3D modeling of tsunami-induced seawater intrusion and aquifer recovery in Niijima Island, Japan, under the future tsunami scenario

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Abstract

A 3D numerical model was developed to simulate seawater intrusion and aquifer recovery in Niijima Island under the future Nankai earthquake and tsunami scenario. The FEFLOW code was used to solve density-dependent groundwater flow and mass transport in unsaturated-saturated porous media. The simulations indicated that the maximum amount of seawater intrusion during the tsunami was controlled by the total unsaturated void space of the soil beneath the inundation area. After the tsunami, directions of seawater movement and flushing time depended on the pre-tsunami groundwater flow conditions and bedrock structures. Some groundwater was found to be survived from salinization, and showed the potential to provide water supply in an equivalent amount of the pre-tsunami level without worsening the recovery process. The simulated attempt to remove the intruded seawater from a polluted well could accelerate aquifer recovery but might not be practical due to the cost of maintaining intensive pumping over years.

Key Words: 3D model; tsunami; seawater intrusion; Niijima Island; pumping behavior

1. Introduction

Coastal groundwater systems are highly vulnerable to seawater intrusion caused by tsunami disasters. As reported after the 2004 Indian Ocean tsunami (Illangasekare et al., 2006; Villholth and Neupane, 2011; Violette et al., 2009) and the 2011 Tohoku tsunami (Ministry of Agriculture, Forestry and Fisheries, 2011; Mori et al., 2012; Nakagawa et al., 2013), seawater flooded over the coastal zones and infiltrated vertically into unconfined aquifers, which caused long-term salinization of fresh groundwater resources. Many coastal areas around the globe are facing future tsunami risks, especially in the vicinity of seismically active zones, such as Japan, Indonesia, Chile, and Peru (UNISDR, 2009). Therefore, predicting seawater intrusion under future tsunami scenarios and seeking countermeasures to secure water resources is of great importance in tsunami-prone zones.

According to the Cabinet Office of Japan (2011), there is a high possibility that a massive earthquake of 9.0 $M_w$ will occur along the Nankai Trough (Figure 1a) on the Pacific side of Japan during the year 2011 to 2040. Under this scenario, Niijima Island, is anticipated to be one of the worst tsunami inundation zones in Japan. According to the simulation results by Tokyo Disaster Management Council (2013), under the worst tsunami scenario, the Maehama coast of Niijima Island would be inundated by seawater up to about 15 m a.m.s.l. (meter above mean sea-level) (Figure...
1b), and would be affected by tsunami waves for around 60 to 120 minutes (Figure 1f). As a result, groundwater, the only freshwater source for the locals living on the island, will face the problem of severe seawater intrusion. Central Disaster Management Council (2014) recommended that isolated islands like Niijima should prepare freshwater stock for 1-week use with the anticipation of no rescue from others. However, it is demonstrated by the tsunami disasters in 2004 and 2011 that the groundwater deterioration can last for years. Hence, to plan for more effective disaster preparedness and rescue activities, it is necessary to take into account countermeasures to secure water resources for the long-term post-disaster recovery period.

Numerical groundwater modeling is a powerful quantitative approach and perhaps one of the only tools available to assess seawater intrusion under future tsunami scenarios. In fact, very few numerical studies (Alsumaiei and Bailey, 2018; Ministry of Agriculture, Forestry and Fisheries, 2011; Sivakumar and Elango, 2010; Violette et al., 2009; Vithanage et al., 2012a) have been established and they were almost exclusively focused on reproducing seawater intrusion processes induced by the 2004 and 2011 tsunamis. Also, these models were based on the limiting assumptions concerning the conceptualization of processes and the underlying geology. For example, the unsaturated zone was not considered in the simulations (Alsumaiei and Bailey, 2018; Ministry of Agriculture, Forestry and Fisheries, 2011), and the bedrock structures were not explicitly modeled (Sivakumar and Elango, 2010), which potentially introduced significant uncertainties to their models. Also, in order to be applied for more practical purposes such as identifying the most vulnerable zone of the aquifer to the tsunami and evaluating the effect of groundwater abstraction after the tsunami, the modeling approach assuming a 2D vertical cross-section adopted in previous simulations (Alsumaiei and Bailey, 2018; Violette et al., 2009; Vithanage et al., 2012a) is necessary to be further improved to 3D. In our previous study (Liu and Tokunaga, 2019), we numerically simulated the tsunami-induced seawater intrusion process in Niijima Island with a 2D vertical cross section model. It was found that the amount of seawater intrusion during the tsunami inundation was controlled by the unsaturated zone, while the migration of the intruded seawater after the tsunami was affected by the bedrock structures. In the current paper, we aimed at improving our previous 2D model to 3D, which allowed us to further confirm the important roles of the unsaturated zone and the bedrock structure in a 3D domain and to offer new discoveries regarding the effects of post-disaster pumping activities.

The objectives of this study include (1) to obtain better understandings on the behavior of the groundwater system with the tsunami, (2) to display how the aquifer would be contaminated and recovered from tsunami-induced seawater intrusion, and (3) to explore the potential of pumping the unaffected groundwater for supplying freshwater and removing the intruded seawater for facilitating aquifer recovery. We numerically simulated seawater intrusion and aquifer recovery processes in Niijima Island under future Nankai earthquake and tsunami scenarios. The obtained simulation results allowed us to discuss key factors in the relevant physical processes and the opportunities for post-disaster water management. The limitations and uncertainties of the simulations were also discussed.

### 2. Study area

Niijima Island is situated at around 150 km south of Tokyo, Japan (Figure 1a). It has a land area of about 24 km² with its north-south distance of around 11.5 km and east-west distance of around 2.5 km (Niijima Village Office, 2015). The island has a warm and temperate climate characterized
by the average annual temperature of 17.7 °C with the highest monthly temperature in August (26.4 °C) and the lowest in February (9.1 °C) (Niijima Village Office, 2015). The average annual rainfall on the island is 2207 mm (Japan Meteorological Agency, 2017). As a tourist resort, the island has nearly 3000 residents and attracts around 46,000 visitors annually (Oshima Subprefecture of Tokyo, 2014).

