Impact of a water diversion project on the groundwater environment of Xiamen Island

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Abstract The water in the Yuandang Lake of Xiamen Island has been seriously polluted by human activities. In order to alleviate water pollution, two schemes have been proposed to divert seawater, one east-to-west and the other west-to-east, both dividing Xiamen Island and posing great risks to the groundwater. From 2002, water has been diverted from west to east, but it has not significantly improved the lake-water quality; the east to west water diversion theme is under planning. In this study, a groundwater model was set up to further understand the local groundwater–seawater interaction, and to assess the risk of seawater intrusion. The finite-element method was adopted to analyse groundwater flow and seawater transport. We conclude that under annual average precipitation, seawater invasion will become stable one year after the project is completed. In low flow years, the seawater fringe will be close to the lakeside, resulting in seawater recharging the lake water through groundwater flow.

Key words water diversion project; seawater intrusion; finite element method; Xiamen Island

INTRODUCTION

The study of seawater invasion and its effects on the groundwater environment is attracting more and more researchers. Seawater intrusion simulation has advanced from the theory to experiment, and it is developing into the process of numerical simulation. Badon Ghyben and Herzberg brought forward the fresh–salt water interface theory, and they proposed the famous formula of Ghyben-Herzberg for freshwater–saltwater interface calculation in 1889 and 1901, separately. So we are already more than 100 years into the study of seawater intrusion. Custodio comprehensively analysed the seawater invasion problem in his book *Groundwater Problems in Coastal Areas,* and this work established the foundation for the study of the fresh–salt water interface. In the past 10 years, with the enhancement of computing capability, numerical simulation has become the mainstream research approach. Zheng (1994) proposed the of HMOC (Hybrid method of characteristic) model for the calculation of conversion weight by using a three-dimensional finite-difference method. Yuan (2001) recommend a mathematical model for evaluation of the after effects of seawater invasion and its prevention, and he applied his method in the area of Shandong Province in China.

Xiamen Island is located in the southeast of China (Fig. 1). In recent years, the economy of Xiamen Island has developed rapidly, but the ecological environment in this island has deteriorated, and this has caused the degradation of the ecosystem service. The most serious problem is water pollution, such the pollution of the main water body, Yuandang Lake and Songbai Lake. In order to solve this problem, and restore the ecosystem service function of the waterfront area, the possibility of using seawater to dilute the sewages was considered. But this scheme may cause seawater intrusion to the groundwater along the project line. In order to understand the extent of the seawater intrusion, a Finite Element Method (FEM) is used to aid decision-making. First, we analyse the hydrological and geological condition of the study area. Second, through a mathematical analogue, we analyse the movement of the phreatic water and transport of salt, and thus understand the movement of groundwater and solutes of the island. Third, regarding the problem of the water diversion, we analyse its effects on the groundwater environment of the island.

WATER DIVERSION PROJECT FROM EAST TO WEST OF XIAMEN ISLAND

The total length of the water diversion project from the east to west of Xiamen Island is planned to be about 14.7 km, which begins from the tide-receive mouth in the East Sea area, and ends at the point of the west dyke located at the Yuandang Lake (Fig. 1). The conduit consists of open ditches and culverts, and results in a 4-km long seawater canal in the east part of Xiamen Island which directs flow to the geometric centre of the island, and then connects with the Jiangtou Park lake. The flow of diversion water will be 60–90 m^3/s, and a total of 1 200 000–1 340 000 m^3/d after the flood tide twice a day. This can completely improve the water quality of Yuandang Lake and the surrounding environment, and build up a travelling route and environmental protection demonstration site. After this project, the tourism and leisure places and inhabited region along the two canal sides will be constructed, and this will stimulate the economic development of this region.

Fig. 1 The location of Xiamen Island and the project position.

WATER BODIES WITHIN THE STUDY AREA

There are two main water bodies along the line of the water diversion project: Yuandang Lake and Songbai Lake (Fig. 1). Improvement of water quality is one of the main purposes of this project. There are 1.5 km^2 of water in Yuandang Lake, and the drainage area is 37.1 km^2, which accounts for 30% of this area of Xiamen Island. Yundang Lake was originally a harbour in the West Sea area of Xiamen, and it was later enclosed and cultivated. It is now composed of a building area and by a saltwater lake. Yuandang Lake may be divided into three parts: the Trunk canal (0.151 km^2), the inland lake (0.518 km^2), and the outer lake (0.820 km^2). The outer lake links the West Sea area (300 m away) with a tidal culvert. Usually, the water level can be adjusted between 0.00 and 0.70 m a.m.s.l. (above mean sea level) by tidewater coming from the West Sea area. The volume of Yuandang Lake is 3.03×10^6 m^3 when the lake water level is 0.00 m a.m.s.l. Currently, Yuandang Lake is not only a landscape feature at the centre of Xiamen island, but also has an important role in flood prevention of the urban area of Xiamen (about 37.1 km^2).

