Land subsidence due to groundwater withdrawal: potential damage of subsidence and sea level rise in southern New Jersey, USA

H. Sun · D. Grandstaff · R. Shagam

Abstract Land subsidence due to groundwater withdrawal combined with a global sea level rise creates a serious environmental problem in the coastal region. Groundwater withdrawal results in fluid pressure change in the layers. The pressure change in the layers induces both elastic and inelastic land compaction. The elastic compaction can be recovered if the water level rises again and inelastic compaction becomes permanent. Groundwater response to barometric pressure change is used to estimate the elastic compaction in this study. The storativity, specific storage and other layer and hydrological information are used to estimate the inelastic compaction of the layers due to fluid withdrawal. The discussed methods are applied to estimate and predict the subsidence potentials resulting from overdrafting of the groundwater in the southern New Jersey. The estimated subsidence is about 2–3 cm near the location of monitoring wells in Atlantic, Camden, Cumberland and Cape May Counties over the past 20 years. If the current trend of water-level drop continues, the average subsidence in southern New Jersey in the vicinity of some monitoring wells will be about 3 cm in the next 20 years. The rise of global sea level is about 2 mm/year on average. Because of the very gentle slope in southern NJ, the combination of subsidence and sea level rise will translate into a potentially substantial amount of land loss in the coastal region in each 20 year period. This combination will also accelerate the coastal flooding frequency and the erosion rate of the New Jersey coastal plain, and pose a serious threat to the coastal economy.

Key words Subsidence · Sea level rise · Groundwater overdrafting

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Introduction

Relationship between water level decline and the rate of subsidence has been observed for many years in various places (Poland and Davis 1956, 1969; Hix 1995; Wilson and Gorelick 1996). The water level drops in confined aquifers cause reduction in the upward pressure born by the fluid. If the downward pressure, placed on the aquifer by the weight of overlying rock and water, remains constant, then, a reduction in upward pressure born by the fluid will result in an increase in the effective stress born by the aquifer. If pumping reduces the pressure head in a confined aquifer, the effective stress acting on the aquifer will increase, the aquifer will consolidate due to this increased stress. The hydraulic head drop in the aquifer will eventually result in the same amount of head drop in the confining layer as well. In response to this drainage, the effective stress will increase, resulting in a commensurate volume reduction in the layer itself. If the solid and fluid in the confining layers are assumed to be incompressible, then, the volume of the fluid removed is equal to the volume of the subsidence (Jacob 1939; Narasimhan and others 1984; Parker and Stringfield 1950). Groundwater overdrafting has been a problem for some time in southern New Jersey (Leahy and Martin 1993; Pucci and others 1994; Smith and Sun 1996). Overdrafting results in the compression of the aquifers and the confining layers as previously stated (Sun 1997). This compression leads to land subsidence and other associated problems, such as changes in elevation and gradient of stream channels, drains, and other water transporting facilities, damage to civil engineering structures, private and public buildings, etc. Sea level rise along the east coastal area has also been observed for some time and has averaged 2–3 mm/year (Titus and Narayanan 1996). A combination of sea level rise and land subsidence could cause a serious increase in the flooding frequency and result in tidal encroachment onto lowlands in a coastal community. The overall cost could be millions of dollars in the long run. This study discusses the methods of estimation of land subsidence due to groundwater withdrawal and its application to the New Jersey's problems. The land subsidence includes the elastic and inelastic components. The estimation of elastic subsidence involves the calculation of compressibility and storativity of the aquifer from groundwater response to atmospheric loading. The inelastic subsidence is estimated from specific storage, water level drop and the thickness of the layers. The prediction of subsidence rates is helpful for water and land resource managers, planners, regulators, and administrators to utilize, to manage, and to protect the coastal resources.

Theory of compaction due to groundwater withdrawal

Elastic consolidation

The elastic consolidation of an aquifer refers to the compaction that can be recovered after the induced stress is lifted. This consolidation of the confined aquifer is related to the storativity and compressibility which can be estimated from the groundwater response to atmospheric loading (Rojstaczer 1988; Rojstaczer and Riley 1990; Furbish 1992).

