

## Office of Science

# Research Project Summary

August, 2009

### Contaminant Transfer in Coastal Aquifers

#### Authors

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#### Abstract

Groundwater flow and contaminant transport processes in coastal aquifers can be complicated by tidal effects adjacent to the coast. This study was designed to evaluate the significance of tidal influences on contaminant transport by focusing on one-dimensional homogeneous coastal aquifers. This study formulated a conceptual model and corresponding flow and transport equations, analyzed coastal boundary conditions, numerically solved the contaminant transport equations, and used experiments to verify the numerical results. Based on the results of the numerical and experimental studies, it was concluded that tides can have a significant impact on contaminant transport in coastal aquifers, especially in unconfined aquifers subject to moderate/high tidal amplitudes, when groundwater flow velocity in the aquifer is low, and within areas of the aquifers adjacent to coastal waters. Quantitatively, under these favorable conditions, contaminant discharge can be enhanced by tides by a factor of two or three during the early stages of contaminant discharge, and the enhanced discharge can still be substantial during later stages by 30 to 50 percent. When the groundwater flow is close to stagnant, the tidal impact is most apparent, resulting in significant contaminant discharge tens of years ahead of the case without tides.

#### Introduction

The quality of coastal and estuarine waters is affected by industrial, agricultural, and other land use practices throughout regional watersheds. However, the effect of the groundwater transport of contaminants resulting from sources of pollution associated with these land uses on coastal water quality has been inadequately studied. Developing a better understanding of the importance of contaminant transport in coastal aquifers can result in the development and implementation of management practices and pollution prevention initiatives to minimize adverse impacts to coastal and estuarine water quality.

Groundwater flow and contaminant transport in coastal aquifers are complicated by dynamic conditions in coastal waters, including tidal fluctuations, waves, and salt water intrusion into aquifers. The present study focuses on developing a better understanding of the transport of contaminants in coastal aquifers subject to tidal fluctuations. Included in this analysis were the identification of appropriate coastal boundary conditions, estimation of the potential impact area induced by tidal fluctuations on water table or piezometric head fluctuations in coastal aquifers, and differential tidal effects in confined and unconfined aquifers.

The approach and scope of work for the study included the use of analytical methods, numerical simulations, and experiments to address groundwater flow and contaminant transport problems in coastal aquifers, including the following:

- 1) Completion of a comprehensive literature review concerning groundwater flow and contaminant transport in coastal aquifers.
- 2) Formulating the equations governing groundwater flow and contaminant transport in a coastal aquifer and analyzing the corresponding boundary conditions of contaminant concentration or flux in coastal waters due to tidal fluctuations.
- 3) Deriving a finite difference solution for the governing equations formulated in (2) incorporating tidal fluctuations.
- 4) Conducting numerical simulations addressing the impact of tides on contaminant transport in coastal aquifers.
- 5) Quantitatively identifying the area of tidal influence in confined and unconfined coastal aquifers.
- 6) Conducting laboratory experiments investigating contaminant transport in coastal aquifers subject to tidal fluctuations.
- 7) Comparing the experimental and numerical simulation results to verify the latter.

The final report for this project is referenced here, and can be obtained on the Department's web site at <http://www.state.nj.us/dep/dsr/coastal/coastal.htm>.

Ding, Y. and Y. Peng 2009. Contaminant transport in coastal aquifers. NJDEP Contract No. SR02-035. April 2009, 308 pp.

### Literature Review

Several mechanisms have been proposed to explain the interaction between sea water and groundwater in coastal aquifers, including tidal pumping and variable density flows. Experimental studies and mathematical simulations have been used in past investigations of the temporal and spatial conditions of groundwater flow regimes adjacent to coastal areas. The major factors that are critical to coastal aquifer studies include tides and tide-induced estuarine waves, moving boundary conditions resulting from tidal fluctuations, beach slope and seepage dynamics, density variable flow, and the saltwater-freshwater interface introduced by saltwater intrusion. The literature review conducted for the present study summarized the results of previous work investigating the importance of these factors to contaminant transport in coastal aquifers.

