Saltwater Intrusion Modeling: Verification and Application to an Agriculturally Used Coastal Arid Region in Oman

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Abstract

This paper deals with numerical modeling of groundwater systems. Ensuring the sustainability of an aquifer’s yield is one of the fundamental tasks for nowadays groundwater management, especially within agriculturally used regions. Within the context of the research project ”International Water Research Alliance Saxony” (Kalbus et al., 2011, submitted), the groundwater quality of near-coastal, agriculturally used areas under the influence of marine salt water intrusion is investigated. In the bounds of the study region’s coastal areas, i.e. the Batinah plains of Northern Oman, an increasing agricultural development and a concurrent lowering of the groundwater level was observed during the last decades. Decreased groundwater levels cause an inversion of the hydraulic gradient which is naturally aligned towards the coast which leads to an intrusion of marine salt water endangering the productivity of farms near the coast.

Utilizing the open source modeling software package OGENEOSYS (OGS, OpenGeoSys (2011)), a three-dimensional, density-dependent model is currently being built up. The model, comprehending a part of three selected

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coastal wadis of interest, will be used to investigate different management scenarios. The modelling’s main focus are the optimization of pumping schemes and, in long-term view, the coupling with a surface run-off model, which is also used for the determination of the groundwater recharge due to wadi run-off downstream of retention dams. Also, the highly uncertain local hydro-geological conditions and scarcity of data are addressed by utilizing an extended inverse-weighted-distance approach for a three-dimensional interpretation of the aquifer’s properties and the model’s calibration.

Based on the current simulations’ output, further scenario investigations will be done, assessing various socio-economic targets (e.g. agricultural water demand, industry etc.). Within these scenarios, marine salt water encroachment should be minimized, thus stabilizing the natural equilibrium between the continental freshwater flux and seawater intrusion ensuring a long-term usage of the agricultural areas. Numerical modeling tools are very important to develop those scenarios.

**Keywords:**
saltwater intrusion, density dependent, three-dimensional numerical simulation, groundwater flow, mass transport, Al-Batinah, Oman, IWAS

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1. Introduction

In many parts of the world, fresh water resources are getting scarcer more and more limiting the access to potable water for a growing number of people. Financed by the Federal Ministry of Education and Research, the International Water Research Alliance Saxony (IWAS) addresses different water issues within several regions of the world; among them, situated in the North-west on the Saudi Arabian peninsula, along the northern Oman coast, is the Al-Batinah region located, which is the focus of the IWAS-Oman project group.

1.1. Water Usage in the Al-Batinah Study Area

The region of Al-Batinah extends along the northern Oman coast (Figure 1). The Al Batinah represents one of the major settling areas in Oman (ca. 800’000 inhabitants) including both, large parts of different branches of industry and service providers, as well as tourism areas. Within the Al-Batinah, three catchments have been chosen for intensive studying: the Wadis Ma’awil, Bani Kharus and Taww (Figure 1). The study area basically
consists of two landscapes: the northern coastal plains and the southern mountainous areas. Since soils are especially fertile in the coastal plains, the area is also intensely used for agricultural cultivation accommodating farms of different size. Most of the water is used for agricultural purposes (86%), followed by potable water (12%) and industrial usage (2%) (Al-Shaqsi, 2004). Despite a small proportion of water gained from desalinization, the substantial part is obtained from the local groundwater resources by a vast number of hand-dug and drilled wells.