2.1 Geophysical settings

Niijima Island is composed of rhyolite lava domes in the northern and southern regions, and a low-lying plain in the central part (Figure 1b). Before 886 AD, the Mt. Minejiyama, Mt. Setoyama, and Mt. Marujimamine were above sea-level and others were below sea-level (Nakaoka and Suzuki-Kamata, 2015). In 886 AD, the eruption of the Mukaiyama Volcano occurred with a phreatomagmatic explosion of rhyolite magma at the southern part of the island (Koyaguchi, 1986). It then released a pyroclastic flow and pyroclastic surge settling in the central part of the island that formed a single-layered unconfined aquifer (Figure 1c). The rhyolite lava from the Mukaiyama Volcano spreaded and overlaid the pyroclastic cone in the southern part of the island (Figure 1d). All the aquifer materials below the sea-level were initially submerged by seawater, then, the fresh groundwater system was gradually developed by receiving and storing freshwater from rainfall. According to the estimated bedrock surface (aquifer bottom) topography by an electrical survey (Shindo, 1980), there is a structural high of the bedrock surface in the central area of the island (Figures 1b and e). The seafloor depth within a horizontal distance of 1000 m from the coastline of Niijima Island is less than 30 m (Nakaoka and Suzuki-Kamata, 2015) (Figure 1b).

2.2 Hydrogeological settings

The measured hydraulic conductivity \( K \) of the aquifer was reported to be varied between \( 1 \times 10^{-6} \) and \( 6 \times 10^{-3} \) m/s (Construction Section of Niijima Village, 2001; Honma et al., 1974; Shindo, 1980). Previous studies (Aichi et al., 2011; Honma et al., 1974) indicated that water table elevations ranged from about 0.5 m a.m.s.l. near the coast to 1.3 m a.m.s.l. in the central plain of the island, and had about ± 0.7 m fluctuations throughout the year. Groundwater is abstracted from the public wells that were constructed in 1980s as shown in Figure 1c, supplying about \( 3.7 \times 10^5 \) m\(^3\) of freshwater annually for domestic purposes (Oshima Subprefecture of Tokyo, 2014; Shindo, 1992). It should be noted that there are very limited amount of surface water resources including few small springs and seasonal creeks on the island, and hence, groundwater is the only option for the freshwater resource.

3. Methods

The numerical problem of tsunami-induced seawater intrusion and aquifer recovery involves variable-density flow and mass transport processes in unsaturated-saturated porous media, which was solved by using the code FEFLOW (the governing equations can be found in Diersch (2013), and are not repeated here).

3.1 Boundary conditions and initial conditions

The locations of model boundaries (Figures 1b and c) were determined based on the consideration that the model domain should cover the important areas including the major tsunami-prone zone near the western coast (Figure 1b), the main aquifer in the central plain (Figure 1c), and the southern part of the island where the potential groundwater stock beneath the lava layer of Mukaiyama Volcano (Figure 1d) may be reserved. As shown in Figure 1c, the northern boundary of the model was set perpendicular to the coastline (A-B and G-F), along a seasonal stream (B-C), and along mountain ridges (C-D-G), and was assumed...
Figure 1  Niijima Island, Japan: (a) location map; (b) topographic map showing land surface elevations (Ministry of Land, Infrastructure, Transport and Tourism, 2015), bedrock surface elevations (Construction Section of Niijima Village, 2001; Isobe and Nakashima, 2001; Shindo, 1980), sea bottom elevations (Nakaoka and Suzuki-Kamata, 2015) and anticipated tsunami hazard zones (Tokyo Disaster Management Council, 2013); (c) geologic map modified after Isshiki (1987) with the location of public water supply wells; schematic geologic cross-sections of (d) N-S (vertical exaggeration by a factor of 2) and (e) W-E (vertical exaggeration by a factor of 10) (simplified and modified from Shindo (1980) and Isshiki (1987)); (f) tsunami wave displacement at the sea surface near the Maehama coast of Niijima Island under the Nankai earthquake and tsunami scenario simulated by Tokyo Disaster Management Council (2013). A tide level of 0.73 m a.m.s.l. was considered in the simulation.
to be no-flow. By several trials of simulating the seafloor of different horizontal distances from the coastline in the model, the boundary at the seaside (A-F) was determined to be located at a horizontal distance of 300 m from the coastline, which was confirmed to be sufficient for the model to capture all the important seawater-freshwater interactions throughout the whole simulation stages.

Except that the no-flow settings at the boundary A-B-C-D-G-F and at the aquifer bottom were kept throughout all the simulation stages, the initial conditions and boundary conditions were varied for three simulations stages: the development of fresh groundwater system since the deposition of pyroclastic materials in 886 AD until it reached to the quasi-steady state; the seawater intrusion processes during the tsunami inundation period; and the years of the post-tsunami aquifer recovery processes.

To obtain the quasi-steady state before the tsunami, the initial conditions and boundary conditions were set to reflect the time when the island was formed in 886 AD (Figure 2a). All the media above the sea-level were set to contain residual water with the concentration $C = 0$ kg/m$^3$ while the media below the sea-level was fully saturated with seawater of $C = 35$ kg/m$^3$ (NaCl). Such setting ignored that small amount of salt can be carried by wind from the sea to inland areas, then be dissolved in groundwater. Compared with seawater intrusion, the contribution of salt aerosol to groundwater salinity was small enough that it can be ignored in our simulations. Along the seafloor where groundwater was in contact with seawater, a boundary condition with constant seawater head (the sea-level elevation with reference to 0 m a.m.s.l.) $h_{sw} = 0$ m a.m.s.l. with $C = 35$ kg/m$^3$ was applied. $h_{sw}$ was converted to equivalent freshwater head $h$ (Diersch, 2013):

$$h = h_{sw} + \chi_s (h_{sw} - z)$$  \hspace{1cm} (1)