However, the study of contaminant transport in coastal aquifers subject to tidal fluctuations has been very limited. These past studies have found that tidal fluctuations cause the contaminant concentration in the coastal aquifer to be significantly diluted by the estuarine water body. In addition, because of the relatively high advective, dispersive, and convective fluxes induced by tides, contaminant transport in the tidally active zone of a coastal aquifer is hastened by the tides. However, the effect of tides on contaminant transport is significant only over a short distance (the tidally active zone) in unconfined coastal aquifers; tidal effects in confined aquifers have not been studied.

### Equations Governing Groundwater Flow and Contaminant Transport

Many numerical models have been developed dealing with one or more factors concerning groundwater flow and contaminant transport in coastal aquifers. However, a comprehensive simulation model that can account for

all of the factors has not yet been constructed. Likewise, this study made a number of simplifying assumptions to focus on the effects of tidal fluctuations on contaminant transport in coastal aquifers, and developed the conceptual model of the problem shown in Figure 1. Groundwater flows from the inland (left) to the coast (right) in Figure 1, and the contaminant source is located at the left boundary of the aquifer system. Equations governing groundwater flow and contaminant transport in confined and unconfined coastal aquifers subject to tidal fluctuations were developed.

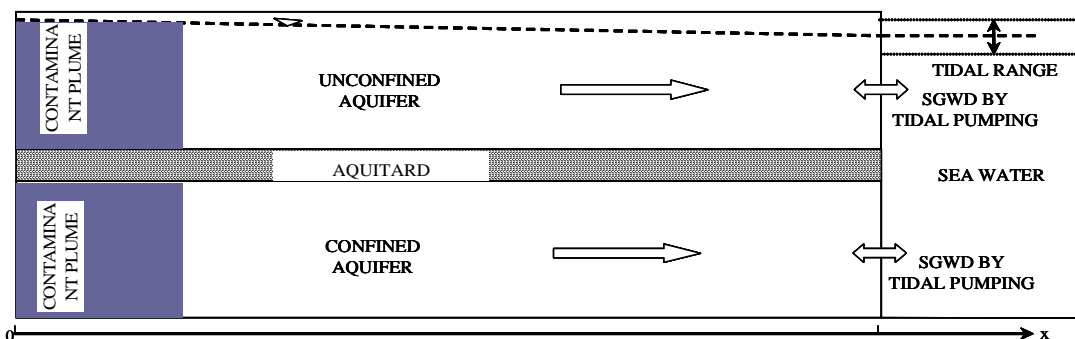
Contaminant concentration initial conditions in the aquifer, and boundary conditions in the coastal waters, were evaluated to simulate pollution release into and subsequent contaminant transport through the aquifer (with and without consideration of tidal effects). The study concluded that the "first-type boundary condition" was the most appropriate for use at the effluent end of the coastal aquifer where it discharges into coastal surface waters:

$$C|_{x=L} = C_L$$

where  $C_L$  is a constant concentration at the effluent boundary, and  $L$  is the length of a finite aquifer system. The condition (with  $C_L=0$ ) is believed to be more realistic when a contaminant is discharged into a large, well-mixed reservoir like a coastal water body and this additional contaminant input will not significantly change the contaminant concentration in the water body. This evaluation demonstrated that the selection of different effluent boundary conditions has a significant effect on the problem solution, and the error induced by the selection of an incorrect effluent boundary condition can be significant.

An analysis and comparison of the results of the application of three analytical solutions to the baseline problem of contaminant transport in a coastal aquifer without tidal influences was also completed.

**Figure 1: Conceptual model of the study problem. (SGWD = submarine groundwater discharge)**



A finite difference scheme was then applied to numerically solve the partial differential equations governing contaminant transport.