Water levels in the subsurface are subjected to two natural external stresses in general, one is the non-periodic barometric pressure and another is the periodic earth tidal stress. The change in water level is a direct measure of the stress born by the porous matrix under undrained conditions. The relation between the portion of stress born by the matrix and its induced strain in the porous structure is the theoretical background for estimating the elastic compressibility of the aquifer (Meinzer 1928; Jacob 1940; Domenico 1983; Ritzi and others 1991).

Consider a homogeneous, isotropic and horizontal confined aquifer. Assume the stress increment producing the abnormal fluid pressure was vertical only and the individual solid component making up the rock is incompressible. From Jacob (1940)

$$S_s = \rho_w g (\beta_p + n\beta_w) \tag{1}$$

where S_s is the specific storativity, ρ_w is the density of water, g is the gravitational acceleration, β_w is the compressibility of the water ($4.6 \times 10^{-10}\ \mathrm{m^2/N}$), β_p is the bulk compressibility of the rock, n is the porosity of the aquifer. As used by Jacob (1940) and Domenico and Schwartz (1998), the tidal efficiency (T.E.) is defined as:

$$\text{T.E.} = \frac{\partial P}{\rho_w g \partial H'} = \frac{\beta_p}{\rho_p + n\beta_w} = \frac{\rho_w g \beta_p}{S_s} \tag{2}$$

where P is the fluid pressure of the groundwater and H' is the oceanic tide height. Barometric pressure has an inverse relationship with water levels in wells. The barometric efficiency (B.E.) is used to describe how faithfully a water level responds to changes in atmospheric pressure, and is given as:

$$\text{B.E.} = \frac{\rho_w g \partial h}{\partial P_a} \tag{3}$$

where P_a is the atmospheric pressure and h is the hydraulic head in a borehole. Given a relatively constant *B.E.* value in a confined aquifer, Eq. (3) implies that incremental increases or decreases in atmospheric pressure acting on a column of water in a well are, respectively, added to or subtracted from the pressure of the water in the well. These same stresses acting on any part of the confined aquifer, however, are supported by both the grain structure and the fluid. Thus, as long as the atmospheric pressure undergoes change, there must exist a pressure difference between the water and the aquifer. When the atmospheric pressure increases, the gradient is away from the well and the water level decreases.

Because $\text{T.E.} + \text{B.E.} = 1$ (Jacob 1940), from Eqs. (2) and (3),

$$\text{B.E.} = \frac{n\beta_w}{\beta_p + n\beta_w} = \frac{\rho_w g n \beta_w}{S_s} \tag{4}$$

In practice, *B.E.* can be calculated from the measured water level data and the barometric pressure data by using Eq. (3). Calculation of the hourly hydraulic gradient ∂h (i.e. h_1–h_2) acts as a high passing filter and effectively removes the effect of variation of water level from earth tide which has periods of 12 h and 24 h. Specific storativity S_s and bulk compressibility of the aquifer β_w can be calculated from Eq. (4).

Storativity is the product of specific storage and aquifer thickness:

$$S = S_s m = \rho_w g m (\beta_p + n\beta_w) \tag{5}$$

where m is the thickness of the aquifer. By definition, the rock bulk compressibility is:

$$\frac{\Delta m}{m} = \beta_p \Delta\bar{\delta} = \beta_p \Delta P \tag{6}$$

where Δm is the layer thickness change and $\Delta\delta$ is the effective stress change which equals to the fluid pressure change ΔP. Combining Eqs. (5) and (6), and solving for Δm gives the elastic subsidence change of a confined aquifer,

$$\Delta m = \Delta P \left(\frac{S}{\rho_w g} - \beta_w n m \right) \tag{7}$$

Inelastic compaction

Inelastic compaction refers to the compaction that cannot be recovered after the stress is lifted. It is mainly caused by water level decline in the confining layer due to its rich content of clay minerals. The maximum subsidence amount in response to the water table drawdown is given by Domenico and Schwartz (1998) and Cernica (1995) as:

$$\Delta M' = S_s' M\left(\frac{\Delta h_1 + \Delta h_2}{2}\right) \tag{8}$$

where $\Delta M'$ denotes the thickness change of the confining layer, S_s' denotes the specific storage of the confining layer, M denotes the thickness of the confined aquifer, and Δh_1 and Δh_2 denote the head change in the upper and lower confining beds.

