A Case Study of Finite-Element Numerical Modeling on Salt Water Intrusion for the Ping-Tung Plain

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INTRODUCTION

Ping-Tung Plain is a center of agriculture and fisheries in Taiwan. Continuing population growth resulted in the increase of water use in the region. The total annual groundwater withdrawals had reached 2,181 million cubic meters. The Water Resources Planning Commission was facing challenges in water resources management and proposed several alternatives, such as construction of the Meinung Reservoir, Machia Reservoir, Nanhua Reservoir, and low dam/weirs along the Kaoping River. A conjunctive surface water and groundwater model was needed to assess the impacts associated with these alternatives to increase the efficiency of the water resources development in the Ping-Tung Plain. Over-pumping for fisheries along the coastal areas resulted in seawater intrusion, which was a major issue.

SIMULATION MODEL

Groundwater is the major source of water supply across the Ping Tung Plain. Groundwater withdrawals have been previously estimated as approximately twice the annual effective precipitation recharge to water-supply aquifers. Aquifers generally range in thickness from 60 to more than 110 meters. These aquifers contain very coarse, high-permeability sands and gravels in the northeast (alluvial fans), and multiple, thinner and less permeable confined aquifers in the southern part of the Ping-Tung Plain. Four soil types were simulated: gravel, sand, clay, and rock using available information on hydraulic properties for these soil types.

A three-dimensional (3D) finite-element model capable of predictive simulation of the effects of reservoirs on the groundwater system for the Ping Tung Plain in southwestern Taiwan was developed. The conjunctive surface water and groundwater simulation model also serves as a long-term management tool for evaluation of the effects from many water management alternatives, including the sea water intrusion of chloride front movement for 50 years simulation. The Ping Tung Plain was visualized in 3D using the Groundwater Modeling System (GMS) system. This system allowed the synthesis of a large number of available data sources, especially the large number of boreholes for which stratigraphic data were available. Importance for model calibration was the integration of complex, wet-season and dry-season river stage elevation with groundwater recharge rates. The finite-element numerical model FEMWATER, was selected as an appropriate model for simulating features at the Plain.

The discretization of the conceptual model contained a total of 9,070 elements and 5,291 nodes distributed in a 3D mesh representing 10 thin layers of elements capable of evaluating many thin and discontinuous confining layers. The 3D visualization was "discretized" into thin triangular prismatic elements that became the 3D finite element mesh used for numerical model simulation of the Ping-Tung Plain. The mesh was extended offshore to include the shelf area for effective simulation of shoreline conditions and seawater intrusion simulation. Bedrock is included on the West, North, and East sides of the model because seepage of water from bedrock to the aquifers is an important source of recharge to the Ping Tung Plain.

and data gaps. Bedrock was explicitly simulated as part of the model. Rainfall-seepage boundaries were used to simulate the recharge of groundwater to bedrock surrounding the Ping Tung Plain. Little or no information regarding the rate of seepage from bedrock into the aquifer system exists, so that sensitivity analyses were used to develop a reasonable constant value for bedrock hydraulic conductivity. Sensitivity analyses showed that bedrock seepage is an important and sensitive term in the numerical model simulation. Important features such as the Chao Chou Fault in the east part of the model were simulated as vertical bedrock interfaces with alluvial material.

Rainfall recharge was simulated as a seepage-type of boundary condition on the upper surface of the model. Pumping was simulated as a constant flux (Cauchy type) boundary condition on the bottom surface of model. The use of separate rainfall and pumping terms increased the complexity of the model and the uncertainties associated with precise estimates of either rainfall recharge or pumping. Extensive re-calibration of groundwater flow was therefore necessary prior to simulating seawater intrusion. Part of this re-calibration process included the use of a new material type " cobbles" in parts of the upper alluvial fans associated with the northwestern Lao Nung Creek and Ailiao Creek.

Initial conditions for chloride proved to be the most important and sensitive part of the modeling process. For this reason, the current chloride concentrations in groundwater were thoroughly evaluated. At several locations, variations in concentrations of compounds related to seawater intrusion varied substantially with depth. In areas immediately adjacent to the coastline, the shallowest aquifer is often highly contaminated by seawater. In several areas, however, chloride concentrations related to seawater intrusion increased with depth. This effect is widely known, and is related to the lateral migration of seawater from offshore areas rather than from downward seepage of seawater. This understanding is important because deeper wells are often viewed as a solution to seawater intrusion when, in fact, they may increase the problem of seawater intrusion.

Numerical modeling requires an initial condition dataset that accurately reflects actual chloride concentrations. To provide this dataset, a three-dimensional calculation of chloride concentrations was made using a numerical gridding algorithm to interpolate the chloride concentration at every model mesh node. The input data for this process was the chloride concentration in groundwater samples collected at monitoring wells. From these data the best approximation of current values of chloride concentration and each location were selected.

MODELING RESULTS

The results of numerical modeling indicate that the advancing chloride front (defined at a concentration averaging 250 ppm) will move north in the more permeable sand and gravel near the mouth of the Kaoping River. North of the Lin Yuan area, near the mouth of the Kaoping River, chloride concentrations will increase substantially over the next 50 years. The chloride front was calculated to be moving north at an average rate of 80 meters per year.

The concentration of chloride will generally increase along the entire Ping Tung County coastline. Deeper aquifers in the areas near the mouths of the Kaoping and Tung Kang creeks will experience continuing increases in chloride concentration. The shallow coastal aquifers already have significant damage. Near the mouths of the Kaoping and Tung Kang Creeks, shallow aquifers have already experienced seawater intrusion damage. The areas where the potential for chloride concentration changes due to the increase in groundwater pumping were identified and evaluated.

Chloride concentrations will increase with well depth, making deeper well drilling along the coast-line problematic. The areas around the southern Kaoping River and southern Tung Kang River will continue to experience increases in chloride content in groundwater. Preventing the expected increases in chloride concentration in coastal areas will require substantial reductions in groundwater pumping by fish farms in coastal areas, especially near the mouths of the Kaoping and Tung Kang Rivers.

The fisheries industry is a likely cause of some of the major groundwater withdrawals in the coastal areas, as are industrial, agricultural and domestic users of groundwater. Because the over-all mass balance for groundwater in the Plain is positive and stable, additional groundwater pumping in the central and northern parts of the plain could be used to provide additional water supplies if coastal pumping were reduced.

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