where $\chi_s = (\rho_s - \rho_0) / \rho_0$ is the ratio of seawater density $\rho_s$ and freshwater density $\rho_0$, and $z$ is elevation with reference to 0 m a.m.s.l. A constant boundary condition of $C = 0$ kg/m$^3$ with a constant flux $R$, representing the rainfall recharge, was applied along the land surface. Strictly speaking, these constant boundary conditions at the seafloor and the land surface were not perfectly representative. The numerical simulation approach for freshwater-seawater mixing zones near the coast indeed required a system-dependent strategy including: at the seafloor, $C = 35$ kg/m$^3$ should be set for seawater inflow from the sea to aquifer while no constraints should be set in the case of groundwater discharge from the aquifer to the sea; and at the beach surface, rainfall recharge should be applied to the nodes except for the nodes where groundwater discharges out. However, this system-dependent boundary condition setting was not adopted in this paper because such complex setting caused serious numerical oscillations and tremendously raised the CPU time; and this setting produced only limited influence on the position of freshwater-seawater mixing zones and did not affect overall seawater intrusion and aquifer recovery processes in our simulations. The transient simulation was run for a period of 200 years to ensure the model to reach a quasi-steady state, and then, groundwater abstraction was introduced by specifying well boundary conditions at public wells where a total amount of freshwater of $3.7 \times 10^5$ m$^3$/yr was pumped out. After the transient simulation of 30 years, another quasi-steady state was achieved which was regarded as the normal condition of the groundwater system in Niijima Island before the tsunami.

The obtained quasi-steady state was used as the initial conditions for simulating the seawater intrusion process during the tsunami inundation period. For simplification, the tsunami-induced seawater flooding was simulated as a spatially and temporally constant sea-level rise event lasting for a certain period of time. This assumption was intended to produce a higher degree of
seawater intrusion than that could happen in the actual disaster. Based on the tsunami simulation results by Tokyo Disaster Management Council (2013), a tsunami inundation event lasting for 120 minutes with a constant inundation elevation $h_T = 15$ m a.m.s.l. was assumed. An extreme tsunami inundation scenario of $h_T = 20$ m a.m.s.l. was also simulated. At the seafloor and the land surface below $h_T$, a constant boundary condition of $h_{sw} = h_T$ with $C = 35$ kg/m$^3$ was assigned (Figure 2b). The land surface that was higher than $h_T$ was set to be a seepage face boundary. The well boundary conditions were disabled during this simulation stage considering the temporary power failure due to the earthquake and tsunami.

The simulation results at the final time step of the tsunami inundation period were used as the initial conditions for simulating the aquifer recovery process. After the tsunami, the sea-level was recovered to 0 m a.m.s.l., and the rainfall recharge began to freshen the salinized aquifer, and hence, the boundary conditions at the seafloor and land surface were resumed to be the same as those in the pre-tsunami simulation stage (Figure 2c). The aquifer recovery processes were compared for three different scenarios: no groundwater abstraction at all, pumping groundwater from unpolluted wells to supply freshwater, and pumping the intruded seawater out from a polluted well and subsequently discharging it into the sea to assist aquifer recovery.

### 3.2 Spatial and temporal discretization

The model contained five layers of numerical elements in the vertical direction (Figure 3). At the model top, the elevations of the land surface and seafloor obtained from Ministry of Land, Infrastructure, Transport and Tourism (2015) and Nakaoka and Suzuki-Kamata (2015), respectively, were assigned. The bedrock depth under the central plain of the island (Figure 1b) based on the information provided by Shindo (1980), Isobe and Nakashima (2001), and Construction Section of Niijima Village (2001), was specified at the model bottom. However, bedrock depth information at the southern part of the island is currently not available. Isshiki (1987) indicated that aquifer materials at least extend towards an elevation as low as $-50$ m a.m.s.l. under the lava layer of the Mukaiyama Volcano (Figure 1d), based on which the bedrock surface elevation of $-50$ m a.m.s.l. at the southern island was assumed in the model. The elements corresponding to the impermeable lava layer and the lava dome described in Section 2.1 were specified as inactive (Figure 3). All the elements in the uppermost layer (Layer 1) with a vertical thickness of 2 m were set to be active to receive rainfall recharge. The vertical thickness of each of other layers in the central part of the island (the main aquifer) was in the range of 8 to 18 m.

The model was discretized into 41,970 prismatic elements with a triangular base. For the sake of avoiding numerical oscillations and improving the accuracy of modeling results, a higher degree of refinement ($\Delta l \approx 60$ m) was adopted to ensure that the Peclet number $Pe_m = \Delta l/\alpha_L < 4$ (Voss and Souza, 1987) ($\alpha_L$ is the longitudinal dispersivity) in important local areas, including the coast (freshwater-seawater mixing zones) and the central plain (the estimated tsunami inundation zone and the groundwater abstraction zone) of the island (Figure 1c). However, further mesh refinement was not carried out because the current simulation involves complex flow and mass transport processes featured with variable-density, unsaturated-saturated conditions, transient simulations, and a 3D domain, which required large computational efforts. Because of this relatively large grid size, the simulations were not able to produce the density-induced fingering patterns. Nevertheless, because fingering was not likely to affect the overall 3D extent of seawater intrusion or the pumping behaviors to secure water resources, this level of spatial discretization would be enough for the corresponding discussion about the roles of the unsaturated zone (Section
Figure 2  3D views (left, vertical exaggeration is by a factor of 5) and vertical cross-section views (right, vertical exaggeration is by a factor of 10) showing the initial and boundary conditions for simulations of (a) the pre-tsunami period, (b) the tsunami inundation period, and (c) the post-tsunami period.
5.1), and groundwater flow and bedrock structures (Section 5.2), as well as the opportunities to cope with seawater intrusion (Section 5.3).

The automatic time-step control with the first-order predictor-corrector method was applied for the temporal discretization (Diersch, 2013). For each of the three simulation stages (the pre-, during, and post-tsunami period), the corresponding initial time step was set to be $1 \times 10^{-6}$ day, $1 \times 10^{-6}$ second, and $1 \times 10^{-6}$ day, and the maximum time step be one day, one second, and one day, respectively. The maximum growth factor between subsequent time steps was restricted to be 1.1.

