Review of Analytical Studies of Tidal Groundwater Flow in Coastal Aquifer Systems

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Abstract: Since the 1950s, numerous publications of analytical studies of tidal wave propagations in coastal aquifers have been appeared. This paper reviews the following aspects: importance of tidal effects in studies of coastal areas, analytical studies of tide-induced groundwater flow and related case studies. Finally several important open problems in analytical studies of tide-induced groundwater flow are proposed.

Keywords: tidal groundwater flow, coastal aquifer system, analytical solutions, review

1 Importance of Studies on Tidal Effects in Coastal Areas

The social and economic development in coastal areas causes various hydrogeological, engineering, ecological and environmental problems such as seawater intrusion, stability of coastal engineering structures, beach dewatering for construction purposes, and deterioration of the marine environment. A great deal of previous studies show that research of the coastal groundwater flow induced by sea tides plays an important and active role in solving these problems. For example, Carr (1969) investigated the tide-related salt-water intrusion in Prince Edward Island; Lanyon *et al.* (1982) provided a comprehensive description of watertable changes over time for particular points along beach profiles and related those changes to tidal fluctuation and variation in beach-face configuration; Chan and Mohsen (1992) used a one-dimensional numerical model to simulate the migration process of a contaminant plume within tidally influenced aquifers; Marquis and Smith (1994) assessed groundwater flow and chemical transport in a tidally influenced aquifer using geostatistical filtering and hydrocarbon fingerprinting; Farrell (1994) analyzed groundwater flow through leaky marine retaining structures using analytical and numerical methods; Pontin (1986) investigated the cyclic pore pressure generation in ground below a tidal estuary caused by tidal fluctuations, which is used to examine uplift (or “heave”) to be avoided during construction inside deep marine excavations. Here the word “uplift” is referred to as the vertical motion and dislocation of the soil and rock formations below the base of the excavations caused by the hydraulic pressure in the formations, wherein tidal inundation is prevented.

Field studies of the groundwater discharge process in unconfined coastal aquifers show that the tide can significantly influence the temporal and spatial patterns of groundwater discharge as well as the salt concentration in the near-shore groundwater (Robinson *et al.* 1998; Robinson and Gallagher, 1999). To model the groundwater discharge process at the field scale, the tide and associated boundary conditions along the beach must be included in the model. Field studies also show groundwater discharge to be a source of nutrients and pesticides from agricultural lands (Simmons *et al.*, 1992; Gallagher *et al.*, 1996), and residential septic tanks (Gablin and Gaines, 1990; Weiskel and Howes, 1992).

Estimations of the submarine groundwater discharge (SGWD) and net inland recharge in coastal areas are of great importance for the correct assessment of the role of groundwater in the global water cycle (Moore, 1996; Church, 1996; Younger, 1996). Based on measurements of enriched radium 226 in the South Atlantic Bight, which stretches from the Cape Fear River to the Savannah River, an alongshore distance of 320 kilometers, Moore (1996) discovered that SGWD in this area could amount to as much as 40% of the total flow entering the ocean from adjacent rivers. The influences of sea tide on the mean groundwater levels are one of the main aspects immediately related to SGWD estimation. Li *et al.* (1999) proposed a conceptual model of SGWD. According to their model, SGWD consists of the net groundwater discharge, the outflow due to wave-setup-induced groundwater circulation, and that due to tidally driven oscillating flow. They applied their model to Moore’s (1996) field study in the South Atlantic Bight and concluded that the outflow due to tidally driven oscillating flow amounts to 37% of the total SGWD, implying the importance of the tidal effects in estimating SGWD. The importance of SGWD to the nutrient budget for a coastal ecosystem and to the marine environment is discussed in e.g. Uchiyama (2000), Simmons (1992), and McLachlan and Illenberger (1986).

2 Analytical Studies of Tide-Induced Groundwater Flow

2.1 Jacob’s solution and its application

The simplest case of tide-induced groundwater flow is the Jacob's (1950) solution that considered the vertical beach, straight coastline and one-dimensional flow in a coastal confined aquifer. The solution indicates that the amplitude of the tide-induced groundwater head fluctuation decreases exponentially with the distance from the coast, whereas the time lag increases linearly with the distance. The attenuation speed decreases with the diffusivity of the aquifer (i.e., the ratio of the transmissivity to the storativity) and increases with the angular velocity of the sinusoidal sea tide. Jacob's solution is also applicable as a good approximation to watertable fluctuations of an unconfined aquifer if the range of fluctuation is small in comparison to the saturated aquifer thickness (Erkine, 1991; Todd, 1980). Based on the superposition principle, Jacob's solution can be directly used to evaluate the tidal groundwater head fluctuation induced by the real sea tide which can be decomposed into the linear superposition of some sinusoidal components.