1.2. Challenges for Groundwater Management

While the natural water stress on the groundwater resources in this (semi)-arid region is apparently demanding, extensive groundwater abstraction leads to several problems threatening the local population’s access to drinking water. Estimations of various sources state increasing rates of abstraction from ca. $30 \cdot 10^6 m^3 \cdot a^{-1}$ in the 1970s, when pumping rates were assumed to be constant before, to a current abstraction rate of up to $120 \cdot 10^6 m^3 \cdot a^{-1}$ within the study region (comp. BRGM (1992), Al-Shoukri (2008)). The approximated inflow from the upstream catchments yields only ca. $50 \cdot 10^6 m^3 \cdot a^{-1}$ (Gerner and Schmitz, in review). The major impact of
this considerably negative water balance of the coastal plain is the decrease of the groundwater table, that was observed since the late 1970s (Figure 2). Insufficient knowledge about agricultural techniques for the efficient usage of water, as well as the unrestricted and uncontrolled possibility to pump water often lead to a waste of high amounts of this limited resource. As a result, shallow wells of smaller farms and households run dry, forcing the people to abandon their homes and therewith endangering the traditional social structures and ways of living.

Additionally, the decline of the water table causes the natural groundwater’s gradient to reverse. With the hydraulic gradient pointing inland, seawater intrudes into the agriculturally used areas, limiting the availability of freshwater by a qualitative constraint. In fact, even the cultivation of salt-tolerant plants, like rhodes-grass, barley or date-palms, has become impossible in the near-coastal areas. The enduring irrigation with brackish water made the highly productive soil over large extends infertile, thus useless for a long time. The evolution of the salt encroachment has been observed at several, selected wells since the late 1970s, however only been assessed in very few investigations within the area (Rajmohan et al., 2009).
1.3. Aim of the Study

When surface water supply is limited, groundwater exploitation is a common problem in near-coastal areas, that usually is being assessed by the use of numerical models; recent work on density dependent flow include Graf and Degener (2011), Park and Aral (2008), Mazzia and Putti (2006), Beinhorn et al. (2005), Mazzia and Putti (2002), datta #, giambastiani #, abd-elhamid #. Although several surveys were carried out about the study area's aquifer and water balance (Gibb (1976), MacDonald (1989), Macumber (1998a), CACE (2004)), none could present a consistent and comprehensive water resources management including the evaluation of the development of the density dependent saline intrusion. Within the IWAS-Oman project, an innovative concept has been developed (Grundmann et al., 2011, in print) that aims to combine the major aspects of the region’s water balance including (among other issues) the saltwater intrusion. This integrated water resources management (IWRM) intends to secure a long-lasting and sustainable usage of the water resources. The article at hand deals with the setup of the three-dimensional, density dependent groundwater model for the coastal plains of the study area, its parameter calibration and results of first scenario simulations.

2. Governing Equations

2.1. Simulation Software Package OpenGeoSys

For the simulation, the open-source scientific modeling software OpenGeoSys (OGS) is used (Kolditz et al. (2008), Kalbacher et al. (2010, in print)). OGS is based on the Galerkin-FEM method and aims to model thermo, hydro, mechanical and chemical processes (THMC) in porous and fractured media including the coupling among these processes. The software has been verified through various benchmarks and applications (Kolditz et al., 1998).

2.2. Basic Equations for Density Dependent Flow

There are a couple of numerical methods available to describe a moving water table, e.g. Dupuit-Forchheimer (Murray and Johnson, 1977), mesh-free methods (Meenal and Eldho, 2011) or the boundary element method (Narayanan et al., 1992). For this study case, the following approach was used to solve water movement in the unsaturated and saturated zone.

\[ S_0 \frac{\partial h}{\partial t} - \nabla (\phi \mathbf{v}) = q \] (1)
with the momentum balance equation for variable density flow in a porous
medium using the Boussinesq approximation (Kolditz et al., 1998) as

\[ \phi \mathbf{v} = -\mathbf{K} (\nabla p + \rho \mathbf{g}) \]  

(2)

where \( S_0 \) is specific storativity, \( h \) is hydraulic head, \( t \) is time, \( \phi \) is porosity,
\( \mathbf{v} \) is fluid velocity vector, \( q \) is source term, \( \mathbf{K} \) is hydraulic conductivity tensor,
\( p \) is pressure, \( \rho \) is density and \( \mathbf{g} \) is unity gravity vector.