3.3 Parameterization and calibration

The present model assumed that the aquifer of Niijima Island was single-layered, homogeneous, and isotropic. Model parameters were summarized in Table 1. van Genuchten model (van Genuchten, 1980) was adopted to describe the unsaturated properties, and was calibrated against the measured soil retention curves by Shindo (1980) (Figure 4a). $\alpha_L$ of 50 m was chosen here based on the relationship between dispersivity and observation scale that was suggested by Gelhar

Figure 3 Layer configurations of the 3-D model.
et al. (1992), and the ratio between longitudinal and transverse dispersivities $\alpha_L/\alpha_T$ was set to be 10 according to literature values (Sivakumar and Elango, 2010; Vithanage et al., 2012a). According to Honma et al. (1974), the recharge rate of the groundwater system in Niijima Island was equivalent to 30 to 50% of the annual rainfall amount. Therefore, a constant recharge rate $R(t) = 883$ mm/yr was adopted, which was derived from 40% of the average annual rainfall amount of 2,207 mm/yr (Japan Meteorological Agency, 2017). Aichi et al. (2011) estimated the ratio $R/K$ to be $3.0 \times 10^{-5}$ by fitting the Dupuit-Ghyben-Herzberg analytical solution (Vacher, 1988) to the measured groundwater table elevations. By several trials using the present numerical model, the ratio $R/K$ was calibrated to be $2.1 \times 10^{-5}$, and $K$ be $1.3 \times 10^{-3}$ m/s. Compared with the measured groundwater table elevations, the calibrated model can generally well reproduce overall groundwater flow patterns in the island (Figure 4b) and achieve a relatively good estimation of $K$ at an order-of-magnitude level (Figure 4c). Hence, this level of calibration was considered as satisfactory for studying the overall migration behavior of the intruded seawater and roughly estimating the time required for the polluted aquifer to be recovered. Other parameters listed in Table 1 were selected based on the typical literature values (Diersch, 2013; Vithanage et al., 2012b; Yu et al., 2016).

4. Results

4.1 Seawater intrusion process during tsunami inundation

As shown in Figure 5, during the tsunami inundation of 15 m a.m.s.l., seawater infiltrated vertically into soil media and reached the water table within 10 minutes. This vertical intrusion process took place rapidly because of the large downwards hydraulic gradients by tsunami water elevation and the highly permeable sands in the island ($K = 1.3 \times 10^{-3}$ m/s). The volume of the intruded seawater increased with a rapid rate in the first 30 minutes and reached a level of about $1.2 \times 10^6$ m$^3$ (Figure 5d), followed by a much slower

| Parameters obtained from literature of Niijima Island | Symbol | Value | Unit | Data source |
|------------------------------------------------------|--------|-------|------|-------------|
| Porosity                                            | $\varepsilon$ | 0.34 | -    | (Shindo, 1980) |
| Net recharge rate                                   | $R$    | 883   | mm/yr| (Honma et al., 1974; Japan Meteorological Agency, 2017) |

| Parameters obtained by calibration                  | Symbol | Value | Unit | Data source |
|-----------------------------------------------------|--------|-------|------|-------------|
| Residual saturation                                 | $s_r$  | 0.209 | -    | Calibrated by fitting van Genuchten model (van Genuchten, 1980) with measured data by Shindo (1980) |
| Pore size distribution index                        | $n$    | 2.3   | -    | Calibrated based on the measured groundwater table elevations |
| Horizontal hydraulic conductivity                   | $K_x$  | $1.3 \times 10^{-3}$ | m/s  | Calibrated based on the measured groundwater table elevations |

| Parameters obtained from typical literature values  | Symbol | Value | Unit | Data source |
|-----------------------------------------------------|--------|-------|------|-------------|
| Longitudinal dispersivity                            | $\alpha_L$ | 50    | m    | (Gelhar et al., 1992) |
| Transverse dispersivity                              | $\alpha_T$ | 5     | m    | (Gelhar et al., 1992) |
| Anisotropy ratio of hydraulic conductivity          | $K_x/K_s$ | 1     | -    | (Diersch, 2013; Vithanage et al., 2012b; Yu et al., 2016) |
| Freshwater concentration                             | $C_0$  | 0     | kg/m$^3$ | Calibrated based on the measured groundwater table elevations |
| Seawater concentration                               | $C_s$  | 35    | kg/m$^3$ | Calibrated based on the measured groundwater table elevations |
| Density ratio                                        | $\rho$ | 0.025 | -    | Calibrated based on the measured groundwater table elevations |
| Gravitational acceleration                           | $g$    | 9.8   | m/s$^2$ | Calibrated based on the measured groundwater table elevations |
| Dynamic viscosity                                    | $\mu$  | 0.001 | kg/(m·s) | Calibrated based on the measured groundwater table elevations |
| Molecular diffusion coefficient                      | $D_0$  | $1 \times 10^{-9}$ | m$^2$/s | Calibrated based on the measured groundwater table elevations |

Table 1 Summary of model parameters
increase in the later period. This was because the initially unsaturated soil medium beneath the inundation area was becoming fully saturated with seawater which prevented further seawater intrusion, and was also evidenced by the fact that the accumulated volume of the intruded seawater agrees with the total unsaturated void space of the soil beneath the inundation area (Figure 5d).

4.2 Aquifer recovery process after tsunami inundation

After the tsunami inundation of 15 m a.m.s.l., the intruded seawater gradually mixed with fresh groundwater (Figure 6a), leading to a maximum loss of freshwater resource of about $4.5 \times 10^6$ m$^3$ at about one year (Figure 6f), which was an striking volume compared with the annual water supply of

![](image.png)

**Figure 4** Comparison of measured and computed data: (a) the modeled saturation curve using the van Genuchten model (van Genuchten, 1980) based on the measured data by Shindo (1980); (b) spatial comparison of modeled and measured water table elevation; (c) the modeled groundwater table elevations using $K = 1.3 \times 10^{-3}$ m/s were compared against the measured data (in black) with the fluctuation ranges based on the historical records provided by the Niijima Office and by Aichi et al. (2011). The model results using $K = 1.3 \times 10^{-4}$ m/s and $K = 1.3 \times 10^{-2}$ m/s were in red and blue color, respectively.
3.7 × 10^5 m^3 on the island (Oshima Subprefecture of Tokyo, 2014). Here, freshwater resource refers to groundwater with a concentration lower than 0.33 kg/m^3 NaCl which is equivalent to the 0.2 kg/m^3 Cl^- standard set by Ministry of Health, Labor and Welfare (2015). After one year, the rainfall recharge continuously kept flushing the intruded seawater out through the west coast (Figure 6a), and the groundwater system was recovered to the pre-tsunami condition after eight years (Figure 6f) in our simulation case.

