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SEA WATER INTRUSION IN COASTAL AQUIFERS

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ABSTRACT

The coastal regions, particularly deltaic regions, are the most developed and most densely populated regions all over the world. These regions are facing many hydrological problems both due to natural conditions and man's activities. The problems due to natural conditions range from flooding due to cyclones and wave surge to drinking fresh water scarcity due to problem of sea water intrusion. Man's activities compound these problems further. Sea water intrusion is one of the severe problems faced by coastal regions. Natural conditions and man's activities both contribute to this problem. There exists an urgent need to study systematically the causes and remedial measures for sea water intrusion problem in coastal areas. This article presents the hydrological aspects, control measures and modelling of sea water intrusion in coastal aquifers.

KEY WORDS: *Groundwater, Salinity, Numerical Model, SUTRA, SEAWAT*

1. INTRODUCTION

Sea water intrusion, or encroachment, is defined by Freeze and Cherry (1979) as the migration of salt water into fresh water aquifers under the influence of groundwater development. Sea water intrusion becomes a problem in coastal areas where fresh water aquifers are hydraulically connected with sea water. When large amount of fresh water is withdrawn from these aquifers, hydraulic gradients encourage the flow of sea water towards the pumped well or wells. Sea water intrusion is a problem that affects coastal areas around the world. "Groundwater Problems in Coastal Areas" (Custodio and Bruggeman, 1987) is an excellent reference for more information on global sea water intrusion problems while Atkinson (1986) details sea water intrusion problems for the coastal areas of United States.

The encroachment of salt water into fresh water supplies has become cause for concern within the last century, as population in coastal areas has risen sharply and placed greater demands on fresh groundwater reserves. Sea water intrusion causes many problems in these areas, perhaps the most severe being the limitation of potable drinking water. Drinking water standards, established by the EPA in 1962, require that drinking water should not contain more than 500 mg/L of total suspended solids (TSS), a common measure of salinity (Atkinson, 1986). Sea water contains approximately 30000 mg/L of TSS. Therefore, it is evident that even a small amount of sea water can cause drinking water problem when mixed with fresh water reserves. Also, salinity in irrigation water can be detrimental to agriculture, reducing yields and killing crops with low tolerance to salt. In some cases, conditions may necessitate a change to crops that are more salt tolerant. Salt water has also been shown to reduce soil erodibility and decrease soil structure and tilth (Jenkins and Moore, 1984).

The development of groundwater resources in oceanic islands and mainland coastal areas are a delicate issue and careful management is required if water quality degradation due to the encroachment of sea water is to be avoided. In many cases, difficulties arise when aquifers are pumped beyond their natural recharge rate and sea water is drawn into the system. Problems can also occur when excessive pumping at individual wells lowers the potentiometric surface on a localized scale and causes upconing of the natural interface between fresh water and saline water. Coastal and island aquifers are also sensitive to sea level changes such as postulated rises due to global warming. The associated volumetric expansion of sea water and melting of snow caps would increase the extent of sea water intrusion and reduce the availability of fresh groundwater resources.

The development and management of coastal groundwater aquifers remain a very delicate issue. Under-utilization of the available resource means that valuable fresh water will discharge naturally to the sea and wasted; overdevelopment, on the other hand, will mine the resource and cause a gradual or sometimes sudden degradation of water quality due to the encroachment of sea water. As an aid to effective management, many models have been developed over the years to represent and study this problem. They range from relatively simple analytical solutions to complex state-of-art numerical models using large computing capacity.