We define

\[ \mathbf{K} = \zeta \mathbf{K}_0 \]  

(3)

where \( \mathbf{K}_0 \) is unreduced hydraulic conductivity tensor and \( \zeta \) is a reduction
factor following a simplified approach after Sugio and Desai (1987).

\[ \zeta = \begin{cases} 
\zeta_{\text{res}} & p \leq p_{\text{res}} \\
\zeta_{\text{eff}} & p_{\text{res}} < p < 0 \\
1 & p \geq 0 
\end{cases} \]  

(4)

where \( \zeta_{\text{res}} \) is a given residual value for the reduction factor and \( p_{\text{res}} \) a given
pressure, where \( \zeta_{\text{res}} \) should be reached. In terms of calculation errors, \( p_{\text{res}} \)
depends on the vertical grid resolution and should not be \( p_{\text{res}} > -100 \) Pa
especially for coarse meshes. \( \zeta_{\text{res}} < 10^{-6} \) may lead to oscillations within the
flow field, and \( \zeta_{\text{res}} > 10^{-1} \) might cause water balance errors due to the low
reduction.

The effective reduction factor \( \zeta_{\text{eff}} \) is defined as follows.

\[ \zeta_{\text{eff}} = \zeta_{\text{res}} + (1 - \zeta_{\text{res}}) \zeta_{\text{smooth}} \]  

(5)

with

\[ \zeta_{\text{smooth}} = \zeta_p^{2(1-\zeta_p)} \]  

(6)

and

\[ \zeta_p = 1 - \frac{p}{p_{\text{res}}} \]  

(7)

Furthermore, mass transport is calculated by the advection-dispersion
equation (Bear, 1988)

\[ \phi \frac{\partial C}{\partial t} + \nabla \cdot (\phi \mathbf{v} C) - \nabla \cdot (\phi \mathbf{D} \cdot \nabla C) = q_c \]  

(8)

where \( C \) is relative mass concentration, \( q_c \) is source term of mass concentra-
tion and \( \mathbf{D} \) is dispersion tensor following Bear (1988) with

\[ \mathbf{D} = \tau D_m \delta + \alpha_T \mathbf{v} \cdot \delta + (\alpha_L - \alpha_T) \frac{\mathbf{v}_i \mathbf{v}_j}{|\mathbf{v}|} \]  

(9)
where $\tau$ is tortuosity, $D_m$ is coefficient of molecular diffusion, $\delta$ is Kronecker-delta, $\alpha_T$ is transverse dispersivity and $\alpha_L$ is longitudinal dispersivity.

Finally, (1) and (8) are iteratively coupled via the equation of bulk fluid density for an isothermal state, neglecting the compressibility of the fluid associated with the change of pressure described via

$$\rho = \rho_0 (1 + \gamma_c C)$$

where $\rho_0$ is fluid density at $C = 0$, $\gamma_c$ is coefficient of expansion resulting from the change of mass concentration of the solute at constant pressure. The coefficient $\gamma_c$ for the relation between the densities of seawater and freshwater is given by (Park and Aral, 2008) $\gamma_c = 0.0245$ or by (Goswami and Clement, 2007) $\gamma_c = 0.026$ and depends on the mass of the dissolved ions.

3. Benchmark for Density Dependent Flow - The Goswami-Clement Problem

3.1. Problem Description

The Goswami-Clement problem shows density dependent groundwater flow under fully saturated, unconfined conditions. The example features a horizontally intruding saltwater from one side with higher density than the initially present freshwater and its displacement. This benchmark will show the applicability of the OGS model by comparing its simulation results with experimental and numerical Seawat simulation data (comp. Seawat (2011)) acquired by Goswami and Clement (2007), who show a Henry-like (Henry, 1960) saltwater intrusion experiment using a laboratory-scale tank.

As described in paragraph 2, the hydraulic flow equation is solved for the unconfined flow, while the mass transport process is linearly coupled via a density correlation as a function of concentration.