The degree of compaction and the expected time to accomplish the compaction can be calculated from Cernica (1995):

$$\frac{t}{T^*} = \frac{tK_v}{M^2 S_s'} \tag{9}$$

where t is the time required to accomplish the compaction, T^* is termed the time constant and K_v is the vertical conductivity of the confined layer. Given the desired degree of compaction, the ratio of Eq. (9) can be found from a chart from Cernica (1995).

Application

The major production aquifers concerned are the Upper, Middle, and Lower Potomac-Raritan-Magothy (abbreviated as PRM) Aquifer System for the southwestern part of the New Jersey state, the Wenonah-Mount Laurel and the Piney Point aquifers in the middle and the 800-ft sand member of the Kirkwood Formation for the southeastern part of the state (Fig. 1). All the aquifers involved are fine- to coarse-grained sand with clay and silt layers alternating in between. For the PRM system, the major confining unit overlying the system is the Cretaceous Woodbury Clay and the clay layer in the Merchantville Formation. For the confining layers involved with the Wenonah-Mount Laurel, the Piney Point aquifers and the 800-ft sand member of the Kirkwood Formation, they are mainly alternating clay and silt layers with varying thickness. The approximated thickness of the layers are listed in Tables 1 and 2. The locations of the USGS monitoring wells studied in this project are shown in Fig. 2.

The barometric pressure data used in this study are the daily average pressures recorded at Atlantic City International Airport by NOAA. The hourly water level data of the monitoring wells were obtained from the US Geological Survey Trenton Office (through Edward Putasky). The daily water level data are from the US Geological Survey water level database. The data period is from 1972 to 1994 (USGS 1972–1994). All the wells studied on the New Jersey coastal plain tap confined aquifers. The water level data are used to calculate the compressibility and storativity of the confined aquifer.

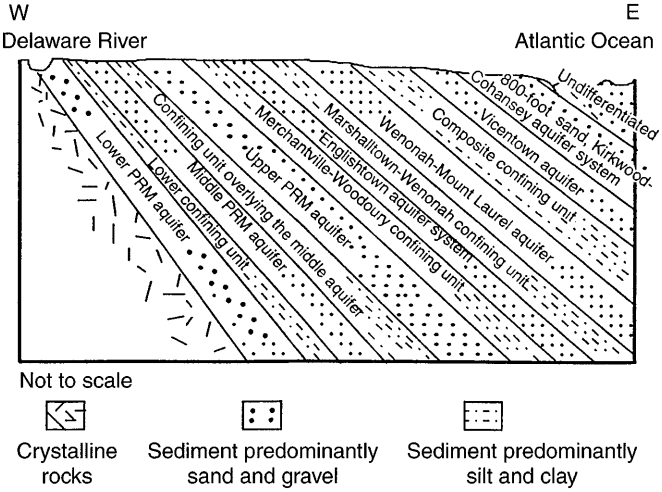

Fig. 1
Sketch of geological cross-section of the aquifers and confining layers in the study area (modified from Zapecza 1989)

The hourly fluctuations of water level in wells of southern New Jersey are mainly controlled by barometric pressure (Fig. 3). The predicted water level, based on the linear regression fitting of barometric pressure, generally shows a very close match with the observed data series over short periods of time (Fig. 4). The seasonal long-term variations of water levels are controlled by well pumping and periodic seasonal changes (Fig. 5). Intensive pumping in southern New Jersey areas has lowered the water levels in wells from a few meters to more than 10 m over the last 20 years (Fig. 5). The water levels in the monitoring wells which are located near the pumping fields in Camden are now more than 15-m below sea level in the confined aquifers (Fig. 7). The decline in the artesian pressure has reduced pore-water pressure in the aquifer system and resulted in the compaction of the aquifers and the confining clay layers, with subsequent land-surface subsidence.