Songbai Lake lies upstream of Yuandang Lake, and the coverage of water is only 0.11 km^2, with a capacity of 160×10^3 m^3. Though Songbai Lake and Yundang Lake are both fed through the trunk canal, the lake water level of the Songbai is 0.7 m higher than that of Yuandang Lake because of the topography. Thus, the water of Songbai Lake is difficult to exchange with Yuandang Lake. Three pump stations were set up to pump seawater out from Yuandang Lake and divert it to Songbai Lake at a rate of 90×10^3 m^3/d, which thus formed an artificial "little circulation" exchange system between the water bodies.

The source area for the project, Zhongzai Gulf, is currently isolated from the outer seawater by a coastal dyke. After the water diversion project is finished, the sea wall will be removed and Zhongzai Bay will be linked with the outer seawater.

The introduction of seawater may have strong influences on the water quality and quantity of the groundwater and surface water near the project. In order to study the process of seawater invasion and quantify its extent when the water diversion project is completed, we adopted a model that used the Finite Element Method.

GEOLOGICAL AND HYDROLOGICAL CONDITIONS AND THEIR CONCEPTUALIZATION

In order to simulate the influence (especially on the project line) of the seawater diversion project from east to west, we simplified the geological and hydrological conditions, and on the basis of the simplification we have simulated the flow of freshwater and seawater.

The hydrogeological setting was divided into the following three zones based on the topography and water storage properties: diluvian deposits (including the marine deposit area), sedimentary deposits, and bedrock (Fig. 2). With pumping experiments, the unit-drawdown pumping rates of the three zones were determined to be 0.085–5.019, 0.05–0.561 and 0.004–0.161 L s^{-1} m^{-1} respectively. Through the experimental data we know that the diluvian area contains relatively abundant water and the sedimentary deposits and bedrock area contain very little water.

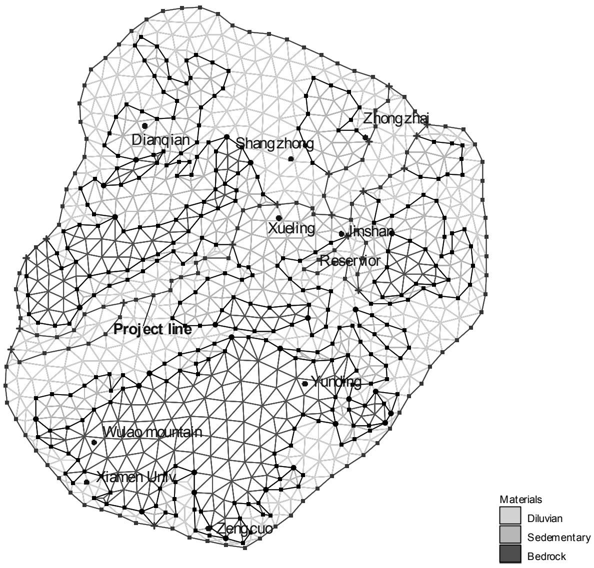

Fig. 2 The geological and hydrological condition conceptualization of Xiamen Island.

The groundwater supply, movement process, and discharge and their relationship are relatively simple in the study area. The precipitation (Table 1) is the major source of supply, although in some locations groundwater gets supply from surface water bodies. Supply and discharge may also occur between different water-contained terraces.

Groundwater flow in Xiamen Island may be described as a three-dimensional unconfined aquifer system. As a simplification, the peripheral sea area is considered to be a constant-head boundary. Groundwater in the coastal regions is in close contact with seawater, and experiences both recharge from and discharge to the sea.

Table 1 Average annual precipitation adopted in the simulation (1952–1990).