3.2. Model Setup

The boundary conditions are depicted in Figure 3: no-flow boundaries are applied on bottom and top horizontal borders, vertical right and left hand side boundaries are described via linear pressure gradients $p_i(z = h_i) = \rho_i g h_i$ (including the appropriate densities of fresh water $\rho_f = 1000 \text{ kg} \cdot \text{m}^{-3}$ or salt water $\rho_s = 1026 \text{ kg} \cdot \text{m}^{-3}$ and pressure heads $h_f = 0.267 \text{ m}$ and $h_s = 0.255 \text{ m}$), the vertical right and left hand side boundary relative concentrations $C_{rel}$ are fresh water (i.e. $C_{rel} = 0$) and salt water (i.e. $C_{rel} = 1$), respectively.
Initial conditions are fresh water for the whole domain, i.e. a linear pressure gradient $p(z)$ with $p(z = h_s = 0.25 \text{ m}) = 0 \text{ Pa}$ and $C_{\text{rel}} = 0$. The domain consists of a homogeneous, isotropic material and resembles a medium coarse sand. The corresponding parameters are listed in Table 1.

The spatial dimensions of the laboratory tank were $0.53 \times 0.26 \times 0.027 \text{ m}^3$ (length x height x width); a vertical 2D model domain was set up following the x-direction. The grid’s discretization was uniform with rectangular quadrilateral elements each of a size $\Delta x = \Delta z = 5 \cdot 10^{-3} \text{ m}$.

The time step size was set to $\Delta t = 10\text{s}$ for total a simulation time of }

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity $\phi$ [–]</td>
<td>0.385</td>
</tr>
<tr>
<td>Permeability (isotropic) $k$ [m$^2$]</td>
<td>$1.239 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>Residual reduction factor $\zeta_{\text{res}}$ [–]</td>
<td>0.0001</td>
</tr>
<tr>
<td>Residual reduction pressure $p_{\text{res}}$ [Pa]</td>
<td>$-100$</td>
</tr>
<tr>
<td>Seawater-freshwater density relation $\gamma_c$ [–]</td>
<td>0.026</td>
</tr>
</tbody>
</table>
$t_{\text{final}} = 4800 \text{s} = 80 \text{min}$ (time until steady state of experiment and simulation).

Values for longitudinal dispersivity $\alpha_L$ were determined by Goswami & Clement’s laboratory experiments to $\alpha_L = 10^{-3} \text{m}$, transversal dispersivity $\alpha_T$ was assumed to be $\alpha_T = 0.1 \cdot \alpha_L = 10^{-4} \text{m}$.

Diffusion effects can be neglected, if these are significantly smaller than mechanical dispersion:

$$\tau D_m \ll \alpha_T v$$ \hspace{1cm} (11)

Tortuosity is $\tau \approx 0.4$ (Bear, 1988), while diffusion coefficient is $D_m \approx 2.2 \cdot 10^{-9} \text{m}^2 \cdot \text{s}^{-1}$ (Tanaka, 1978). Comparing dispersive and diffusive flow in (12), it can be seen, that diffusion effects are of minor importance and can in fact be neglected.

$$0.4 \cdot 2.2 \cdot 10^{-9} \text{m}^2 \cdot \text{s}^{-1} \ll 10^{-4} \text{m} \cdot 5 \cdot 10^{-4} \text{m} \cdot \text{s}^{-1}$$ \hspace{1cm} (12)

$$8.8 \cdot 10^{-10} \text{m} \ll 5 \cdot 10^{-8} \text{m}.$$ \hspace{1cm} (13)

3.3. Comparison of Simulation Results

The steady state of the experiment is shown in Figure 4; the figure depicts the OGS simulation results for relative concentrations and the typical pattern of a saltwater intrusion front. The comparison of the experimental measurements with the modeling software outputs for Seawat and OGS are presented in Figure 5 for relative concentration values of $C_{\text{rel}} = 0.5$; the numerical results fit very well to the experimental observations. The slight deviations observed may be due to inhomogeneities of the sand material, or due to the visual observation measurement technique used to obtain the isolines of $C_{\text{rel}} = 0.5$. Goswami & Clement describe the latter as follows:

“The color variations [...] indicate that the dispersion zone is relatively narrow and is estimated to be about 1 cm wide. Therefore the wedge delineation line [...] (which is assumed to be the $C_{\text{rel}} = 0.5$ isoline) has an error in the range of $\pm 0.5 \text{cm} [...]$”. As the dispersion zone was estimated to be about 1 cm wide an in such a way identified $C_{\text{rel}} = 0.5$ isoline could very well also depict the $C_{\text{rel}} = 0.1$ or $C_{\text{rel}} = 0.9$ isoline.

Additionally, the right boundary’s inflow fluxes from Goswami & Clement’s measured experimental data, the Seawat results, and the equivalent values simulated with OGS are shown in Table 2. Again, both simulation outputs resemble the measured experimental data within acceptable error limits.
Table 2: Simulation results: Steady state right side boundary influx $Q_{in}$ and deviation from experimental measurement $\sigma$

<table>
<thead>
<tr>
<th>Origin of value</th>
<th>$Q_{in}$ [cm$^3 \cdot s^{-1}$]</th>
<th>$\sigma$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>SEAWAT</td>
<td>1.46</td>
<td>2.82</td>
</tr>
<tr>
<td>OGS</td>
<td>1.41</td>
<td>-0.70</td>
</tr>
</tbody>
</table>

Figure 4: Relative concentrations, velocity vector flow field and grid resolution of the OpenGeoSys steady-state simulation.
4. Three-dimensional Modeling in Study Area

The groundwater model domain has the size of 640 km$^2$ (comp. Figure 1) and lies at the northern, coastal region of the study area. # hier mu noch was hin zum filen.

4.1. Data Availability

For the development of possible scenarios within the IWRM of the study region, it is crucial to deal with proper real world data, especially for calibration purposes. However, data existence is sparse and the available data often lacks of completeness as well as consistence while containing few obviously wrong data due to systematic measurement errors, of which the latter was excluded from the data base.

Available data are:

- Groundwater level measurements, roughly monthly for 1974 - 2005, only 15 of ca. 40 stations starting 1974, remaining series starting later
- Salinity measurements, temporal arbitrary measurements, no depth information

Figure 5: Comparison of the $C_{rel} = 0.5$ relative concentration isolines of Goswami & Clement’s experimental data with his SEAWAT and the OGS steady-state simulation, altered after Goswami and Clement (2007)
• Location of groundwater extraction sites, dug wells and borehole wells (comp. Figure 7(a) and Figure 7(b))
• Total extraction estimates for 1970s and current time, temporal development of extraction rate increase
• Hydrogeological data, borehole logs and hydrogeological sections, data from pumping tests

4.2. Hydrogeology

The hydrogeology of the study area exhibits a complex structure of fluviatile (esp. wadi), aeolian, and marine deposits, consisting of locally cemented gravels, different sized sand, silt, loam and clay, as well as calcereous media. In the southern, mountainous areas, karstic structures are reckoned, that generally are subject to high modeling uncertainties (Bakalowicz, 2005) and which is why the groundwater model domain first starts where porous media deposits form mainly two aquifers: an upper, highly conductive and productive quaternary layer, and a lower, medium conductive tertiary layer. The aquifer structure is limited below by a clayey aquiclude, which extend is subject to speculation in the near coastal zone due to missing observations (e.g. exploration boreholes, time-domain-electro-magnetic measurements). The total aquifer thickness increases from south to north, while the quaternary aquifer has a maximum thickness in the center of the model domain (the "Ma’awil trough") and thins out northwards (Macumber, 1998b).

