux (Q) = 6.6.10^{-2} kg/sec entering the aquifer along the vertical at x = 0, and the seaside boundary at x = 200 cm is a constant saltwater head. Hydrogeological parameters of the aquifer are that hydraulic conductivity (K) is 1 cm/sec, effective porosity is 0.35, coefficient of molecular diffusion (D_m) is 6.6.10^{-6} m^{2}s^{-1}, and specific storage (S_s) is set to zero. Reference density (\rho_0) is 1,000 kg.m^{-3}, and brine density (\rho_b) is 1,025 kg.m^{-3}.

Simulation was performed in a regularly aquifer discretization with 231 nodes with time step increased 60 seconds. The problem, initially, was composed of freshwater, and then saltwater begins to intrude the freshwater by moving under the freshwater from the sea boundary. The steady state was obtained by applying the maximum change in pressure head was less than 1.0 kg.m^{-1}.s^{-2} and concentration was less than 1.0.10^{-4} kg. Comparison of the numerical result with some other published results is shown at figure (1) at iso-chlor 25%, 50%, and 75 % of seawater salinity.

Furthermore, in order to investigate the effect of jagged form of mesh to the numerical results the vertical sea side of original geometry of Henry’s problem is modified. A coastal slope is created by prolong the bottom of layer until 1 meter at seaside boundary. A simulation was run by discretizing the problem domain with the FEM mesh and the Cartesian mesh of 300 elements. Numerical results in figure (2) show a good agreement for both types of mesh.

Fig. 1 Comparison of the simulated result with other solution for modified boundary conditions

The 3D-Model Verification

Verification of the 3D-Model used the circular island problem that concerns to post-drought recharge and restoration of groundwater lens on coastal unconfined aquifer. The problem poses flow in the sea undergoes a prolonged drought, and all ground water beneath the island becomes saline. Then, fresh rainwater recharge to the island begins and continues at a constant rate, raising the water table on the island, flushing out seawater, and eventually establishing a stable freshwater lens and a diffuse saltwater-freshwater interface.

Voss (2003) simulated the problem by representing only one fourth of the entire island to reduce size of simulation. The 3D FEM mesh consist of 40 by 40 elements horizontally and 25 elements vertically, giving 43,706 nodes and 40,000 elements. The horizontal direction is discretized with 20 m spaces, vertically 5 m except 5 meter from top surface with 1 m. By using the Cartesian mesh, it was created 33,218 nodes and 29,800 elements. Boundary condition of the hydrogeological system is set to be no flow crosses the inner (the axis of radial symmetry) and the bottom boundary. The vertical outer boundary is specified as hydrostatic seawater pressure. Along the top boundary, nodes above sea level receive freshwater recharge totaling 18.6658 kg/s (equivalent to 75.0 cm/yr) of recharge for the entire circular island. The amount of recharge at each node was determined by the surface area of its cell on the top surface. At nodes below sea level, the pressure is specified to be hydrostatic seawater pressure and concentration of seawater. Values of hydro-geological parameter of model are shown on table (1).

Initial condition of salt concentration is set as seawater, and initial pressures are obtained through an extra simulation. The extra simulation was carried out by setting boundary condition that no recharge at the surface and specified pressure head along the sea bottom and the outer boundary. The model was run under transient condition to approximate both pressure and concentration using the time step of 0.2 year. The modeling achieves a new steady state after 100 time steps (20 years). The numerical results of both mesh systems are compared in figure (3) with small bias.
around the top of surface boundary. However, the simulations provide consistent variable-density fluid flow and solute transport results by exhibiting a good agreement to produce concentration distribution.