Month	1	2	3	4	5	6	7	8	9	10	11	12
Precipitation (mm)	36.3	74.2	91.6	139.5	162.6	191.6	147.0	148.7	115.1	25.9	32.5	23.2
Intensity (mm/d)	4.4	6.5	6.6	10.1	10.0	1.9	14.7	13.3	13.1	6.5	6.9	4.6

NUMERICAL SIMULATION OF SEAWATER INVASION

Based on the mass conservation and continuity equation, we have the three-dimensional saturated groundwater-flow equation:

$$\frac{\rho}{\rho_0}F\frac{\partial h}{\partial t}=\nabla\cdot\left[K\cdot\left(\nabla h+\frac{\rho}{\rho_0}\nabla z\right)\right]+\frac{\rho^*}{\rho_0}q \qquad (1)$$

where F is the coefficient of storage, h is hydraulic head, t is time, K is the conductivity tensor, q is the source/sink flow rate, ρ is the water density at a concentration of C, ρ_0 is the density of water , and ρ^* is the density of source water. Similarly, the salt transport equation can be written as:

$$\theta \frac{\partial C}{\partial t} + \rho_b \frac{\partial S}{\partial t} + V \cdot \nabla C - \nabla \cdot (\theta D \cdot \nabla C) = -\left(\alpha' \frac{\partial h}{\partial t} + \lambda\right)(\theta C + \rho_b S) - (\theta K_w C + \rho_b K_s S) + m - \frac{\rho^*}{\rho} qC + \left(F \frac{\partial h}{\partial t} + \frac{\rho_0}{\rho} V \cdot \nabla\left(\frac{\rho}{\rho_0}\right) - \frac{\partial \theta}{\partial t}\right) C \quad (2)$$

where θ is the water content, ρ_b is the density of the porous media, C is the solute concentration, S is the density of absorption, V is the permeability velocity, D is the dispersion coefficient tensor, α' is the compression ratio of the porous medium, λ is the constant of attenuation, m is the mass of injected water, q is the flux of infused water, K_w is the coefficient of degradation of the dissolved phase, and K_s is the coefficient of degradation of absorption phase. The boundary conditions can be written as:

$$h = h_1(x, y, z, t) \quad (x, y, z) \in \Gamma_1 \quad (3)$$

$$C = C_1(x, y, z, t) \quad (x, y, z) \in \Gamma_2 \quad (4)$$

where h_1 and C_1 are known functions relating to spatial and temporal factors, and Γ_1 and Γ_2 are prescribed hydraulic head and concentration boundary conditions, respectively. In this study h_1 = 4 m and C_1 = 29 g/L. The initial conditions are:

$$h = h(x, y, z, 0) \quad (x, y, z) \in \Omega \quad (5)$$

$$C = C(x, y, z, 0) \quad (x, y, z) \in \Omega \quad (6)$$

where Ω is the study area.

THE POSSIBILITY AND EXTENT OF SEAWATER INTRUSION

In order to estimate long-term seawater intrusion to the groundwater within the island, FEMWATER (Lin, 1996) is utilized to simulate the groundwater flow field and the distribution of salinity after the project operation. The results are shown in Figs 3 and 4. Figure 3 is the flow field one year after the project has been completed. It represents the equilibrium of the groundwater supply from the precipitation and the groundwater discharge to the ocean from inside the island.

Analysis of the groundwater velocity field indicated that, because the project line is low and flat in topography, and the permeability of the terrace is weak, there is low possibility that the project line can be supplied by adjacent places. We conclude that there is only a low risk of a large-scale invasion of seawater because of the topography and geological conditions along the line of the project. The same conclusion can be drawn from the distribution of the flow field one year after project completion (Fig. 5).

Figure 5 shows the range of seawater intrusion (salinity >0.1g/L) one year after the project completion. We conclude that the salinity will change noticeably along the project in the range of 150–800 m, with an average of 400 m, and the total area affected area will be 13.67 km^2 (including the Zhongzai Gulf).

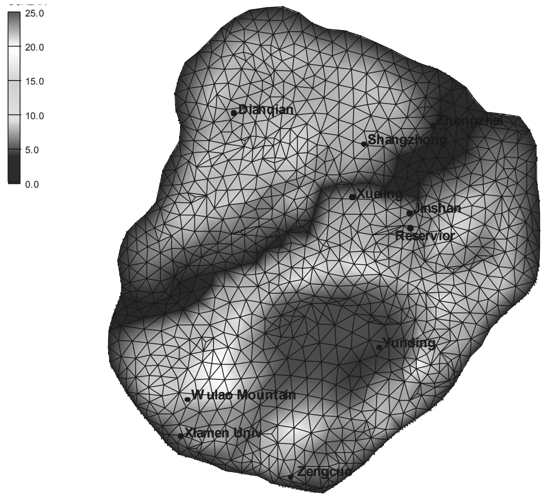

Fig. 3 The groundwater levels after one year of operation (m).

