Impacts of sea-level rise on groundwater environment in coastal areas: Laboratory experiments, numerical analyses, and a case study in Turkey

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Introduction

According to the third assessment report released in January, 2001 by the Intergovernmental Panel on Climate Change (IPCC,2001), global average sea-level is projected to rise by 9 to 88 cm between 1990 and 2100. The impacts of sea-level rise are complex both Physically and socio-economically. Sea-water intrusion into fresh water aquifers in deltaic areas is however one of the major impacts of the sea -level rise.

To assess impacts of the sea-level rise on saltwater intrusion, field studies have been performed in the Sayhan River Delta along the Mediterranean sea, Turkey, with collaboration of Turkish researchers as a part of an integrated study on "Impact of climate changes on agricultural production system in the arid region" carried out by Research Institute for Humanity and Nature. Recent investigation revealed that groundwater table is less then 5m deep from the surface in the lower half of the delta. It means that the sea-level rise can cause severe water logging and salt accumulation in low land areas. **Table 1** shows measured electric conductivity (μS/cm) of waters in the area. Measured EC values indicate that EC values of the Akyatan Lagoon close to the Mediterranean is almost the double of the sea water and that the condensation of salt has been taking place in the lagoon.

On the other hand, the Japanese archipelago is surrounded by sea and important socio-economic activities concentrate in areas below sea-level. The sea -level rise can not only enhance saltwater intrusion into coastal aquifers but also force us to keep draining inland water induced in low land areas below sea level. Most of the mega cities in Japan have subsided areas due to the past, excessive withdrawal of groundwater. Actually, 862 km2 of lands in Japan, inhabited by 2 million people, lies below high-tide sea level. In the low lying delta of Tokyo, suffering from historical land subsidence, outer dykes of 4.6-8.0 m high and inner dykes of 3.0 m high have been constructed to protect inland area of 124 km2 from storm surges and excess water is kept drained to control inland surface-water level.

The impacts of the sea-level rise on coastal groundwater systems and the effects of conservational measures were investigated by conducting laboratory

Table 1 Electric conductivitiy values measured in Nov. 2003 and Nov. 2004

Classification [ ]: number of sample		Electric conductivity (μs/cm) (mean)	(max)	(min)	Note
Groundwater	[13]	837	2,733	423	max value is located in the north side of Tuz lagoon.
Akyatan Lagoon (deep part)	[7]	100,386	104,300	94,700	
Akyatan Lagoon (other part)	[7]	78,229	99,900	60,100	
Mediterranean Sea(shore line)	[3]	57,500	58,400	56,100	
Other (Riv., Irrigation)	[3]	406	488	357	

experiments contained with glass-beads. Laboratory experiments with an inclined surface which allow surface water ponding were conducted. An impermeable barrier was then installed inside of the domain to set back salt water. The effects of barrier walls and the drainage of seeped-out inland water for preventing inundation were then investigated.

We further developed a nnumerical simulation technique, SIFEC (Salt-water Intrusion by Finite Elements and Characteristics), based on the coupling of Galerkin-finite element method for density-dependent flow and the method of characteristics for mass transport, which enables its application to areas with inclined land surfaces by allowing the handling of surface water. Results of the experiments were used to validate the numerical model.

Governing Equations and Model Characteristics

Within saturated-unsaturated porous media, the governing equation for flow of water with variable density is given by

$$\rho(SS_s\frac{\partial h}{\partial t}+C_s\frac{\partial h}{\partial t})+n_pS\frac{\partial \rho}{\partial t}=\nabla\bullet\{\rho K\nabla(h+\frac{\rho z}{\rho_f})\} \qquad (1)$$

where ρsC and fρ are the density of salt water and fresh water, is the degree of saturation, is the specific storage, is the hydraulic head in terms of fresh water, is the soil water capacity, is the porosity, *SsShnpK* is the hydraulic conductivbity, and z is the upward vertical coordinate.

When density dependent flow in coastal aquifers is described, we can define relative salt concentration as c

$$c=(\rho-\rho_f)/(\rho_s-\rho_f) \qquad (2)$$

where sρ is the density of sea water.

The governing equation for transport of conservative mass in porous media is given by

$$\nabla\cdot D\nabla c-\mathbf{v}\cdot\nabla c=\frac{\partial c}{\partial t} \qquad (3)$$

where is the pore velocity vector and is the dispersion coefficient. Boundary conditions for density-dependent flow in saturated-unsaturated media is given in **Figure 1** while boundary conditions for mass transport isgiven in **Figure 2**.

A standard Galerkin-finite element method can be applied to solve Eq.(1) , which procedure are referred in ordinary text books and omitted here. With respect to numerical methods for solving Eq.(3), there are various variations to deal with numerical oscillation and numerical dispersion.

The method of characteristics proposed by Garder et al. (1964) can improve the accuracy of convection term while dispersion term is solved separately by using finite difference methods. Eulerian-Lagrangian schemes proposed by Neuman (1984) are similar techniques.