From the hydrogeological model, a three-dimensional grid of 126660 elements was built up using the Gmsh meshing software (Geuzaine and Remacle, 2009) forming a total of 30 layers. For the interpolation of the three-dimensional hydrogeological model volume, an adapted inverse weighted distance approach was used combining the available evaluated hydrogeological data from which a total of twelve individual material properties could be distinguished. Figure 6 shows several vertical cross sections through the study area. From the interpolation, the two before mentioned regional specialities can be identified: the Ma’awil trough, which serves as a highly conductive region for the throughflow of the groundwater recharge from the upstream mountainous area and the relatively thin quaternary aquifer in the coastal zone.

4.3. Conceptional Model / Setup

The three basic components of the groundwater model’s boundary conditions are: the marine saltwater and level-zero-pressure boundary, the extrac-
Figure 6: Vertical cross sections of discrete interpolated hydrogeological aquifer types within groundwater model study area, aquifer types from highly permeable (blue) to less permeable (white)

The parameterization for the marine boundary is a linear pressure head $p(z) = \rho_s g z$ while the upstream inflow flux is based on an estimation of the mountainous recharge from the application of the APLIS-method (Gerner and Schmitz, in review). For the extraction from pumping, no information is available on the ca. 5000 single wells’ extraction rates; however, the development of the pumping activity for the period 1974-2005, an overall estimation of the groundwater abstraction rate for the study area (Al-Shoukri, 2008) and the location of the single wells are known. While assuming an equal pumping rate per well type (dug well or borehole), the following procedure will incorporate the soft data of the known well locations into the numerical model: applying the overall specific abstraction (see (14)) on the simplified contour isoline polygons of a spatial kernel density filter (Brunsdon, 1995), the uncertainties of the extraction boundary condition could be reduced (see
Figure 7: Kernel density distribution and simplified contour isoline polygons of the known extraction locations for drilled borehole and dug wells

Figure 7(a) and Figure 7(b)).

\[ q_{\text{spec}} = \frac{Q_{\text{total}}}{\sum_{i=1}^{n} A_i} \]  

(14)

where \( q_{\text{spec}} \) is specific abstraction, \( Q_{\text{total}} \) is total estimated abstraction by pumping activity and \( A_i \) is area of a simplified contour isoline polygon.

4.4. Calibration Techniques

For the calibration of the model setups, the parameterization optimization software package PEST (Doherty and Hunt, 2010) was utilized. Basically, PEST uses the Marquard-method to minimize a given target function (e.g. sum of weighted squared residuals) by varying a determined set of parameters until a critical threshold of the optimization criterion is reached. The adjustable parameters depend on the simulation type (i.e. steady state or transient). PEST is a widely used parameter estimation tool (Sun et al., 2011).

As only 15 groundwater level data points were available from measurements beginning in the year 1974, a multiple linear correlation was setup for each of the 25 additional data series. The correlations’ periods are variable and depend on the individual begin of the groundwater level measurements. Each correlation coefficient was \( \rho'(x, y_1...y_i) > 0.81 \) with a mean of \( \rho'(x, y_1...y_i) = 0.94 \), resembling an acceptable correlation. The achieved additional data series were weighted by 0.1 within the target function of PEST.

Table 3 shows the used model parameters for the steady state, transient and mass transport simulations. Dispersion is estimated from Gelhar et al.
(1992) and, again, diffusion was neglected:

\[ \tau D_m \ll \alpha_T \nu \]  
\[ 8.8 \cdot 10^{-10} m \ll 10^{-1} m. \]  

(15) (16)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>Porosity ( \phi [-] )</td>
<td>( 0.02 - 0.385 )</td>
</tr>
<tr>
<td>Permeability (isotropic) ( k [m^2] )</td>
<td>( 1.239 \cdot 10^{-18} - 1.239 \cdot 10^{-9} )</td>
</tr>
<tr>
<td>Residual reduction factor ( \xi_{\text{res}} [-] )</td>
<td>0.0001</td>
</tr>
<tr>
<td>Residual reduction pressure ( p_{\text{res}} [Pa] )</td>
<td>(-1000)</td>
</tr>
<tr>
<td>Longitudinal dispersion ( \alpha_L [m] )</td>
<td>200</td>
</tr>
<tr>
<td>Seawater-freshwater density relation ( \gamma_c [-] )</td>
<td>0.0245</td>
</tr>
</tbody>
</table>