The compaction of the aquifer is directly proportional to the water level drop in the aquifer and is considered elastic or nearly elastic (Domenico and Schwartz 1998). The severest water level drops are in the pumping fields of Camden, Atlantic, Cumberland and Cape May Counties (Figs. 5 and 6). The water level drops in some of the monitoring wells from 1972 to 1994 are listed in Table 1. If the study period extended back to 1930 before commercial development, based on the numerical simulation by USGS, the water table was 6-m above sea level on average and the water level decline in the monitoring wells near the four pumping fields named above has been more than 20 m on average (Pucci and others 1994; Leahy and Martin 1993). Porosity for the elastic subsidence calculation is assumed to be 0.25 as used by most of the groundwater modelers in the area (Navoy and Carleton 1995).

The calculation of elastic consolidation follows Eqs. (3)–(7). Barometric efficiency is calculated first by Eq. (3). It is noticed that the response of daily water table to atmospheric loading is completely in phase (Fig. 3). Barometric efficiencies averaged 0.50 in Camden County,

Table 1

Barometric efficiency, compressibility, specific storage and elastic subsidence rates. Assume porosity $n = 0.25$; PRM Potomac-Raritan-Magothy Aquifer System; L, M, U denote Lower, Middle and Upper aquifer respectively; 800kirk 800-ft sand of the Kirkwood Formation; PineyP Piney Point Aquifer. Water level drop is counted from 1972 to 1994

Well	5-683	4-476	5-258	7-413	5-261	5-645	15-323	11-096	9-306	1-703	1-180
Aquifer	PRM	PRM	UPRM	MPRM	MPRM	LPRM	LPRM	PineyP	800Kirk	800Kirk	800Kirk
Water drop (m)	3	8	11	10	10	6	0	7	6	2.5	6
Barometric effic.	0.501384	0.441181	0.255447	0.266213	0.35272	0.322631	0.295203	0.295203	0.48453	0.273747	0.210859
Compressibility	1.14E-10	1.46E-10	3.35E-10	3.17E-10	2.11E-10	2.41E-10	2.75E-10	2.75E-10	1.22E-10	3.05E-10	4.3E-10
Sp. Storage (m^{-1})	2.25E-06	2.55E-06	4.41E-06	4.23E-06	3.2E-06	3.49E-06	3.82E-06	3.82E-06	2.33E-06	4.12E-06	5.34E-06
Subsidence (m)	0.000658	0.002245	0.007173	0.006164	0.004087	0.00281	0	0.003733	0.001409	0.001483	0.005032
Subsidence (in)	0.025896	0.088379	0.282394	0.242673	0.160919	0.110629	0	0.146957	0.055487	0.058375	0.198109

Table 2

Maximum amount of inelastic subsidence and time for 95% consolidation. Assume vertical conductivity 1×10^{-4} m/day and specific storage of 5×10^{-5} m^{-1} on average (estimated from Pucci and others 1994). CUOM Confining Unit Overlying Middle PRM Aquifer; MAWO Marshalltown-Wenonah Confining Unit; CCU Composite Confing Unit; OKIRK Confining Unit Overlying Kirkwood Formation. The thickness in the table refers to the estimated thickness of the confining layer. Time of 95% refers to the time of days required for a 95% compaction of the maximum amount