2. MECHANISM OF SEA WATER INTRUSION

In many coastal areas, the development and management of fresh groundwater resources are seriously constrained by the presence of sea water intrusion. Sea water intrusion is a natural phenomenon that occurs as a consequence of the density contrast between fresh and saline groundwater. Normally, the denser saline water forms a deep wedge that is separated from the fresh water body by a transition zone of variable density. In some cases, this wedge can extend for many kilometers inland. Providing conditions to remain unperturbed, the saline water body will remain stationary, its position being largely defined by the fresh water potential and hydraulic gradient. However, when the aquifer is disturbed by pumping of the fresh water, sea level change or by changing recharge conditions, the saline water body will gradually move until a new equilibrium condition is achieved. Problems arise when saline water from the deep saline wedge enters pumping wells and affects the water quality. Most commonly, this occurs at individual wells where heavy pumping lowers the fresh water potential in the immediate vicinity of the well and causes saline water to be drawn upwards to the well, a phenomenon known as “upconing”. This type of problem is often very localized and can be rectified by distributing production amongst a group of smaller shallower wells. A similar but potentially more serious problem occurs when a coastal aquifer is overdeveloped on a regional scale. This results in lowering of the fresh water potential throughout the area and progressive and extensive invasion of the aquifer by sea water. In some heavily exploited aquifers, the inflow of sea water may represent a significant component of the aquifer’s flow budget.

Saline water is the most common pollutant in fresh groundwater. Intrusion of saline water occurs where saline water displaces or mixes with fresh water in an aquifer. In a coastal aquifer, there is direct contact between continental fresh water and marine salt water. Besides difference in viscosity between the two fluids, there exist a density change that depends mainly on salinity differences (Custodio and Bruggeman, 1987). In a stable system, the fresh water floats on the salt water and a landward sloping interface exists between them. The salt groundwater body adopts the form of wedge resting on the aquifer floor. The fresh water thickness decreases from the wedge toe towards the sea. Since the fresh water flow thickness decreases seaward, the slope of the piezometric head or the water table must increase towards the coast. Thus, the interface is concave upwards.

Sea water intrusion into fresh groundwater formations generally results from activities of man. In coastal aquifers, sea water intrusion occurs due to invasion of sea water. This situation commonly occurs in coastal aquifers in hydraulic continuity with sea when pumping of wells disturbs the natural hydrodynamic balance. Groundwater abstraction reduces the coastal fresh water discharge and alters the dynamic equilibrium. The final result is a deeper and more penetrating sea water wedge. When abstraction is greater than actual recharge, no final equilibrium position can be attained, but the sea water intrudes very deeply. Fresh water abstractions create local water head drawdowns and when the well is located over the salt water wedge, a salt water upconing develops.

A rapid recharge of fresh water increases the fresh water head. Such situation occurs in water table aquifers where direct recharge by rainfall infiltration is possible and recharge also occurs by irrigation return flows, floods, river channels etc. Both fresh water and salt water flow towards the sea and the mixing zone moves slowly seaward and downwards increasing its slope. The reverse is true in dry period. Sea tides produce the same effect. Many other activities such as urbanization, industrialization, suppression of irrigated areas, river regulations with upstream dams and deforestation can lead to an increase in the potential for sea water encroachment.

3. GHYBEN - HERZBERG PRINCIPLE

Until fairly recently, most research on the relationship between fresh and saline groundwater in coastal aquifers has been based on the analytical solutions. Ghyben (1888) and Herzberg (1901) independently developed similar formulations on sea water intrusion, widely known as the Ghyben-Herzberg principle. Their formulation was based on the hydrostatic equilibrium between fresh water and saline water (assumed immiscible) in a U-shaped tube. It states that the fresh water-saline water interface in an aquifer occurs at a depth of Z below mean sea level, as represented by

$$Z = \frac{\rho_f}{\rho_s - \rho_f} h_f$$

where, ρ_f is the density of fresh water (M/L^3), ρ_s is the density of saline water (M/L^3), and h_f is the elevation of the fresh water level above mean sea level (L).

Substitution of ρ_f (1000 kg/m^3) and ρ_s (1025 kg/m^3) in equation shows that $Z = 40\ h_f$. In other words, the depth to the saline water interface below mean sea level is 40 times the elevation of water table above sea level (h_f). It also follows from equation that if water table in an unconfined coastal aquifer is lowered by 1 m, the fresh water-saline water interface will rise by 40 m. This simple formulation has been used widely by hydrogeologists, but it is an inadequate representation, because it describes a steady state equilibrium and does not take into account important mechanisms such as advection and dispersion.