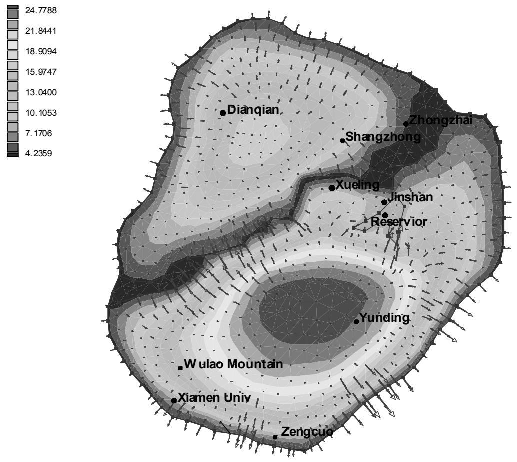

Fig. 4 The groundwater velocity fields after one year of operation.

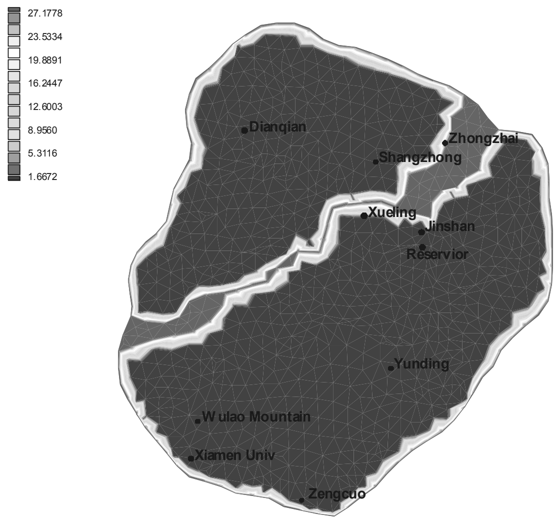

Fig. 5 The spatial extent of seawater intrusion after one year of operation (g/L).

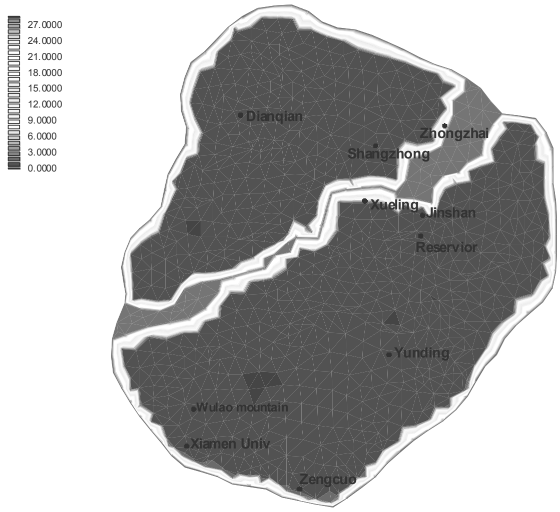

Fig. 6 The spatial extent of sea water intrusion after 10 years of operation (g/L).

The groundwater flow field and salinity distribution up to 10 years after the project operation were also simulated. The result indicates that the range of seawater intrusion has not noticeably expanded (Fig. 6). It may be concluded that the range of the seawater intrusion is almost stable one year after the project is completed. However, in years with inadequate precipitation, when the peripheral groundwater level falls, the distance that the seawater will invade will increase accordingly.

As shown in Fig. 5, the seawater intrusion will reach the Hubian Reservoir (major freshwater supply of the island) after one year of operation. If the precipitation is low and the water level of the reservoir recedes, seawater may enter the reservoir, and cause the salinity of the reservoir to rise.

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REFERENCES

Cheng Jianmin (2003) Automatic generation method of triangle mesh with inner specific restriction. *J. Yangtze River Scientific Research Institute* **20**(04), 39–43.

Du Qungui & Liu Shaohong (2004) 2D Finite element adaptive mesh generation based on geometric features - Part I Detailed algorithm description. *J. Computer-Aided Design & Computer Graphics* **7**(3), 85–90.

Lin, H. C., Yeh, G. T., Cheng, J. R., Cheng, H. P. & Jones, N. L. (1996) FEMWATER: A three-dimensional finite element computer model for simulating density-dependent flow and transport in variably saturated media. US Army Engineers Waterways Experiment Station Technical Report.

Moor, Y. H., Stoessell, B. K. & Easley, D. H. (1992) Fresh-water/sea-water relationship within a groundwater flow system, northeastern coast of the Yucatan Peninsula. *Ground Water* **30**(3), 343–350.

Pinder, G. F. & Cooper, H. H. (1970) A numerical technique for calculating the transient position of the saltwater front. *Water Resour. Res.* **6**(4), 875–883.

Zheng, C. (1990) MT3D: A modular three-dimensional transport model for simulation of advection, dispersion and chemical reactions of contaminants in groundwater systems. Report to the US Environmental Protection Agency. Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, USA.