According to Garder et al., Eq.(3) is equivalent to the following set of ordinary differential equations.

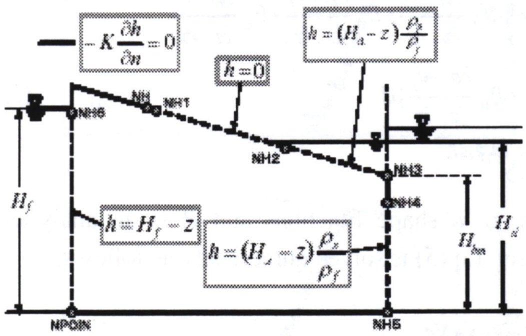

Figure 1 Boundary conditions for density dependent flow equation.

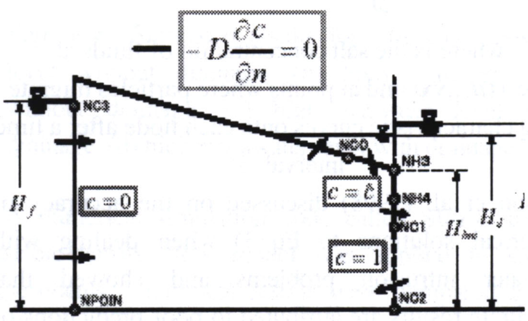

Figure 2 Boundary conditions for mass transport equation.

$$\frac{dc}{dt} = \nabla \cdot (D \nabla c) \tag{4}$$

$$\frac{d\mathbf{x}}{dt} = \mathbf{v} \tag{5}$$

We developed a numerical scheme for solving Eq.(3) called SIFEC (Saltwater Intrusion by Finite Elements and Characteristics), where the dispersion term is solved by the Galerkin finite element method and the convection term by the method of characteristics.

Application of the Galerkin finite element method to Eq.(4) leads to

$$[F]\{c\} + [G]\{\frac{dc}{dt}\} = \{0\} \tag{6}$$

where

$$F_{ij} = \iint_R [D_{xx} \frac{\partial \phi_i}{\partial x}\frac{\partial \phi_j}{\partial x} + D_{xz}\frac{\partial \phi_i}{\partial x}\frac{\partial \phi_j}{\partial z} + D_{zx}\frac{\partial \phi_i}{\partial z}\frac{\partial \phi_j}{\partial x} + D_{zz}\frac{\partial \phi_i}{\partial z}\frac{\partial \phi_j}{\partial z}]dR \tag{7}$$

$$G_{ij} = \iint_R \phi_i \phi_j dR$$

where φ is shape functions and R is an analytical domain. Eq.(5) is solved numerically as follows,

$$\frac{dc}{dt} \equiv \frac{\partial c}{\partial t} + \mathbf{v} \bullet \nabla c = \frac{c(\mathbf{x}, t+\Delta t) - c(\mathbf{x}, t)}{\Delta t} + \frac{1}{2}\{\frac{c(\mathbf{x}, t) - c(\mathbf{x} - \mathbf{v}\Delta t, t)}{\Delta t} + \frac{c(\mathbf{x}, t+\Delta t) - c(\mathbf{x} - \mathbf{v}\Delta t, t+\Delta t)}{\Delta t}\} \tag{8}$$

where is the salt concentration of fluids at time),(*ttc*..**vx***t* and at points where particles migrate along characteristic curves onto each node after a time interval . *t*.

Benson et al. (1998) discussed on the accuracy of numerical solutions to Eq.(3) when dealing with saltwater intrusion problems and showed that inaccurate results are attributed to poor predictions of velocity vectors in a transition zone and resultant poor interpolations of concentration for moving particles due to drastic changes in the velocity vector in the transition zone. To improve accuracy for interpolating concentrations in solving the convection equation, a single-step reverse particle tracking is used in conjunction with a bi-quadratic interpolation scheme.

Results of Laboratory Experiments and Numerical Simulations

Figure 3 shows the results of the experiments with inclined surface at equilibrium stages, in which stream lines of fresh water are also drawn by solid lines. When boundary salt-water level was low ①, inundation was not severe compared to high salt-water level ②. In both cases, fresh water seeped out along the inclined surface, dived down along impervious dike foundation, and finally discharged to the right boundary. When the level of seeped-out water along the inclined seepage face was lowered by drainage ③, the salt water intrusion was strongly enforced and the salt water seeped out through the inclined surface. When a barrier wall of 250 mm deep was installed ④, the salt water intrusion was reduced but at the cost of inland inundation.

These experiments reveal that the sea-level rise causes the acceleration of salt-water intrusion in coastal aquifers and the inundation of low-lying areas, and that impervious barriers are effective to prevent the salt water intrusion but this time at the expense of inundation.