In comparison, under the extreme scenario of h_T = 20 m a.m.s.l. (Figure 6b), the intruded seawater traveled towards the east, and some public wells became not appropriate to provide drinking water due to their salinity to become over the 0.33 kg/m^3 NaCl standard. This extreme tsunami scenario caused a maximum loss of fresh groundwater resource of about 7.2 × 10^6 m^3, and the recovery required more than 18 years (Figure 6f). This distinct seawater intrusion pattern and flushing time (the time required for the loss of freshwater resources to be recovered to the pre-tsunami level in Figure 6f) were associated with two factors: (1) the tsunami of 20 m a.m.s.l. from the western coast traveled further inland and caused seawater intrusion to cross the groundwater divide and reached to the eastern part of the island where groundwater normally flowed eastwards (Figure 6e); (2) the dense seawater plume had the tendency to sink to the aquifer bottom and to move along the slopes of the bedrock surface, and hence,
Figure 6  The simulated aquifer recovery process after the tsunami of (a) 15 m a.m.s.l. and (b) 20 m a.m.s.l. under the condition of no pumping. Simulation results of pumping out the survived freshwater and the intruded seawater were shown in (c) and (d), respectively. In (e), flowlines show directions and remaining travel time of groundwater which discharges out to the sea at the normal quasi-steady state (before the tsunami). Flowlines were calculated through the entire 3D model domain including both unsaturated and saturated zones. Temporal changes of the loss of freshwater resource after tsunami for different simulation cases are shown in (f).
the concave down shape of the bedrock surface in the model may have facilitated dense seawater moving only westwards in the case of $h_T = 15$ m a.m.s.l., while both westwards and eastwards in the case of $h_T = 20$ m a.m.s.l. (Figure 7).

It was observed that the overall flushing time of the intruded seawater generally agreed with the groundwater travel time from the inundation zone all the way to the sea at the quasi-steady state condition. For example, the overall flushing time was about eight years after the tsunami of 15 m a.m.s.l. (Figure 6f), while the groundwater travel time was about 10 to 15 years from the inundation zone (Figure 6e). The recovery of the groundwater system after the tsunami of 20 m a.m.s.l. required a period of about 18 years (Figure 6f), and groundwater in the corresponding inundation zone at inland had a remaining travel time ranging from 15 to 20 years (Figure 6e). This is because, even though tsunami-induced seawater intrusion caused the rise of the water table and increased the groundwater salinity which significantly affected the groundwater flow conditions within the first year, after the first year, the direction and speed of groundwater flow were almost recovered to their pre-tsunami conditions which controlled the long-term flushing of the intruded seawater.

4.3 Effect of pumping out survived freshwater

According to our simulations, groundwater survived from seawater intrusion was found in the southeastern part of the aquifer even under the extreme scenario of 20 m a.m.s.l. tsunami (Figure 6b). Here, the feasibility of pumping this survived groundwater for post-disaster water supply was
numerically investigated. In this simulation, fresh groundwater was pumped from four wells located in the southeastern part of the island (Figure 6c) with a pumping rate of each well to be 253 m$^3$/d (note that the maximum capacity of wells was 300 m$^3$/d) so that the wells can provide the equivalent total amount of water supply as that before the disaster. Compared with the no-pumping condition (Figure 6b), this pumping behavior (Figure 6c) had very negligible impacts on the aquifer recovery process. Furthermore, this centralized pumping behavior did not produce any noticeable groundwater drawdown or seawater intrusion from the eastern coast, probably because the aquifer materials are highly permeable and because groundwater resources underneath the lava dome of the Mukaiyama Volcano (Figure 1) would supply enough amount of water to this pumping activity.

4.4 Effect of pumping out intruded seawater

To investigate the effect of pumping the intruded seawater out and subsequently discharging it into the sea for aquifer recovery, the pumping activity was set to be carried out at one tsunami-affected well that was located in the central area of the island (Figure 6d) as an additional simulation. The pumping rate was set to be 300 m$^3$/d which was the maximum pumping capacity of the well. Compared with the aquifer recovery only by natural rainfall recharge (Figure 6b), this pumping resulted in the reduction of the volume of seawater intrusion to the eastern half of the groundwater system (Figure 6d) and shortened the aquifer recovery period for about five years at maximum (Figure 6f).

5. Discussion

5.1 The volume of seawater intrusion controlled by unsaturated zone

In our simulation results, the seawater intrusion process became slowed down when the unsaturated zone beneath the inundation area became fully filled with the intruded seawater (Figure 5). This agrees with our previous 2D model of Niijima Island (Liu and Tokunaga, 2019), in which we argued that the unsaturated zone acted as an initial storage of the intruded seawater during the inundation. The maximum amount of seawater that could possibly infiltrate into a groundwater system was estimated by the total unsaturated space of the soil beneath the inundation area (e.g., Figure 5c). Thus, a coastal unconfined aquifer with a greater vertical extent of its unsaturated zone can, in principle, store a larger amount of infiltrated seawater. It suggests that, without conceptualization of the unsaturated zone, a numerical model is likely to underestimate the volume of seawater intrusion during the simulated tsunami. However, it should be noted that, in the case of low permeability aquifers where tsunami inundation would not necessarily fill the entire unsaturated zone, the flow and mass transport in the unsaturated zone may show more complicated 3D patterns, which could not be accurately captured by a 2D vertical model. Also, air compression may occur in the unsaturated zone during an inundation event over a large area, which could reduce the infiltration rate. For example, the air compression and subsequent air counterflow may reduce infiltration rates for heavy rainfall related infiltration processes (Kuang et al., 2013). Compared to a heavy rainfall event, tsunami inundation could intensify the air compression effect because the rapid inundation with considerable depths occurs nearly simultaneously over a large spatial extent. The establishment and dynamics of air compression would also require 3D simulations with two-phase flow processes in the unsaturated zone.

5.2 Infiltrated seawater movement controlled by groundwater flow and bedrock structures

Our simulations indicated that directions of post-tsunami seawater migration and flushing
time generally agreed with the pre-tsunami groundwater flow path and travel time, respectively (Figure 6e). This may imply that, depending on the relative position between the inundation area and the groundwater divide, seawater intrusion would affect groundwater quality not only in the tsunami inundation area but also in no-inundation areas. Therefore, obtaining general groundwater flow directions using field measurement techniques and numerical modeling can substantially assist to evaluate the vulnerability of groundwater resources to tsunami disasters. Moreover, knowing groundwater flow velocity and its travel time may provide rough estimations of seawater flushing time.