### Laboratory Experiments

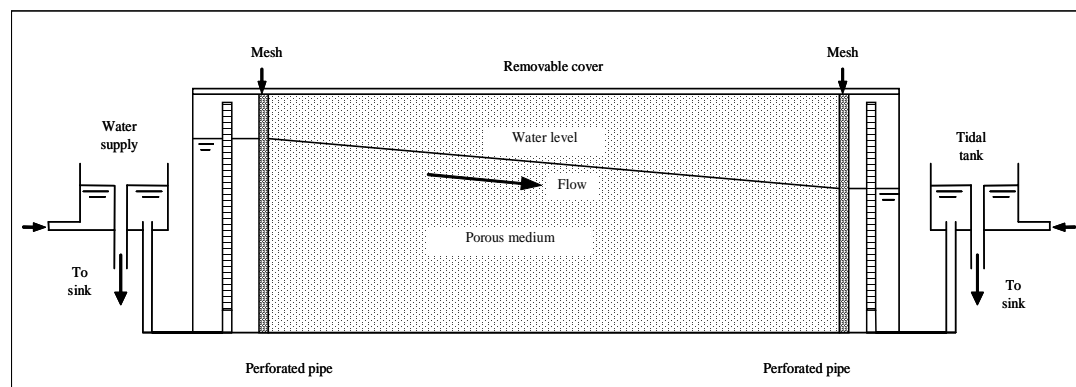
Past experimental studies of the impact of tides on groundwater flow and contaminant transport in coastal aquifers have been very limited. The experimental facility used in this study is shown in Figure 2. The sand tank was designed such that it could be used to simulate groundwater flow and contaminant transport in both unconfined and confined aquifers by switching the seal cover, and with a periodic boundary condition (i.e. tidal fluctuations) imposed at the effluent end of the tank. The sand tank was constructed with cast acrylic sheets and had dimensions of 12 feet long, 3 feet high, and 6 inches wide. The water level in each end of the tank

portant – resulting in an increase in the mass of contaminants discharged - under certain conditions: a combination of low groundwater flow velocity, high dilution at the coastal boundary, moderate to large tidal amplitude, and low tidal period. The enhanced contaminant discharge may be tripled during the initial time period of discharge, and can be 40% higher even after a prolonged period of time since the discharge had started.

In both confined and unconfined aquifers, the experimental results indicate that tidal fluctuations result in a slight reduction in contaminant concentrations in the aquifer, but a larger increase in the rate of contaminant discharge from the aquifer. Under unconfined conditions, the tidal impact is slightly larger than under confined conditions with similar tidal parameters. The degree of the influence of the tides is approximately proportional to the tidal amplitude – the larger the tidal amplitude,

the greater the effect. However, the tidal effect is also influenced by other factors (hydraulic gradient, tidal period, and degree of dilution), and in unconfined aquifers the effect of the tides may only be noticeable when the tidal amplitude is relatively large. When the

Figure 2: Experimental facility.



was controlled such that tidal fluctuations could be simulated. Ottawa sand was used as the porous medium. Two arrays of penetration ports were used, one for sampling the tracer solution and the other for water head measurements (piezometers). Red food color was used as the tracer; a UV-visible Spectroscopy System (Hewlett-Packard Model HP 8453) was utilized to measure the concentration of the tracer. Aquifer conditions that were evaluated during the various experimental runs were the type of aquifer (confined/unconfined), hydraulic gradient, tidal period and amplitude, and dilution and mixing of contaminants.

In general, the experimental results were consistent with the analytical results and the numerical model developed as part of the study (see [Equations Governing Groundwater Flow and Contaminant Transport](#)). The experiments demonstrated that, consistent with the predicted "first type boundary condition", contaminant concentrations in a coastal aquifer are reduced near the coastline and the contaminant discharge rate out of the aquifer is slightly increased. The tidal effect can be im-

portant – resulting in an increase in the mass of contaminants discharged - under certain conditions: a combination of low groundwater flow velocity, high dilution at the coastal boundary, moderate to large tidal amplitude, and low tidal period. The enhanced contaminant discharge may be tripled during the initial time period of discharge, and can be 40% higher even after a prolonged period of time since the discharge had started.