Some results of these experiments were simulated using SIFEC. Simulated results are shown in **Figure 3**, where (a)~(d) correspond to ①~④ of **Figure 4**. Contour lines of relative salt concentration, 0.1, 0.5, 0.9, are drawn from the left to the right, respetively and arrows show velocity vectors. Drastic changes are observed in the direction of velocity vector near the toe of saltwater-freshwater interface. Since transition zones seemed very narrow, saltwater-freshwater interfaces were observed in each case visually and are also shown in Figure 5 by symbols.

Conclusions

Laboratory experiments were performed to investigate impacts of sea-level rise on salt water intrusion into coastal aquifers and the effect of barrier walls. It was

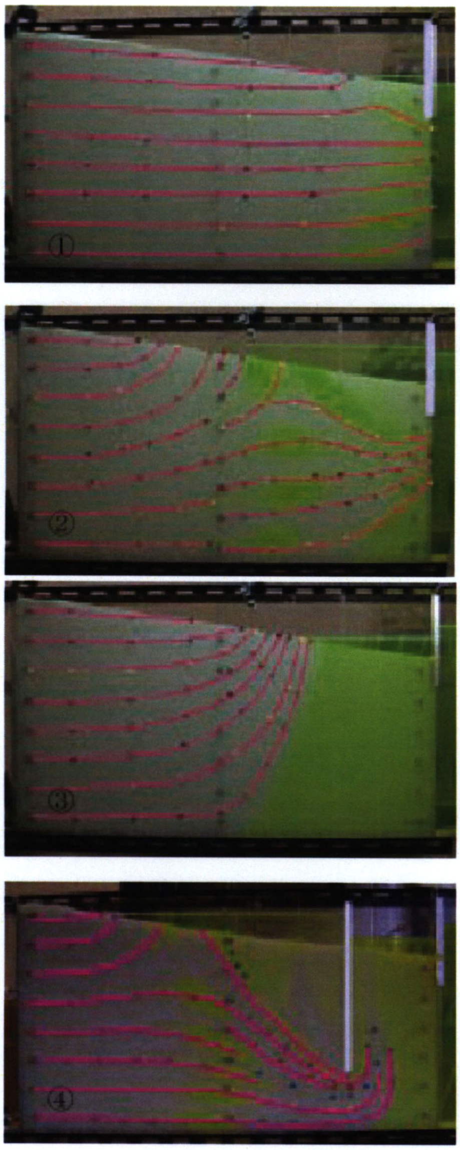

Figure 3 Experimental results for: ①lowsea water level without drainage, ②highsea water level without drainage, ③highsea water level with drainage, ④high seawater level with drainage and a barrier

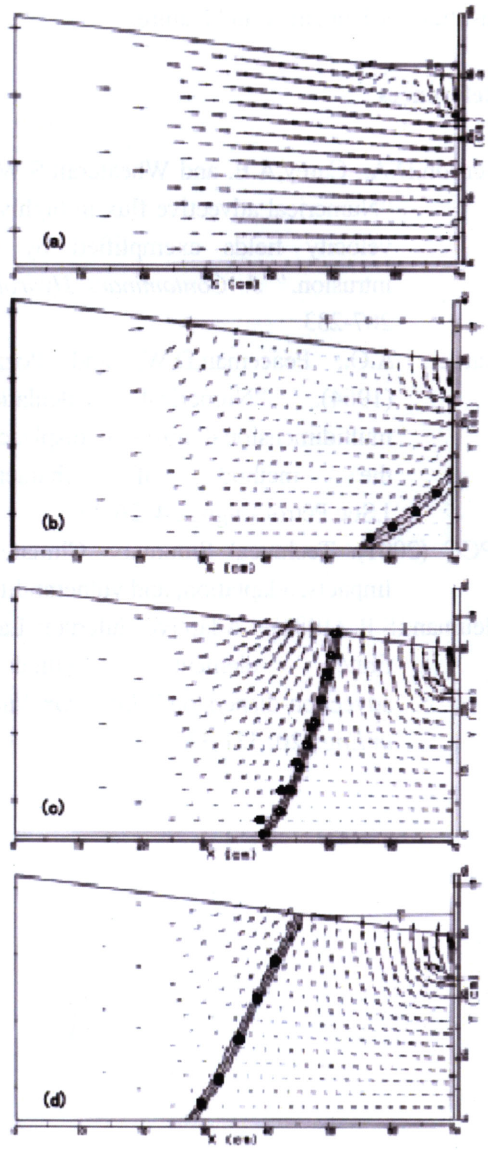

Figure 4 Simulated results for : (a) low seawater level without drainage, (b) high seawater level without drainage, (c) high seawater level with drainage, (d) higher seawater level with drainage.

revealed from these experiments that the reinforcement of dike may prevent storm surges but cannot prevent salt water intrusion and water logging in lowland area. Drainage of excess surface water may further enhance salt water intrusion. Installation of barrier walls can prevent salt water intrusion to some extent but at the cost of excess surface water.

A numerical simulation code called SIFEC for a variable-density flow model was applied to some experiments. Numerical results were compared quite well with the experimental results.

Acknowledges

This study was financially supported by Research Institute for Humanity and Nature.

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