Table 1. Hydrogeological parameter of model of circular island problem

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressibility of matrix</td>
<td>(\alpha)</td>
<td>ms(^2)/kg</td>
<td>1.00 x 10(^{-8})</td>
</tr>
<tr>
<td>Compressibility of fluid</td>
<td>(\beta)</td>
<td>ms(^2)/kg</td>
<td>4.47 x 10(^{-10})</td>
</tr>
<tr>
<td>Porosity</td>
<td>(\varepsilon)</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>Fluid viscosity</td>
<td>(\mu)</td>
<td>kg/ms</td>
<td>1.00 x 10(^{-3})</td>
</tr>
<tr>
<td>Freshwater density</td>
<td>(\rho_0)</td>
<td>kg/m(^3)</td>
<td>1000.00</td>
</tr>
<tr>
<td>Seawater density</td>
<td>(\rho_{sea})</td>
<td>kg/m(^3)</td>
<td>1024.99</td>
</tr>
<tr>
<td>Horizontal intrinsic permeability</td>
<td>(k_h)</td>
<td>m(^2)</td>
<td>5.00 x 10(^{-12})</td>
</tr>
<tr>
<td>Lateral intrinsic permeability</td>
<td>(k_v)</td>
<td>m(^2)</td>
<td>5.00 x 10(^{-13})</td>
</tr>
<tr>
<td>Molecular diffusivity</td>
<td>(D_m)</td>
<td>m(^2)/s</td>
<td>1.00 x 10(^{-9})</td>
</tr>
<tr>
<td>Longitudinal dispersivity</td>
<td>(\alpha_L)</td>
<td>m</td>
<td>10.0 and 2.5</td>
</tr>
<tr>
<td>Transversal dispersivity</td>
<td>(\alpha_T)</td>
<td>m</td>
<td>0.10</td>
</tr>
<tr>
<td>Rainfall recharge</td>
<td>(Q_{IN})</td>
<td>kg/m(^2)</td>
<td>2.3776 x 10(^{-4})</td>
</tr>
<tr>
<td>Seawater salinity concentration</td>
<td>(C_{sea})</td>
<td>-</td>
<td>0.0357</td>
</tr>
<tr>
<td>Residual fluid saturation</td>
<td>(S_{res})</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Van Genuchten soil parameters</td>
<td>(\alpha)</td>
<td>ms(^2)/kg</td>
<td>5.0 x 10(^{-5})</td>
</tr>
<tr>
<td></td>
<td>(n)</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of salinity concentration at \(t = 20\) years resulted by simulation with FEM-mesh and Cartesian mesh (dash line).

**HYDRODYNAMICS OF THE INTERFACE OF SEMARANG AQUIFER**

**Hydrogeological System of Semarang Aquifers**

The Semarang area is a flat terrain with average surface elevation of about 5.0 m above mean sea level (MSL) and becoming gently undulating in the southern part. There are two seasons for a year cycling a wet and a dry season. The mean annual precipitation is about 2,644 mm.

Geological condition of the area consists of two types of geological formation (fig. 4); Alluvium (Qa), and Damar Formation (Qtd). The Alluvium is composed coastal plain, river, and lake deposits. The materials arrange alternating layers of medium grained sand with clayey materials, with thickness of 50 m or more. Sand deposit commonly forms a river-mouth deposit as reservoir with thickness of about 10 m in depth about of 60 m. The Damar formation is composed tuffaceous sandstone, conglomerate, and volcanic breccia.

The groundwater system in the aquifer is characterized with interaction between coastal area and hilly area. Rainwater infiltrates mountains area and flows to Jawa Sea. Observation of piezometric head on the confined aquifer in 1980, before intensive groundwater exploitation commenced, recorded that the piezometric head up to 5 m above MSL on the well located close to hill area. Since 1990, the intensive groundwater exploitation reveals a decline of the piezometric heads. The groundwater supplies most of water demand with trend of abstraction of confined aquifer exhibits a parabolic curve (fig. 5). The groundwater extraction from unconfined aquifer was recorded about 6.20 x 10\(^4\) m\(^3\)/year in 1990. To support modeling effort, trend of the exploitation by dug wells was be interpolated with a linear increment of 1.17 % based on population growth.

Fig. 4. Geological map of Semarang – Indonesia (GRDC in Arifin, et al. 2000)

Fig. 5. Estimation and actual discharge of groundwater pumping of confined aquifer.
Two-Dimensional Profile Modeling

A two-dimensional profile model was aimed to achieve two objectives; to help facilitate development of 3D model, and to simulate the groundwater flow and solute transport patterns in detail with a fine level of spatial resolution. Despite of the profile model simulates only two dimensions problem, the model is better suited for calibrating certain aquifer parameters. This simulation was designed to obtain average piezometer heads and salinity concentrations from 1984 to 1998 in which was selected according to data availability.