In practice, the spatial relationship between fresh and saline groundwater in coastal and island aquifers is complex and management of the fresh water resource may be a difficult and sensitive issue. The aquifer system is rarely near equilibrium and the fresh and saline water bodies are normally separated by a transition zone created due to chemical diffusion and mechanical mixing. Under these conditions, the response of the saline water body to pumping is difficult to predict and depends on various factors including aquifer geometry and properties (intrinsic permeability, anisotropy, porosity, dispersivity); abstraction rates and depths; recharge rate; and distance of pumping wells from the coastline. Sophisticated tools are required to quantify the aquifer response to these factors. With the advent of large scale and widely available computing resources, the numerical approach to sea water intrusion analysis has moved to the forefront.

4. MODELLING OF SEA WATER INTRUSION

In the past few decades, modelling has become an important and powerful tool in many branches of science. Models allow engineers and scientists a way to test hypotheses in a manner that is non-destructive to the actual problem at hand. In studies involving sea water intrusion, modelling has been used for many purposes. One common goal of these models is to predict and characterize the movement of the transition zone in the aquifer where fresh water and salt water meet. Another purpose of modelling is to predict the degree and extent of mixing that occurs in the transition region. These are only two examples of how models are used to quickly predict the future conditions that may actually take many years to occur. In this way, models allow problems to be defined before they actually occur.

Sea water intrusion models can be categorized into three broad categories: physical, analytical and numerical. Of these three, numerical models are by far the most commonly used today, with the availability of high speed computers that can solve many systems of equations in a short time. Physical models find unique applications as visual aids that allow the actual problem to be scaled down to a size that is manageable and controllable. Analytical models involve solving equations where a definite closed answer is reached at the end of calculations, offering ease of calculation and a simplified version of the real problem.

Physical Models:-

Physical models consist of miniature physical analogs of the geology and/or hydrology of the situation being studied. Custodio and Bruggeman (1987) describe physical models as an analog which has the same dimensions as the prototype and in which every prototype element is reproduced, differing only in size. Physical models often come into use in situations where numerical and analytical models are inappropriate due to insufficient historic and hydrogeologic data. Physical models have the added advantage of providing a means of visually understanding the problem being studied, a crucial element when dealing with the lay population. One simple type of physical model is a sand box type model. A container is filled with a porous media, such as sand or glass beads, and movement of fluids through the media is observed. Another type is the ion-motion analog. In this type of model, the movement of ions, under an electrical gradient through an electrolytic solution, is used to model the movement of fluids through porous media. By introducing other electrically charged probes into the system, hydraulic phenomena such as impermeable layers and pumping wells can be simulated in the system (Custodio and Bruggeman, 1987). Another commonly used physical model is the

Hele-Shaw analog. This model is used to represent two-dimensional flow in groundwater systems and consists of two transparent parallel plates placed close together with a porous media in between. Flow of fluid between the two plates under different hydraulic gradients is observed and studied.

Analytical Models:-

The first analytical model, that accurately represented hydrogeologic conditions, appeared in the 1960's (Custodio and Bruggeman, 1987). Analytical models are similar to numerical models, except that the equations involved can be solved exactly without the use of approximation methods. In order to arrive at equations that provide an exact solution, many simplifying assumptions must generally be made. Therefore, these models are not suited for systems that involve complex flows and geometries. For this reason, analytical models have limited use in sea water intrusion modelling. However, when analytical models are suitable, they provide solutions that are relatively simple to calculate and understand.

Numerical Models:-

Numerical models consist of mathematical algorithms that represent the hydraulic and/or chemical aspects of the situation being studied. Systems of partial differential equations that relate parameters such as head and water flow are commonly utilized by this type of model. Studies involving the numerical modelling of sea water intrusion have been conducted by Cantatore and Volker (1974), Cheng (1975), Christensen (1978) and many others in last few decades. According to Atkinson (1986), the types of algorithm commonly used for numerical modelling are finite difference methods, finite element methods and the method of relaxation. Finite difference methods involve replacing the differential equations that govern flow with finite divided differences at specific grid points. The system of resulting equations is solved simultaneously to determine necessary flow parameters at specific grid points. In this manner, the hydraulic characteristics are found at specific points throughout the system. Finite element methods are similar to finite difference, with the main difference being that an approximation solution replaces the partial differential equations at specific nodes. The overall solution is then found by combining these individual solutions. Finite element methods, unlike finite difference which require symmetric and equally sized grid elements, utilize elements of various sizes and shapes, enabling these methods to better handle irregular shapes, non-homogeneity, etc. The method of relaxation involves obtaining steadily improved approximations of Laplace and Poisson equations that describe the character of the system (Atkinson, 1986).