Well	5-683	4-476	5-258	7-413	5-261	5-645	15-323	11-096	9-306	1-703	1-180
Aquifer	PRM	PRM	UPRM	MPRM	MPRM	LPRM	LPRM	PineyP	800Kirk	800Kirk	800Kirk
Water drop (m)	3	8	11	10	10	6	0	7	6	2.5	6
Confining layer	CUOM	CUOM	CUOM	CUOM	CUOM	CUOM	CUOM	CCU	OKIRK	OKIRK	OKIRK
Thickness (m)	50.4	50.4	50.4	50.4	50.4	30.4	50.4	180	60	60	60
Subsidence (m)	0.00756	0.02016	0.02772	0.0252	0.0252	0.00912	0	0.063	0.018	0.0075	0.018
Subsidence (inches)	0.297638	0.793701	1.091339	0.992126	0.992126	0.359055	0	2.480315	0.708661	0.295276	0.708661
Time of 95% (days)	317.52	317.52	317.52	317.52	317.52	115.52	317.52	4050	450	450	900

0.4 in Atlantic County and 0.35 in Cumberland County (Fig. 7). These values show a range of values due to differences in compressibility of aquifers. The compressibility of the aquifers are listed in Table 1. The elastic subsidence, given the amount of water table drop, is calculated and listed in Table 1 as well.

The compaction of the confining layers is considered more inelastic because of the large clay contents. It is determined by the thickness and the specific storage of the confining layers. The main confining layers overlying the main aquifers are sketched in Fig. 1. The thickness of the confining units increases generally toward the coastal plain (Zapecza 1989). The specific storage of the confining layers used in Eq. (8) is 5.0×10^{-5} m^{-1} (adjusted from Zapecza 1989). Assume the head change in the aquifer will eventually fully propagate into the confining layer, i.e. the head drop in the confining layer will be the same as that in the aquifer. The estimated total potential inelastic subsidence is listed in Table 2.

The total subsidence rate is the sum of the elastic subsidence and the inelastic subsidence. The estimated total subsidence is approximately 2–3 cm for about a 10-m drop of water table over the past 20 years. The only available measured subsidence data is a well in Atlantic County. It was measured by USGS from 1981 to 1995, with a total subsidence around 1.7 cm (data is provided by P. Lacombe of USGS office at Trenton, NJ). Our total estimated maximum subsidence at well 01-180 in Atlantic County for the past 20 years is about 2.3 cm (0.5 cm from elastic subsidence and 1.8 cm from inelastic subsidence if 100% compaction occurs). This estimation is in general agreement with the measured data (Fig. 8).

Given the current trend of decreasing water level, we predict that the subsidence in Atlantic County in the vicinity of the monitoring well 1-180 will be about 2.5 cm over the next 20 years. The subsidence amount near the monitoring wells 07-413, 11-096 and 09-306 in Camden (07), Cumberland (11) and Cape May (09) Counties might be around 3 cm over the next 20 years, if the current trend of water withdrawal continues.

Sea level rise

For the last century, the global level of the sea appears to have risen at an average rate of nearly 2 mm/year (Titus and Narayanan 1996). Geographical and temporal variations from the long-term mean value occur for a variety of causes, such as interdecadal fluctuations of ocean density and circulation, continuing isostatic adjustment of the land level from the last deglaciation, subsidence due to the extraction of underground fluids, and others.