Model Conceptual and Design

A two-dimensional profile model was constructed along groundwater flow lines toward central of the Semarang city (fig. 4) at line A-A’. The cross section extends from inland boundary at 7,000 meter of coastline to sea boundary at 500 m of coastline. The profile covers from topographical surface to depth 85 m below MSL. This physical domain was discretized vertically 5 meter for area below MSL, and 1 m above the MSL. Laterally, the domain was discretized 20 m from seaside to 3,800 m inland, and 25 m from 3,800 m to inland boundary. The discretization produces 9,410 nodes, and 9,024 elements. By using longitudinal dispersion of 50 m and tranversal dispersion of 10 m, mesh Peclet number is 2 – 2.5 for lateral grid and 0.1 – 0.5 for vertical grid.

Fig. 6. The 2D-Cartesian mesh of Semarang Aquifer

The geological materials composed the area are classified into three types; tuffaceous sand, sandy clay, and silt & sand. These materials can be categorized into three aquifers; an unconfined aquifer and two confined aquifers. The unconfined aquifer is composed silt and sand material. The confined aquifers are composed silt and sand material, and tuffaceous sand. A sandy clay aquitard exist between the unconfined aquifer and Delta Garang aquifer conceptualized such as figure 6.

Model Boundaries and Initial Condition

The boundary conditions applied in this modeling is exhibited on figure (7) consisting of: Neumann type of no-flux boundary condition was assigned to the bottom of the aquifer, and above groundwater table; Neumann influx boundary condition was assigned at the land surface with net recharge of 3.5 x 10^-4 m/day and salt concentration is 9 mg/liter; and Dirichlet type to the below MSL at seaward boundary, and below 5 m at inland boundary. The constant pressure head was prescribed at the seaward with the salt concentration of seawater is 35.7 kg/m^3. The pressure head is set equal to pressure head 5 m above MSL, with salt concentration is 9 mg/liter at the inland.

To simulate the effect of pumping stress on the aquifer, several internal sinks were assigned (fig. 7). Each internal sink does not act for actual position of production well in the field, but to represent a group of wells with relative pumping to distance from coastline (fig. 8).

Fig. 7. Boundary conditions are applied in the modeling

Fig. 8. Relative pumping discharge to distance from coastline

Initial condition was obtained after long time simulation under transient condition to achieve steady state by using two extra simulations. First, the model was run by setting boundaries in which no pumping was assigned and rainfall intensity is set to be zero. The initial condition for this run is arbitrary freshwater pressure head and 0.9 kg/m^3 of groundwater salinity. Simulation was run for time step of one month, and numerical convergence of freshwater pressure head is 1.0 x 10^-2 kg/m^2, and solute transport is 1.0 x 10^-4 kg/m^3. The second, the running was continued with the pressure head and the salinity distribute obtained on the first run, and setting the sinks with approximated pumping discharge on 1982. The simulation was carried out to achieve steady state.

Model Calibration and Simulation Results

This profile model was calibrated by adjusting the boundary stress and aquifer parameters, within a range of reasonable values, until simulated conditions generally matched with the conditions observed in the field. Aquifer parameters for each layer of material are generally matched with the conditions observed in the field. Each internal sink does not act for actual position of production well in the field, but to represent a group of wells with relative pumping to distance from coastline (fig. 8).
The model was calibrated to data which is collected from monitoring wells located on or near the model transect. For monitoring wells that are not located directly on a model transect, the horizontal distance was specified as the approximate distance of the monitoring well from the coastline. This projecting assumes that contours of head and salinity are parallel to the coastline and perpendicular to the model cross section. The final calibrated parameters are presented in Table 2.