Currently, several solute transport models, suitable for the simulation of sea water intrusion and upconing of saline water beneath pumping sites, are commercially available. These include SUTRA (Voss, 1984), HST3D (Kipp, 1987), SALTFLOW (Molson and Frind, 1994) and SEAWAT (Weixing and Langevin, 2002) etc. These models provide solutions of two simultaneous, non-linear, partial differential equations that describe the “conservation of mass of fluid” and “conservation of mass of salt” in porous media. SUTRA (Saturated-Unsaturated TRAnsport) employs a three-dimensional finite-element approximation of the governing equations in space and an implicit finite-difference approximation in time. HST3D (Heat and Solute Transport in 3 Dimensions) employs three-dimensional finite-difference approximations of the governing equations. This model is capable of simulating an aquifer with irregular geometry. SALTFLOW is also three-dimensional but utilize a finite-element approximation of the governing equations for an aquifer that is subject to the intrusion of sea water. SEAWAT is a generic MODFLOW/MT3DMS-based computer program designed to simulate three-dimensional variable-density groundwater flow coupled with multi-species solute and heat transport. The program has been used for a wide variety of groundwater studies including those focused on brine migration in continental aquifers as well as those focused on saltwater intrusion in coastal aquifers.

5. CONTROL OF SEA WATER INTRUSION

The first step in correcting problems with sea water intrusion is to evaluate the size and extent of the problems. This is commonly accomplished by the installation of monitoring wells which are used to determine the boundaries of the salt/fresh water interface and the rate at which salinity levels are increasing. Using this data and information on the hydrologic and geologic properties of the contaminated aquifer, numeric and computer modelling is often incorporated into problem analysis in order to predict future conditions and to evaluate remediation alternatives.

Newport (1977) and Todd (1974) have listed the following methods for controlling sea water intrusion in coastal aquifer systems:

1. Reduce pumping
2. Relocate wells
3. Directly recharge aquifer (primarily surficial aquifers)
4. Fresh water recharge into wells paralleling the coast, creating a hydrodynamic barrier
5. Create a trough parallel to the coast by excavating encroaching salt water from wells
6. Extracting sea water before it reaches wells
7. Extraction/injection combination

8. Construction of impermeable subsurface barriers.

As long as the cone of depression from fresh water pumping wells does not fall below sea level, the threat of sea water intrusion can be averted (Atkinson, 1986). Control methods 1 and 2 above are used to reduce the cone of depression by reducing the rate at which water is withdrawn and by spreading wells apart so that concentrated areas of drawdown are avoided. Methods 3 to 5 involve creating a hydrodynamic barrier of fresh water that blocks the further encroachment of sea water. Extraction techniques, methods 6 and 7, require the use of extraction wells that pump sea water from the aquifer before it can reach fresh water supply wells. Method 8, installing impermeable barriers such as grout and steel sheet piles, is normally limited to areas where the contaminated aquifer is relatively shallow and the subsurface geology allows for a proper seal. Each of these methods can be applied to certain situations and the method used will depend on the problem to be solved.

6. CONCLUDING REMARKS

The coastal areas often contain some of the most densely populated areas in the world. The availability of flat land, communication arteries, easy sea transportation, good soils and high productivity of organic matter explains this fact. Intrusion of sea water into heavily exploited aquifers is a serious problem being faced in coastal areas. The development of groundwater resources, therefore, requires careful management in coastal areas.

As population continue to expand in coastal communities, the need for greater groundwater withdrawals is certain to increase. The modelling methods will prove to be instrumental in finding an equilibrium between man's needs and nature's ability to supply. Computer modelling has already been used to design better groundwater withdrawal networks so that the effects of sea water intrusion are reduced. As technology and experience expand, new techniques for controlling intrusion are likely to become practical and economical, ensuring fresh water supplies for future generations.

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