Table 3: Groundwater model domain simulation material parameters (\( ^* \) parameter ranges given for the twelve hydrogeological materials)

4.5. Steady State 1974 Simulation

In the steady state calibration, the parameter groups for variation were hydraulic conductivity (from twelve hydrogeological materials), upstream inflow and aquifer extraction, all within their respective estimation ranges from preliminary investigations. As this system will be under-determined when all parameters have free boundaries, it was taken care of that Pest\’s parameter optimization results were limited to stay within the expected ranges (see 1.2) without running into the given parameter range boundaries.

Figure 8 shows the scatter diagram for the steady-state calibration. The calibration result shows a good concordance between observed and simulated groundwater levels, especially for the 15 measured data points, while the additional correlation originating data points also have low residuals. Statistical parameters for the parameter optimization underline the good calibration (see Table 4). Pest\’s results for the upstream subsurface inflow \( Q_{\text{in,sub}} = 6.80 \cdot 10^7 \text{m}^3 \cdot \text{a}^{-1} \) and for the abstraction \( Q_{\text{abstr,total}} = 3.69 \cdot 10^7 \text{m}^3 \cdot \text{a}^{-1} \) lie within the expected ranges.
Figure 8: Steady state 1974 scatter diagram for comparison of field measurements and simulation output.

Table 4: Statistical parameters for the steady state 1974 calibration

<table>
<thead>
<tr>
<th>Statistical parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum of squared weighted residuals [m$^2$]</td>
<td>29.610</td>
</tr>
<tr>
<td>Correlation coefficient [−]</td>
<td>0.979</td>
</tr>
<tr>
<td>Standard variance of weighted residuals [m$^2$]</td>
<td>1.184</td>
</tr>
</tbody>
</table>
4.6. Transient Mass Transport Simulation

Using the estimated raise of pumping activity as a boundary condition, interim results of a mass transport simulation are shown in Figure 9(a); Figure 9(b) shows an interpolation of salinity measurements within the study area as comparison; both figures depict similar patterns of the saltwater intrusion along the coast of the study area and confirm the successful reproduction of the principle conceptual model (i.e. hydrogeological model, boundary conditions). Still, these results are subject to a calibration applying the same technique as described before to decrease the simulation output residuals of hydraulic head and salinity concentration and increase the prediction accuracy of future scenario calculations.

5. Summary and Outlook

We presented the development of a Finite-Element-Model for non-linear coupled PDEs to represent density-dependent flow processes for a real world application. The work shows the successful application of the open source scientific software package OGS for the numerical modeling of density dependent groundwater simulations both in small and large scale domains. The Goswami-Clement problem is solved to a sufficient degree in comparison to experimental data and SEAWAT simulation results. Although data availability is limited for the Oman study area, groundwater levels for a steady and a transient state could be calibrated and mass transport simulations depict equivalent saline intrusion spatial patterns as measurements; first scenario simulations show possible future developments of the saline intrusion.
In the future, the existing groundwater model will be coupled with groundwater recharge models for surface flow infiltration of the wadis and recharge dams of the study area (governed by the Saint-Vernant equations, eg. Delfs et al. (2009)). Also, within the focus of the IWRM strategy, a multiple target optimization method can be utilized for the optimization of possible future pumping sites’ locations and their abstraction rates. Depending on prospective available salinity measurement data, also a depth-specific calibration for the mass transport model is possible. Finally, the resolution of the groundwater model domain’s grid can be increased for studying local density dependent flow phenomena in more detail. Introducing advanced numerical methods into practical applications is a challenging interdisciplinary field for both mathematicians and engineers.

6. Acknowledgements

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21