### Table 2. Calibrated parameter for Semarang aquifer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic permeability (silty sand)</td>
<td>$1.02 \times 10^{-11}$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Intrinsic permeability (sandy clay)</td>
<td>$1.02 \times 10^{-17}$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Intrinsic permeability (silty sand)</td>
<td>$3.57 \times 10^{-11}$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Intrinsic perm. (tuffaceous sand)</td>
<td>$4.08 \times 10^{-12}$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Porosity of aquifer</td>
<td>0.30</td>
<td>-</td>
</tr>
<tr>
<td>Porosity of aquitard</td>
<td>0.40</td>
<td>-</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.001</td>
<td>m s$^{-2}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>9.81</td>
<td>kg m$^{-2}$</td>
</tr>
<tr>
<td>Longitudinal dispersivity</td>
<td>50</td>
<td>m</td>
</tr>
<tr>
<td>Transversal dispersivity</td>
<td>10</td>
<td>m</td>
</tr>
<tr>
<td>Molecular diffusion</td>
<td>$3.656 \times 10^{-3}$</td>
<td>m$^2$s$^{-1}$</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Density of freshwater</td>
<td>1000</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>Density of seawater</td>
<td>1025</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>Compressibility of water</td>
<td>$4.47 \times 10^{-10}$</td>
<td>m$^2$kg$^{-1}$</td>
</tr>
<tr>
<td>Compressibility of soil matrix</td>
<td>$1.00 \times 10^{-8}$</td>
<td>m$^2$kg$^{-1}$</td>
</tr>
</tbody>
</table>

Three-Dimensional Modeling

Although the two-dimensional model can be applied in various situations of seawater intrusion problem, practical application is rather limited in which requires a proper cross section to represent a hydrogeological system. Under some circumstances, 3D models should be applied even more effort require than the 2D model. Main problem often arise are; the data availability, the computer memory, and the numerical dispersion problem (Oude-Essink, 2001).

Spatial and Temporal Discretization

To simulate groundwater flow of Semarang area, a regularly spaced, Cartesian model grid was constructed. The x-axis would roughly parallel the coast. Each cell is 500 m by 100 m in the horizontal plane. The grid consists of 31 columns and 51 rows. In the vertical direction (z-axis) is discretized 2 m from land surface to MSL, and 5 m from the MSL to bottom boundary of the modeling area. As result, after eliminating non-active background mesh, the computational domain consists of 61,421 nodes and 55,358 elements. Input data into the 3D-model used calibrated parameter of the 2D-model. Time discretization of this simulation is one month (2.6298 x $10^8$ seconds).

The modeling area consists of three types of material, silt & sand, sandy clay, and tuffaceous sand. These materials builds four different layers of hydrogeological unit; silt & sand of unconfined aquifer, sandy clay of aquitard, silt & sand of confined aquifer, and tuffaceous sand of confined aquifer. These material layers incline to north-west, so that the unconfined aquifer becomes thicker on that direction.

Simulation was run with time periods of 1982 – 2010. These simulation periods are aimed to calibrate model parameters and to predict the groundwater and solute transport behavior resulted by groundwater development policy on the model area.

**Boundaries and Initial Condition**

For most simulations of groundwater flow, boundaries of the model are extended to locations in the aquifer where hydrogeologic boundaries reside. Ideally, these hydrogeological boundaries are persistent flow linier, impermeable barriers, or areas that can be represented do not exist for the inland portion of the model domain. The boundaries conditions of modeling area can be described as;

a. **Seaward boundary.** Contact between modeling area with Jawa Sea is specified with a constant pressure head and concentration boundary. The pressure head is obtained 0.0 kg.m$^{-2}$.s$^{-1}$, and the salinity seawater concentration is 0.0357 kg.m$^{-3}$

b. **Inland boundary.** To represent lateral inflow of groundwater, specified pressure head and concentration boundary was assigned to each node in the southern boundary. The hydraulic head on is assumed not to be affected by withdrawal due to exploitation, and the salt concentrations were assumed constant throughout the simulation periods by setting this value to 0.9 kg/m$^3$.

c. **Lower model boundary.** The lower model boundary represents the base of the Semarang aquifer. This boundary is assigned as an impermeable barrier.

d. **Upper model boundary.** The upper model boundary represents water recharge due to rainfall evidence according to calibrated recharge in the 2D-model.