The modeling results showed that the intruded seawater had the tendency to sink to the aquifer bottom and migrated along the slopes of the bedrock surface, which may have contributed to the eastward movement of seawater in the case of $h_T=20$ m a.m.s.l. (Figures 6b and 7b). In this paper, the bedrock surface was inclined with a small slope (around 2 m over a horizontal distance of 100 m in average). It can be inferred that the transport of salt mass in an aquifer would be more strongly influenced by a much steeper bedrock surface than that in this paper. The concave down bedrock structure assumed in this paper was based on the interpretation of the electrical survey results by Shindo (1980), which may remain uncertain. In our previous 2D model (Liu & Tokunaga, 2019), a concave up bedrock setting would result in the retention of the seawater plume in the depression of bedrock surface and prolong the aquifer recovery process. Therefore, it is necessary to further confirm the bedrock condition of Nijjima Island. As for other unconfined aquifers in tsunami-prone areas, it is also important to have a clear image of the shape (e.g., concave or convex structures) of the bedrock surface.

5.3 Opportunities for Nijjima Island to cope with tsunami-induced seawater intrusion

According to the simulation results (Figure 6c), the southeastern part of the aquifer would very likely be survived from seawater intrusion caused by the anticipated tsunami, and the survived portion of the aquifer would have great potential to provide freshwater for the island in the post-tsunami recovery period. According to the interview with one officer of the local government of Nijjima Island, bottled drinking water has been reserved for the local residents with about 3 L water per person per day for 3-days emergencies. However, this 3 L of water is only for drinking purpose, while water demands for other daily activities such as washing and showering were not considered. Furthermore, this plan does not take into account the number of tourists who may be on the island at the time of disaster. The demands for freshwater could be much higher if the earthquake and tsunami occur in the peak tourist seasons. Utilizing those unpolluted groundwater resources could provide reliable water supply in terms of water quantity, quality, and operation cost on a long-term basis. Currently, groundwater is abstracted from the public wells by using electric pumps on Nijjima Island. However, after the 2011 Tohoku tsunami, it took a long time to restore the water supply systems due to a series of factors, including lack and delay of restoration resources, electricity blackout, damages to regional water-supply systems, liquefaction, etc. (Okamoto and Kuwata, 2012). Therefore, in order to ensure the pumping capacity immediately after the tsunami, backups of pumps, generators, fuels, and relevant equipment, should be prepared in advance.

Our simulations indicated that removing the intruded water could, to some extent, mitigate seawater intrusion (Figure 6d) and facilitate the aquifer recovery process (Figure 6f). However, this was achieved by intensive pumping operated with the maximum well production capacity for several years, which may not be a long-term feasible
solution. In fact, after the 2004 Indian Ocean tsunami, in some areas, local people initiated well cleaning activities including removal of sands, debris, and pumping saline water out, but it was proven to be ineffective for recovering polluted wells, sometimes even to prolong the salinity level in wells (Illangasekare et al., 2006; Vithanage et al., 2009) or to cause upconing of saltwater (Vilholth et al., 2005). Therefore, in the plan for coping with water shortages due to tsunami-induced seawater intrusion, activating and utilizing alternative water resources (e.g., unaffected fresh groundwater) may be prioritized than rehabilitating the polluted aquifer.

5.4 Limitations and uncertainties

Our 3D model adopted a relatively large grid size of 60 m with a relatively coarse vertical discretization of five layers. Therefore, the simulations of the mass concentration distribution and flow processes of the intruded seawater at meter-scale resolutions may have large uncertainties, and thus, relevant interpretations should be avoided in this paper. The overall seawater intrusion process (Figure 6) and hundred-meter-scale seawater transport (e.g., the eastward movement of seawater in the case of \( h_T = 20 \) m a.m.s.l. in Figures 6b and 7b), however, were well captured by the model. It is thus still reasonable to argue about the key roles of the unsaturated zone (Section 5.1) and groundwater flow (Section 5.2) by using our simulation results. Also, due to the limitation of the large grid size, this 3D model could not simulate fingering patterns of seawater intrusion in the saturated zone. Previous numerical simulations (Vithanage et al., 2012b) and laboratory experiments (Illangasekare et al., 2006; Vithanage et al., 2012a) of tsunami-induced seawater intrusion indicated that fingering could facilitate the speed of vertical mixing of intruded seawater with freshwater. Hence, in this paper, the duration for the intruded seawater to reach the aquifer bottom was likely to be overestimated, and the vertical extent of the contamination be underestimated, while the horizontal extent of the simulated seawater intrusion may not be strongly affected. The vertical transport of seawater in a short-term period (days and months) after the tsunami is thus not discussed in this paper. Nevertheless, the descending trend of the seawater plume along the bedrock surface over the long-term (years) aquifer recovery period was well preserved in the model (e.g., Figure 7), which was sufficient for discussing the effect of bedrock structures in Section 5.2.

Hydraulic conductivity of the model was manually calibrated by using the measured data of water table levels and assuming a homogeneous aquifer. Due to the complexity of the governing equations for solving density-driven flow and mass transport in unsaturated-saturated media, and scarcity of the field data, calibration of hydraulic conductivity distributions using automatic parameter estimation codes such as PEST (Doherty, 2016) was not performed. The limitation of the calibration process may have resulted in uncertainties of the simulated flushing time and the simulated position of seawater-freshwater mixing zones. Hence, accurately predicting flushing time and locating seawater-freshwater interactions in detail were excluded in this paper.