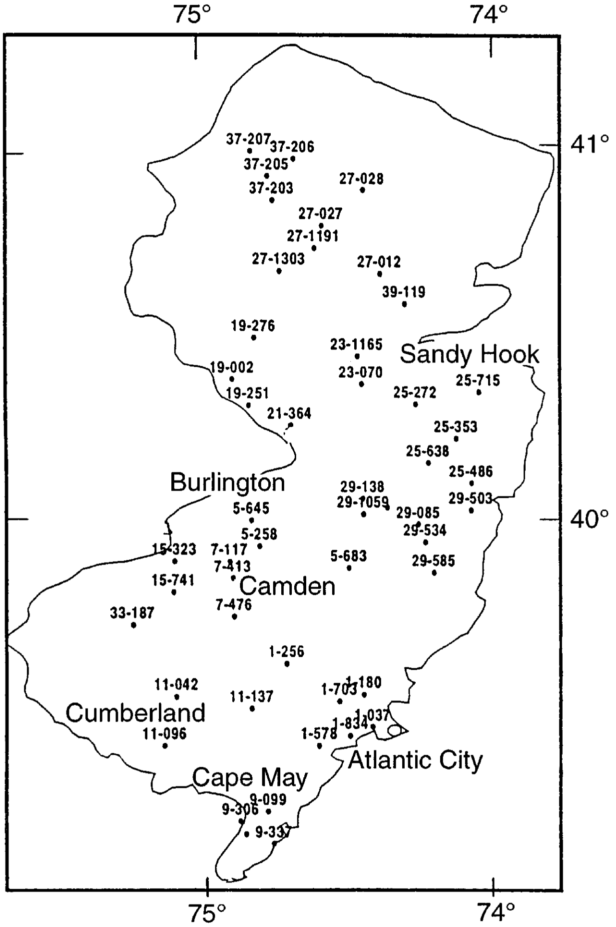

Fig. 2
Locations of USGS monitoring wells studied for this project

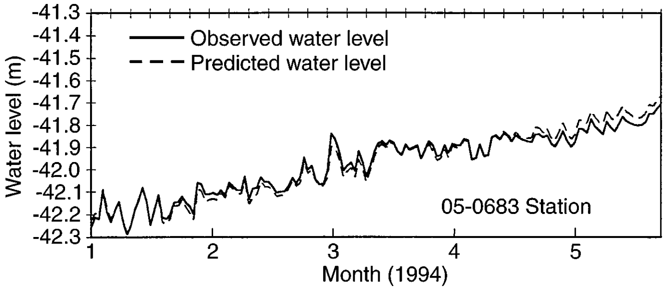

Fig. 4
Comparison of observed water level with predicted water levels by linear regression of barometric pressure at monitoring well nr. 5-0683

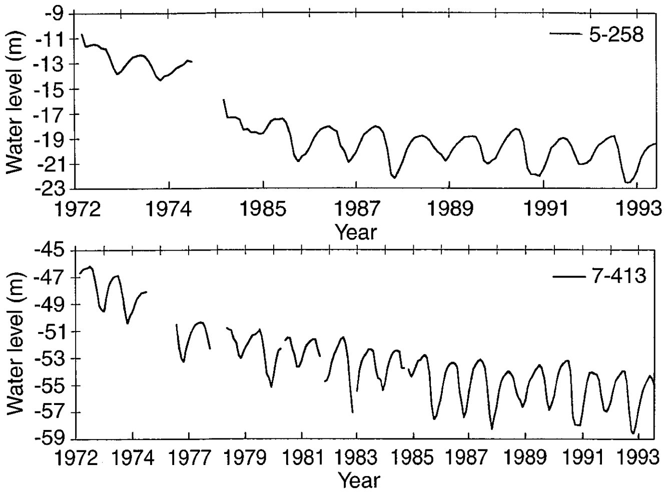

Fig. 5
Monthly average water level drops from 1972 to 1994 for two of the wells in the study area (monthly water level data are averaged from USGS daily water level in the monitoring wells)

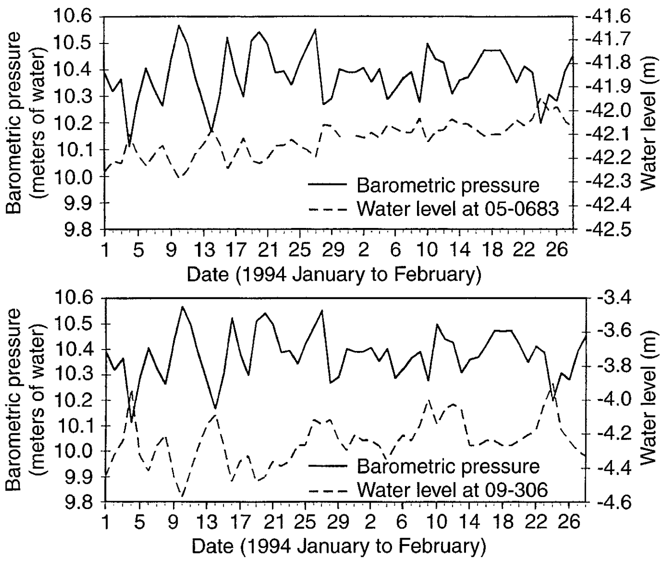

Fig. 3
Hourly water level fluctuations in response to barometric pressure change from two monitoring wells nr. 5-683 and nr. 9-396 (data source, NOAA and USGS)