Jacob's solution has been used to analyze field observation data in many case studies. For example, Ferris (1951) estimated the diffusivity of an aquifer beside a tidal river-Platte River using Jacob's solution. Similar methods were used by Carr and van der Kamp (1969) to determine the tidal efficiency, storativity and permeability of a coastal aquifer in Prince Edward Island, Canada, and yielded results compatible with pumping test data. Usually Jacob's solution can only estimate the diffusivity (ratio of the transmissivity to the storativity). If the aquifer storativity can be estimated by means of the tidal efficiency (or barometric efficiency) and the porosity of the aquifer rock, as was done by Carr and van der Kamp (1969), the aquifer transmissivity can also be determined from the diffusivity and the storativity. Drogue *et al*. (1984) used different analytical solutions including Jacob's to analyze the tidal groundwater fluctuation in a coastal Karstic aquifer. Serfes (1991) estimated hydraulic gradients in a shallow (9 m), layered aquifer system using simple filtering techniques based on Jacob's solution. Erskine (1991) analyzed the effect of tidal fluctuation on a deep (50 m), unconfined and highly permeable coastal aquifer around a working nuclear power station in the UK based on the Jacob's solution. Diffusivity is estimated using time lag and tidal efficiency factor. Millham and Howes (1995) compared five methods (tidal damping method based on Jacob's solution, tracer method, slug test, permeameter, and grain-size analysis) for determining hydraulic conductivity in a medium-depth (15 m), highly permeable, unconfined coastal aquifer.

For the analysis of the observed tidal groundwater level fluctuation, Jacob's solution provides two methods: the amplitude attenuation method and the time lag method. Significant inconsistency was often found when both methods were used to estimate the diffusivity of the coastal aquifers, as is indicated by, for example, Drogue *et al*. (1984), Erskine (1991), Trefry and Johnston (1999). The reason for this is most probably the model errors. Jacob's solution is based on the strictest assumptions of the aquifer configurations such as single, horizontal, and landward infinitely-extending aquifer, vertical beach and straight coastline. Therefore, the leakage of the semipermeable layers, irregular boundary shape, and a definite length of the aquifer, etc. may make the Jacob's solution inapplicable. Due to this, analytical solutions for complicated aquifer configurations were derived.

2.2 L-Shaped coastal aquifers

In the case that the tidal water is in an estuary or a bay, the tidal level fluctuation in the sea will attenuate along the estuary or the bay (e.g., Fisher, 1986; Sun, 1997) and the tidal loading boundary condition along the estuary coastline becomes two-dimensional. Sun (1997) considered this kind of situation and derived an analytical solution that involves the attenuation of the sea tide along the estuary. In reality, coastal areas are usually bounded by very irregular coastlines full of inlets, bays, and headlands. In this case, tidal wave propagation in the confined aquifer will be affected by the irregular water-land boundaries. L-shaped coastlines are an idealized situation but this situation is believed to be of some practical use. For example, in most estuaries, which are frequently-studied coastal areas, the coastlines are often approximately of L-shape (e.g., Drogue *et al*., 1984; Li *et al*., 2000b; Cheng and Chen, 2001). Li *et al*. (2000b) derived a spatially two dimensional analytical solution in an unconfined aquifer with L-shaped coastlines located at an estuary. One side of the L-shaped boundaries represents the river-land boundary on which the attenuation and phase shift of tidal movement in the river is considered as did by Sun (1997). The other side is the ocean-land boundary with spatially constant boundary condition. Because of the hypothetical initial condition, the solution of Li *et al*. (2000b) is not periodic. Li *et al*. (2002) and Li and Jiao (2002b) obtained a periodic analytical solution independent of initial condition and generalized the single L-shaped aquifer into an L-shaped coastal leaky aquifer system. Their improvements include the computationally efficient solution form, simple approximate solution as well as consideration of the storativity of the semi-permeable layer. Error analysis and case study show that the approximate solution has adequate accuracy for both groundwater level prediction and parameter estimation for an L-shaped leaky aquifer system. The solution of the L-shaped aquifer was used in estimating the diffusivity of an L-shaped, deep unconfined aquifer formed by the reclamation fill of Type A/B around Lam Chau Island, which is now a part of the Hong Kong International Airport, Hong Kong SAR, P. R. China.