Comprehensive sensitivity analysis with respect to boundary conditions and parameters was not performed. For example, a constant tsunami elevation was assumed over the inundation period, which was likely to overestimate the amount of seawater intrusion during an actual tsunami which should have temporal variations in elevation. Our simulations indicated an intruded seawater volume with a magnitude of \( 10^6 \) m\(^3\) (Figure 5c), which should be interpreted as an upper bound of the total amount of seawater that could possibly enter the groundwater system in Niijima Island during the actual tsunami inundation event. In addition, the tsunami inundation elevation was assumed to be spatially homogenous in our simulations. However, in a real tsunami event, spatially varied inundation
elevations would create horizontal hydraulic gradients that can potentially enhance circulation of fresh groundwater and intruded seawater, which should be carefully investigated in future research. Also, the pumping rates in the simulations were set to be high, i.e., equivalent amount of pre-tsunami water supply (Figure 6c) and maximum well production (Figure 6d), yet such setting was reasonable to argue that the survived groundwater could potentially supply enough freshwater after the tsunami and that pumping seawater out to speed up long-term aquifer recovery may not be practical (Section 5.3) for the case of Niijima Island. However, for the coastal aquifers that have different hydrogeological properties (e.g. a much lower hydraulic conductivity) from that of Niijima Island, the efficiency of the pumping activities to supply freshwater or mitigating seawater intrusion, and the risks of causing groundwater drawdown or inducing seawater intrusion from the coast, are still unclear, which should be investigated in future research.

Though the model was limited with respect to the grid size, the calibration process, and the number of scenarios, the 3D model showed a promising capacity to assess the most vulnerable part of the groundwater system and to evaluate the post-disaster pumping behaviors. 3D numerical simulations with a much finer grid size, a more comprehensive calibration strategy, and a wide range of sensitivity analysis can be realized by employing the available supercomputer systems, e.g., the Earth Simulator (Habata et al., 2003) and the K Computer (Miyazaki et al., 2012).

6. Conclusions

This study numerically simulated tsunami-induced seawater intrusion and aquifer recovery processes in a 3D model of Niijima Island, Japan, under future Nankai earthquake and tsunami scenario. The main findings include:

(1) The total unsaturated void space of the soil beneath the inundation area controlled the maximum volume of seawater that could possibly infiltrate into a coastal unconfined aquifer. An aquifer with a thicker unsaturated zone would be more vulnerable due to storing a larger amount of seawater.

(2) Directions of seawater movements in the saturated zone and flushing time after the tsunami were controlled by the 3D groundwater flow and bedrock structures. The intruded seawater may migrate to and affect other uninundated areas under certain conditions of groundwater flow and bedrock structures and prolong the aquifer recovery time.

(3) Some groundwater in the southeastern part of Niijima Island was survived from the simulated seawater intrusion, and this survived portion of groundwater resource had the potential to provide post-disaster water supply in an equivalent amount of the pre-tsunami level \((3.7 \times 10^5 \text{ m}^3/\text{year})\), and at the same time, did not worsen the recovery process.

(4) Pumping the intruded seawater out could shorten the simulated aquifer recovery process. However, this solution may not be practical due to the cost of maintaining intensive pumping over a long-term period.

Based on these findings, we can generally recommend that:

(1) Consideration of the unsaturated zone and reliable 3D information on bedrock structures and pre-tsunami groundwater flow conditions are essential for assessing tsunami-induced seawater intrusion and flushing time.

(2) Utilization of survived groundwater for post-disaster water supply can have great potential and is worth being considered in disaster preparedness. Yet, the efficiency and potential risks should be carefully evaluated according to site-specific hydrogeological conditions.

The 3D model can be further improved with respect to its grid size, calibration process, and
scenario settings, to achieve better predictions and more comprehensive analysis.

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**References**

Aichi, M., Shiokari, M., and Tokunaga, T. (2011): A new analytical solution of water table response to tidal fluctuations and its application to estimate aquifer properties at the Niijima Island, Japan (in Japanese with English abstract). Journal of Groundwater Hydrology, 53(3), 249–265.

Alsumaiei, A. A., and Bailey, R. T. (2018): Quantifying threats to groundwater resources in the Republic of Maldives Part II: Recovery from tsunami marine overwash events. Hydrological Processes, 32(9), 1154–1165.

Cabinet Office of Japan. (2011): Tsunami height and distribution of seismic intensity from the Huge Nankai Trough Earthquake (in Japanese). http://www.bousai.go.jp/jishin/nankai/taisaku/pdf/1_1.pdf (Inspected on October 19, 2019)

Central Disaster Management Council. (2014): Nankai Trough Earthquake disaster prevention countermeasures promotion area (in Japanese). http://www.bousai.go.jp/jishin/nankai/pdf/nankaitrough_keikaku.pdf (Inspected on October 19, 2019)

Construction Section of Niijima Village. (2001): Niijima Village Specific Environment Conservation, Public Sewage System Design and Geological Survey Report.

Diersch, H. J. G. (2013): FEFLOW: Finite element modeling of flow, mass and heat transport in porous and fractured media: Springer, Berlin, Heidelberg.

Doherty, J. (2016): PEST model-independent parameter estimation user manual (Vol. 3338): Watermark Numerical Computing, Brisbane, Australia.

Gelhar, L. W., Welty, C., and Rehfeldt, K. R. (1992): A critical review of data on field-scale dispersion in aquifers. Water Resources Research, 28(7), 1955–1974.

Habata, S., Yokokawa, M., and Kitawaki, S. (2003): The earth simulator system. NEC Research and Development, 44(1), 21–26.

Honma, J., Hagiwara, G., and Shindo, S. (1974): Observation and analysis of the ground water in Niijima Island (in Japanese). Proceedings of the Japanese Society of Civil Engineers, 1974(222), 79–92.

Illangasekare, T., Tyler, S. W., Clement, T. P., Villholth, K. G., Perera, A. P. G. R. L., Obeysekera, J., et al. (2006): Impacts of the 2004 tsunami on groundwater resources in Sri Lanka. Water Resources Research, 42(5), W05201.

Isobe, I., and Nakashima, R. (2001): Molluscan fossil found from pyroclastic of the Niijima volcano and its basement rocks (in Japanese with English abstract). Bulletin of the Geological Survey of Japan, 52(1), 41–48.

Isshiki, N. (1987): Geology of the Niijima Island with Geological Sheet Map at 1:50,000 (in Japanese). Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Tokyo.

Japan Meteorological Agency. (2017): Historical Weather Data (in Japanese). http://www.data.jma.go.jp/ (Inspected on October 19, 2019)

Koyaguchi, T. (1986): Evidence for two-stage mixing in magmatic inclusions and rhyolitic lava domes on Niijima Island, Japan. Journal of Volcanology and Geothermal Research, 29(1–4), 71–98.