The sea levels measured by NOAA from 1911 to 1996 at two tidal gauge stations in New Jersey demonstrate a strong relative trend of sea level rise (Fig. 9). Trends for 1911–1996 display the relative rise in millimeter per year. Although there are ups and downs in the trend curves, the general sea level rise is obvious. The interval 1911–1996 is long enough, at 85 years, to establish that the Atlantic City region has a systematically higher rate of sea level rise than the long term global average of nearly 2 mm per year. The approximately 1.5 mm/year extra rise for the region comes from a general subsidence of the area. One of the reasons is the localized subsidence due to fluid withdrawal. The effect of land subsidence in New Jersey adds to the overall global rise in sea level to produce a high rate of long-term local sea level rise relative to the global average.

An excess rate of sea level rise of 1.5 mm/year might, at first glance, appear to be of insignificant consequence. However, the slope of the coastal plain in southern New Jersey is very shallow, being in many places between one part per 300–500 based on the topographic map. Thus, an

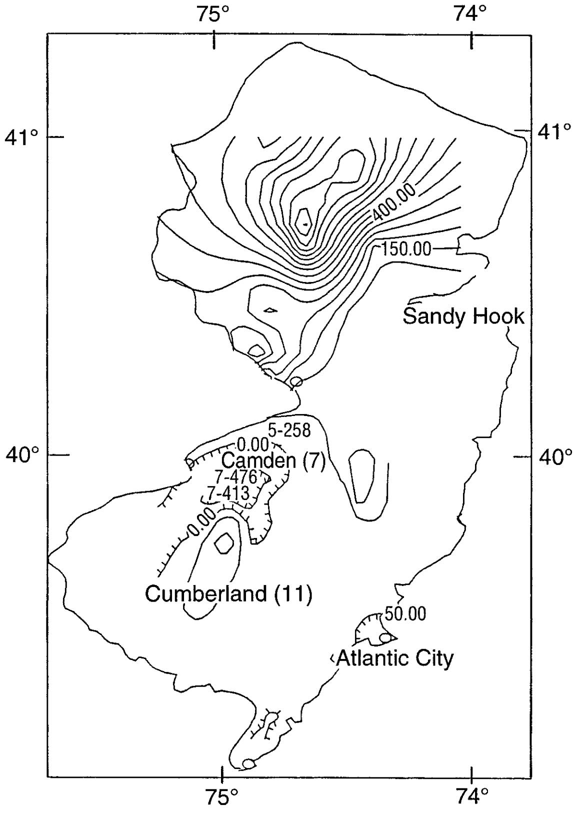

Fig. 6
The water table contours for the PRM aquifer system (*lower left* around Camden), 800-foot-sand of Kirkwood Formation (*lower right* near Atlantic City) and other aquifer systems in the north (north of Sandy Hook) for New Jersey 1994 (data source, USGS)

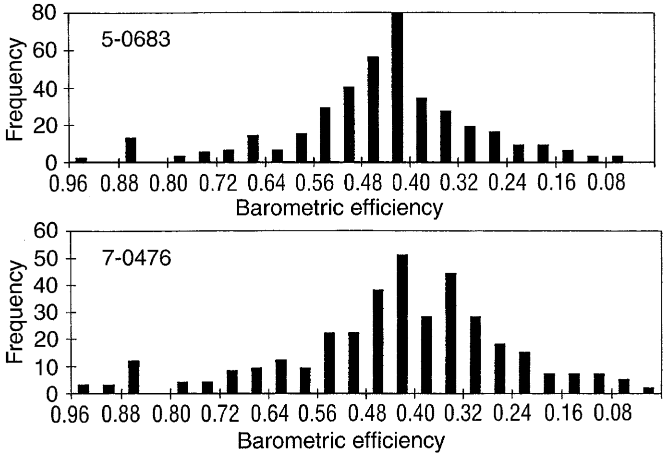

Fig. 7
Histograms of the barometric efficiency from monitoring wells nr. 5-683 and nr. 7-476

extra 1.5-cm rise of regional relative sea level in each 10 years will translate into a 15–20 meters or more loss of land in the next 20 years, with heavy loss of the commercial and residential development along New Jersey's coastal zone! This rate of loss can persist for decades.