2.3 Confined aquifers extending under tidal water

In reality, the roof of a coastal aquifer, i.e., the overlying confining layer, may extend for a certain distance under the tidal water. It is of great importance to estimate the roof length since it represents a key boundary condition in the coastal groundwater flow model for seawater intrusion studies or coastal groundwater resources evaluation. Under the extreme assumption that the roof length is infinite, van der Kamp (1972) derived a solution to describe the groundwater fluctuation in the aquifer. Liu (1996), Maas and De Lange (1987) considered the groundwater head fluctuations in confined aquifers overlain by tidal rivers using different analytical methods. The later successfully explained an interesting phenomenon−negative phase shift of tidal groundwater flow observed at Gouderak, the Netherlands. Li and Chen (1991a) considered the situation where the roof length is finite. All these studies assumed that there is no leakage from the confining layer. Li and Chen (1991b) took into account the leakage from the seawater through the offshore part of the confining unit. Li and Jiao (2001a) improved these results by considering a three-layered coastal aquifer system consisting of an unconfined aquifer, an underlying confined aquifer and a semi-permeable layer between them. The unconfined aquifer terminates at the coastline, while the semipermeable layer extends under the sea and its offshore part forms the roof of the confined aquifer. Both the aquifer configuration and their analytical solution generalize the above mentioned previous analytical studies. The water level fluctuations in the inland part of the confined aquifer decrease significantly with the roof-length for small roof-lengths and become insensitive to change of roof-length for those roof-lengths greater than a certain threshold. The effects of leakage from the offshore and inland portions of the confining unit are different. The leakage from the offshore portion tends to increase the fluctuations while that from the inland portion to decrease. The fluctuations increase as the tidal efficiency increases but it is important only when the roof-length is great and leakage is small.

2.4 Three-layered coastal aquifer system

In many coastal areas, there are more than two aquifers separated by semipermeable layer(s) (e.g., van der Kamp, 1973; Jiao and Tang, 1999; Li and Chen, 1991a and b). van der Kamp (1973) studied a three-layered coastal aquifer system consisting of one aquifer bounded by two semipermeable layers from up and down. Jiao and Tang (1999) derived an analytical solution to study the groundwater head fluctuations in the confined aquifer of a coastal aquifer-aquitard-aquifer system. Following Hantush and Jacob (1955), they ignored the elastic storage of the leaky layer (aquitard). They also assumed that the watertable fluctuation in the shallow unconfined aquifer is negligible. This assumption may not be valid when the leakance of the leaky aquifer system is great (Volker and Zhang, 2001). However, Jiao and Tang (2001) examined the leaky aquifer systems reported in literature and found that the leakance is usually very small for a real leaky aquifer system and there is no problem to use the assumption. On the basis of their analytical solution, Jiao and Tang (1999) found that the leakage has a significant damping effect on the groundwater fluctuation amplitude in the confined aquifer. Tang and Jiao (2001) generalized the solution of Jiao and Tang (1999) by considering the attenuation of the sea tide along the estuary. Li *et al*. (2001) used a perturbation method to investigate the tidal wave interference between the unconfined and confined aquifers, but they ignored the effects of the elastic storage of the leaky layer. Also ignoring the effects of the elastic storage of the leaky layer, Jeng *et al*. (2002) presented an analytical solution to describe the tidal wave propagation in the unconfined and confined aquifers separated by a thin, no-storativity leaky layer. Li and Jiao (2001b; 2002a) presented complete analytical solutions describing tidal groundwater wave propagation in coastal two-aquifer systems. The previous analytical solutions which either ignored the watertable variation or the storativity of the leaky layers were improved and generalized by taking into account both the leakage and the storativity of the leaky layer, as well as the water level variations in the upper and lower aquifers. It is found that the leaky layer's storativity behaves as a buffer to the tidal wave interference between the two aquifers. The buffer capacity increases with the leaky layer's thickness, specific storage, and decreases with the leaky layer's vertical permeability. Great buffer capacity can result in negligible tidal wave interference between the upper and lower aquifers so that the solution can be simplified significantly. The analytical solution indicates that both storativity and leakage of the semi-permeable layer play an important role in the groundwater head fluctuation in the confined aquifer.