Kuang, X., Jiao, J. J., and Li, H. (2013): Review on airflow in unsaturated zones induced by natural forcings. Water Resources Research, 49(10), 6137–6165.

Liu, J., Tokunaga, T. (2019): Future Risks of Tsunami-Induced Seawater Intrusion Into Unconfined Coastal Aquifers: Insights From Numerical Simulations at Niijima Island, Japan. Water Resources Research, 55, doi: 10.1029/2019WR025386.
Ministry of Agriculture, Forestry and Fisheries. (2011): The Damage and Measure of The 2011 off the Pacific coast of Tohoku Earthquake. http://www.maff.go.jp/e/quake/press_110313-1.html (Inspected on October 19, 2019)

Ministry of Health, Labor and Welfare. (2015): Drinking Water Quality Standards (in Japanese). http://www.mhlw.go.jp/stf/seisakunitsuite/bunya/topics/bukyoku/kenkou/suido/kijun/kijunchi.html (Inspected on October 19, 2019)

Ministry of Land, Infrastructure, Transport and Tourism. (2015): National Land Numerical Information (Elevation Data) (in Japanese). http://nlftp.mlit.go.jp/ksj/old/old_datalist.html (Inspected on October 19, 2019)

Miyazaki, H., Kusano, Y., Shinjou, N., Shojo, F., Yokokawa, M., and Watanabe, T. (2012): Overview of the K computer system. Fujitsu Scientific & Technical Journal, 48(3), 302–309.

Mori, K., Takahashi, T., Okaniwa, N., Shibasaki, N., and Ouchi, T. (2012): Change in groundwater environment caused by the 2011 off the Pacific Coast of Tohoku Earthquake in the southern part of Sendai Plain (in Japanese with English abstract). Journal of Groundwater Hydrology, 54(1), 11–23.

Nakagawa, K., Wada, N., Kaihotsu, I., Tokunaga, T., Kondo, A., Onodera, S., et al. (2013): Effect of Tsunami induced by the 2011 off the Pacific coast of Tohoku Earthquake on groundwater (in Japanese). Journal of Groundwater Hydrology, 55(1), 21–28.

Nakaoka, R., and Suzuki-Kamata, K. (2015): Rock-magnetic evidence for the low-temperature emplacement of the Habushiura pyroclastic density current, Niijima Island, Japan. Geological Society, London, Special Publications, 396(1), 51–66.

Niijima Village Office. (2015): Introduction of Niijima Island.

Okamoto, T., and Kuwata, Y. (2012): Influence to Water Outage due to Damage to Regional Water Supply during the 2011 off the Pacific Coast of Tohoku Earthquake. Proceedings of the 15th World Conference on Earthquake Engineering.

Oshima Subprefecture of Tokyo. (2014): Overview of administration.

Shindo, S. (1980): Research on Groundwater Balance on Volcanic Islands: Examples of Izu Islands (in Japanese).

Shindo, S. (1992): Problems related to the development and conservation of groundwater in volcanic islands: The case studies of Izu Islands (in Japanese). Journal of Groundwater Hydrology, 34(3), 137–152.

Sivakumar, C., and Elango, L. (2010): Application of solute transport modeling to study tsunami induced aquifer salinity in India. Journal of Environmental Informatics, 15(1), 33–41.

Tokyo Disaster Management Council. (2013): Report of Estimations of Damage in Tokyo by Nankai Earthquake (in Japanese). https://www.bousai.metro.tokyo.lg.jp/taisaku/torikumi/1000902/1000402.html (Inspected on October 19, 2019)

United Nations Office for Disaster Risk Reduction (UNISDR). (2009): Risk and poverty in a changing climate: Invest today for a safer tomorrow. https://www.preventionweb.net/english/hyogo/gar/report/index.php?id=9413 (Inspected on October 19, 2019)

Vacher, H. (1988): Dupuit-Ghyben-Herzberg analysis of strip-island lenses. Geological Society of America Bulletin, 100(4), 580–591.

van Genuchten, M. T. (1980): A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44(5), 892–898.

Villholth, K. G., Amerasinghe, P., Jeyakumar, P., Panabokke, C., Woolley, O., Weerasinghe, M., et al. (2005): Tsunami impacts on shallow groundwater and associated water supply on the East Coast of Sri Lanka. http://s3-us-west-2.amazonaws.com/ucldc-nuxeo-ref-media/464e0d92-2e21-4211-a0dd-b10a9d45327c (Inspected on October 19, 2019)

Villholth, K. G., and Neupane, B. (2011): Tsunamis as Long-Term Hazards to Coastal Groundwater Resources and Associated Water Supplies. In Tsunami: A growing disaster (pp. 19): InTech.

Violette, S., Boulicot, G., and Gorelick, S. M. (2009): Tsunami-induced groundwater salinization in southeastern India. Comptes Rendus Geoscience,
341(4), 339–346.
Vithanage, M., Engesgaard, P., Jensen, K. H., Illangasekare, T. H., and Obeysekera, J. (2012a): Laboratory investigations of the effects of geologic heterogeneity on groundwater salinization and flush-out times from a tsunami-like event. Journal of Contaminant Hydrology, 136–137, 10–24.

Vithanage, M., Engesgaard, P., Villholth, K. G., and Jensen, K. H. (2012b): The effects of the 2004 tsunami on a coastal aquifer in Sri Lanka. Ground Water, 50(5), 704–714.

Vithanage, M., Villholth, K. G., Mahatantila, K., Engesgaard, P., and Jensen, K. H. (2009): Effect of well cleaning and pumping on groundwater quality of a tsunami-affected coastal aquifer in eastern Sri Lanka. Water Resources Research, 45(7), W07501.

Voss, C. I., and Souza, W. R. (1987): Variable density flow and solute transport simulation of regional aquifers containing a narrow freshwater-saltwater transition zone. Water Resources Research, 23(10), 1851–1866.

Yu, X., Yang, J., Graf, T., Koneshloo, M., O’Neal, M. A., and Michael, H. A. (2016): Impact of topography on groundwater salinization due to ocean surge inundation. Water Resources Research, 52(8), 5794–5812.

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