Summary and conclusion

Groundwater over drafting could result in a slow but cumulatively significant amounts of land subsidence. This

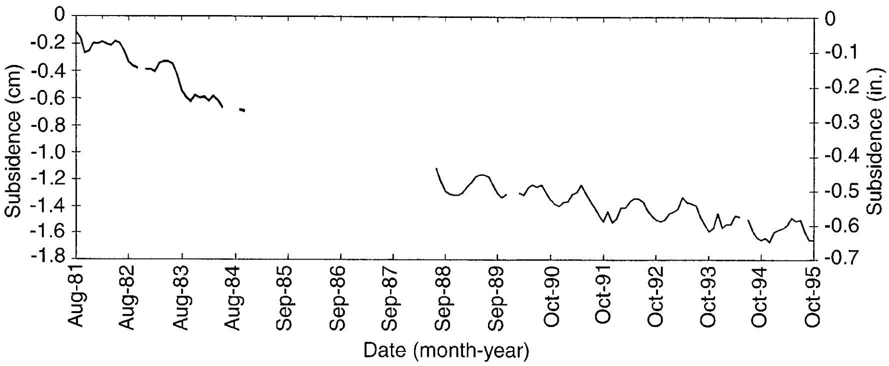

Fig. 8
Measured land subsidence amount in Atlantic City from 1981–1995 by USGS, Trenton Office near monitoring well nr. 1-180

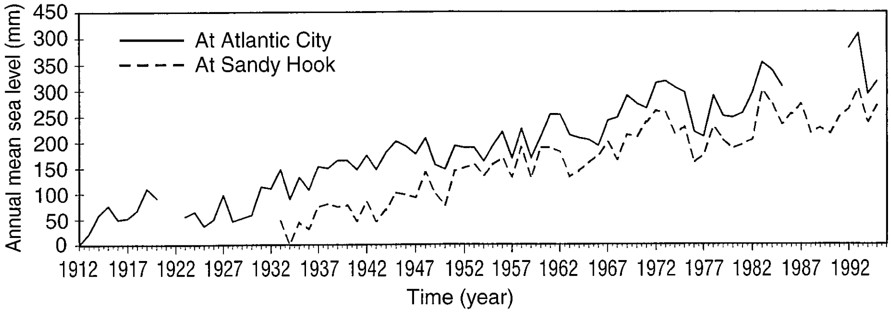

Fig. 9
Sea level changes over the last 85 (1911 to 1996) years in the Atlantic ocean (data source, NOAA)

subsidence includes the elastic consolidation of the aquifers and the inelastic consolidation of the confining layers. The elastic consolidation of aquifers is related with compressibility, which can be estimated from the fluctuations of water level in response to atmospheric pressure variations. The inelastic, permeant consolidation resulted from the fluid withdrawal is mainly due to the rich clay contents in the confining layers. From 1972 to 1994, the total subsidence estimated is 2–3 cm for a 10-m water level drop on average in the monitoring wells studied in Camden, Cumberland, Atlantic and Cape May Counties of southern NJ. The estimated subsidence based on the water level data from the monitoring wells near Atlantic City is generally in agreement with a subsidence rate measured there. With the current rate of water level decline, we predict 2–3 cm of land subsidence near those monitoring wells over the next 20 years. We predict that a significant land loss along the southern coastal area will result from this subsidence in the future. This is certainly no good news for the coastal areas in southern New Jersey where residents have been trying hard to cope with more frequent tidal flooding resulted from a global sea level rise of 2 mm/year.

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