### Numerical Simulations

The numerical studies evaluated the impact of tidal fluctuations on hydraulic heads and contaminant transport in coastal aquifers. The significance of the tidal effects was also evaluated under conditions of varying groundwater flow velocity, retardation, decay, aquifer dimensions, and aquifer type (confined/unconfined). These studies demonstrated that the tidal amplitude is damped quickly in an unconfined aquifer as it goes inland, while a confined aquifer tends to have a much smaller capability to damp the tidal fluctuations. The distance that tides have an effect on hydraulic heads in a confined aquifer is 200-300 meters inland, substantially greater than that in an unconfined aquifer (about 40 meters).

In contrast, the tidal effect on contaminant transport is much greater in an unconfined aquifer than that in a confined aquifer. The distance of the potential tidal effect is within a range between 40 to 70 meters for unconfined aquifers and between zero (no influence) and 85 meters for confined aquifers. Likewise, tidal fluctuations have a significant impact on mass discharge of contaminants, especially in unconfined aquifers and during the early stages after the initial discharge starts. However, in both the confined and unconfined aquifers, the increase in contaminant mass discharge over the no-tide condition decreases as time after the initial discharge increases, particularly in the confined case. In addition, tides can result in a large decrease in contaminant concentrations in aquifer areas near the coast.

The numerical studies also demonstrated that the effect of tides is more significant when the groundwater flow velocity is lower and with retardation due to the adsorption of contaminant onto the aquifer soil matrix. However, contaminant discharge is enhanced by tidal activities (compared to the no-tide condition) to a greater degree the larger the retardation factor. In addition, consistent with conclusions reached in the experimental studies, the tidal effect is significant under certain conditions: a combination of low flow velocity, moderate to large tidal amplitudes, and certain retardation, decay, and aquifer domain conditions. Likewise, the significance of the tidal effect is subject to tidal amplitude: the larger the tidal amplitude the more significant the tidal effect.

### Summary of Major Conclusions

The major conclusions that can be derived from the experimental and numerical results include the following

(1) The coastal boundary condition is more correctly represented by the first-type boundary condition than by the second-type boundary condition.

(2) Tides have a greater influence in confined aquifers in terms of tidal efficiency factor (or hydraulic head fluctuations). This potential influence distance for confined aquifers is 200 to 300 meters extending inland, while it is only about 40 to 60 meters for unconfined aquifers.

(3) In sharp contrast to the above conclusion with regard to the tidal impact on hydraulic heads, the tidal effect on contaminant transport is generally greater in unconfined aquifers than in confined aquifers.

(4) Tidal fluctuations have greater impact on contaminant transport in unconfined aquifers than in confined aquifers.

(5) Consistently in both the experimental and numerical studies, the tidal effect is significant under certain conditions: a combination of low flow velocity, moderate to large tidal amplitudes, and certain retardation, decay, and aquifer domain conditions. Tidal influence is manifested in the concentration profiles to a greater degree in regions close to the coastal boundary, and in the discharge profiles particularly during the early stages in time after the contaminant begins to discharge into the aquifer.

(6) The significance of the tidal effect is subject to tidal amplitude: the larger the tidal amplitude the more significant the tidal effect.

(7) The significance of the tidal effect is also subject to flow velocity: the tidal influence is more significant under lower groundwater flow velocity. When the groundwater flow is close to stagnant the tidal impact is most apparent, leading to a significant discharge of the contaminant tens of years ahead of the case without tides.

(8) Under unconfined conditions, in general, retardation, decay, and aquifer domain have only a slight influence on the significance of tidal impact on contaminant transport. This is different under confined conditions, where high retardation, quick decay, and a large aquifer domain more easily cause the tidal impact to diminish.

### Acknowledgments

Funding for this project was provided by the New Jersey Department of Environmental Protection. The support and assistance of the Department of Civil and Environmental Engineering, NJIT, and Robert Hazen (NJDEP-DSRT) was instrumental in the implementation of this project.

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### RESEARCH PROJECT SUMMARY

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