2.5 Enhancing effect of the sea tide on the mean watertable of a coastal unconfined aquifer

Due to the watertable-dependent transmissivity of an unconfined aquifer, the sea tide has an enhancing effect on the mean watertable even for a vertical beach and in the absence of net inland recharge. This nonlinear effect has been studied by many researchers under the assumptions that the coastal unconfined aquifer is isotropic, homogeneous and the tide comprises only one sinusoidal component. For example, Philip (1973) concluded that the mean watertable as the landward distance approaches infinity can be higher than the mean sea level by 23% of the tidal amplitude if the depth of the unconfined aquifer below the mean sea level equals the tidal amplitude. Philip's result was based on the Dupuit-Forchheimer (D-F) assumptions. Knight (1981) proved theoretically that Philip's result exactly holds independent of the validity of the D-F assumptions. Philip's theoretical prediction was examined and confirmed by a Hele-Shaw experiment conducted by Smiles and Stokes (1976). Parlange *et al*. (1984) used second-order theory to describe the propagation of steady periodic motion of liquid in a porous medium. Their laboratory experiments, analytical and numerical analyses support Philip's prediction. Nielsen (1990) developed an approximate analytical solution based on a perturbation method to investigate the mean watertable in the inland region near the coastline.

In reality, the sea tide consists of tens of sinusoidal components. Due to nonlinearities of the model equations describing an unconfined aquifer, the superposition principle does not apply and the consideration of all the tidal components is necessary. In addition, all the above-mentioned theoretical and numerical results use the assumptions of isotropy and homogeneity of the aquifer, and some of them are based on the D-F assumptions. Li and Jiao (2003a) considered the watertable-enhancing effect in a more general case when the aquifer is inhomogeneous and anisotropic and the tide is multi-sinusoidal-component. Based on a two-dimensional free groundwater surface model of a coastal unconfined aquifer, the asymptotic watertable as the landward distance approaches infinity is discussed. An important finding was that the watertable-enhancing effect is independent of the vertical permeability and can be reinforced if the horizontal permeability decreases with depth. For a coastal aquifer-aquitard-aquifer system, the enhancing effect will lead to landward positive gradients of both the mean watertable and mean head in the region near the coastline, which consequently results in a seawater–groundwater circulation (Li and Jiao, 2003b). Seawater is pumped into the unconfined aquifer by the sea tide and divided into two parts. One part returns to the sea driven by the mean watertable gradient. The rest part leaks into the confined aquifer through the semipermeable layer, and returns to the sea through the confined aquifer driven by the mean head gradient. The total discharge through the confined aquifer is significant for coastal leaky aquifer system with typical parameter values. This seawater–groundwater circulation has impacts on better understanding of submarine groundwater discharge and exchange of various chemicals such as nutrients and contaminants in coastal areas. If the observed mean water levels in coastal areas are used for estimating the net inland recharge, the enhancing processes of sea tide on the mean groundwater levels should be taken into account. Otherwise, the net inland recharge will be overestimated.

3 Conclusions

Previous works of the tide-induced groundwater flow in coastal aquifer systems are reviewed. Numerous previous studies show that studies on the tide-induced groundwater flow play an important and active role in solving problems arising in hydrogeology, engineering, ecology and environment in coastal areas. As the simplest analytical solution describing the tidal wave propagation in a confined aquifer, Jacob's solution provides two methods to analyze the observed data of tidal groundwater level fluctuations and has been widely used in many case studies. Significant discrepancy was often found between the diffusivity values estimated by the two methods. This is most probably because Jacob's solution is based on the strictest assumptions of the aquifer configurations such as single, horizontal, and landward infinitely-extending aquifer, vertical beach and straight coastline. Any violation of these assumptions by the real aquifer, e.g., the leakage of the underlying or the overlying semipermeable layers, irregular boundary shape, and a definite length of the aquifer may make Jacob's solution inapplicable. In order to improve this situation, analytical solutions for complicated aquifer configurations were derived by many hydrologists.

Various factors were considered such as the tidal attenuation along the estuary, the vertical flow in the aquifer, the L-shaped coastline, the beach slope, and the semi-permeable roof of a confined aquifer under the tidal water. Three-layered aquifer systems structured as aquifer-aquitard-aquifer or aquitard-aquifer-aquitard were also considered. The enhancing effect of the sea tide on the mean watertable in a coastal unconfined aquifer was studied analytically and experimentally. Nevertheless, the potentials of generalizations and improvements to these works are great. There are still a great deal of new situations to be investigated, for example, the effects of the elastic storage of a semipermeable roof of a confined aquifer extending under tidal water, the effect of the sloping beach in a coastal aquifer or aquifer system, the enhancing effect of the sea tide on the watertable in a generic unconfined aquifer with sloping beach. All of them are meaningful task full of challenge.

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