Initial condition of the model was determined through a number of time steps of extra simulation with two running systems. The first running began to reach steady state condition through long-term transient simulation from arbitrary initial condition. The run was
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Simulation performed by applying above-mentioned boundary conditions except upper boundary in which was set to be zero recharge value, and also there was no pumping discharge assigned. The second running was done with initial condition based on the obtained result from the first running. This simulation set pumping discharge equal to observation data at 1982 for 5 years of time periods. The final results of the second running system were assigned to be initial condition for simulation of the hydrodynamics at Semarang aquifer.

Simulation Results

Since the input parameter of this 3D-model used the calibrated parameter of 2D-model, no calibration effort had been performed in this 3D simulation. A different approach has been done in assignment pumping discharge to the model, in which in 2D-model converted the well discharge to a line by dividing with wide of aquifer interest, yet such kind assignment is not required in this 3D-model. To ensure that the variable density component of the model was working properly, special attention was focused on the salinity distribution that has simulated within the observation time. Within the observation periods, simulation was able to produce measured data to ensure the accuracy in representing the physical process within the hydrogeological system.

![Fig. 10. The simulated interface form in 1985, 1995, and 2010 at depth of 35 m below MSL.](image)

Numerical simulation results are visualized with maps (fig. 10) to represent iso-chlor 50% of seawater salinity at depth of 35 below MSL. Obviously, the map shows that there is no seawater intrusion problem appears in 1985. In 1995 reflects a movement of seawater intrusion inland. The figure shows invasion of the seawater into aquifer at east side deeper than west side. Prediction of condition at 2010 by using assumption that the groundwater discharge increase according to trend 1982-1999, shows that the interface move far enough inland. The predicted interface has similar pattern that happened in 1995. These simulation results can be understood that a severe of the seawater intrusion problem will occur if the groundwater is continuously developed without mitigation efforts.

Model Limitations

The 3D numerical models of the groundwater flow and the solute transport are limited in their representation of the physical system because they contain simplifications and assumptions that may or may not valid. The groundwater flow simulation result has a degree of uncertainty primarily because detailed three-dimensional distribution of aquifer parameters that are rarely available. Result from the solute transport model has more uncertainty because it depends on groundwater velocities calculated from flow models and other uncertain parameters specific to solute transport. Modeling of freshwater-seawater interface at Semarang aquifer is also suffered from these uncertainties. The uncertainties correspond to lack of data and grid size. Unavailability the aquifer parameters and detail data of pumping wells are main difficulty in this 3D modeling. The aquifer parameters value was adopted from 2D-model in which is also approximated by literature approach. While, the incomplete information of groundwater production wells was represented by distributing a number of nodes with uniform space and define same discharge for those nodes. Combination these two approaches may produce bias to real field condition.

Employing the Cartesian mesh system has also contribution to discrepancy between the simulated with the observed hydraulic head and groundwater salinity. This discrepancy is closely related to size of mesh, because an observation point will be defined into the nearest node. Therefore, picked simulated the hydraulic head and the salinity does not represented real position of the field observation point.

CONCLUSIONS

A new numerical code of groundwater flow and solute transport employing the Finite Element Method with the Cartesian mesh has been developed. Even though the code emphasizes for the implementation of the Cartesian mesh, this code is also applicable to the computational domain discretized by using the FEM mesh. Verification by using benchmark problems of variable saturated-density flow of the original and modified Henry’s seawater intrusion problem, and the
circular island problem shows a good agreement with some others published numerical result.

Application of the code to simulate the seawater intrusion phenomena at Semarang aquifer could produce a reasonable interface form. The final calibration of the 2D-model shown an accurate the hydraulic head and the groundwater salinity compared with the observed data of 1982-1998. Sensitivity analysis was also done in this 2D-model in which the interface position is highly controlled by hydraulic conductivity, and is small effect by underflow recharge. The other parameters seem to have almost no influence to the interface form. By using the calibrated parameter of the 2D-model, the 3D simulation produced reasonable form of the interface comparing with the observed data in 1982-1998. Extension the simulation periods to 2010 estimated that the interface invades too far inland. The thickness of aquifer has significant influence to seawater intrusion into the aquifer.

REFERENCES
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