Appendix K
Climate Change Impacts on Water Supply Wells in the Delaware River Estuary

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One of the many threats that climate change and sea level rise may bring to the Delaware Estuary is saltwater intrusion into groundwater aquifers. Many communities in the region rely on groundwater as a significant source of potable water (Barnett et al 130).

Coastal aquifer systems are bordered on the seaward side by saltwater (see Figure 1). Due to the presence of dissolved solids, such as sodium and chloride, this saltwater is heavier than the freshwater in the aquifer, and the freshwater will float above it. The margin between fresh and saltwater is known as the zone of dispersion. When freshwater is reduced, saltwater migrates (intrudes) upward and inland, taking the place of the reduced freshwater in the aquifer.

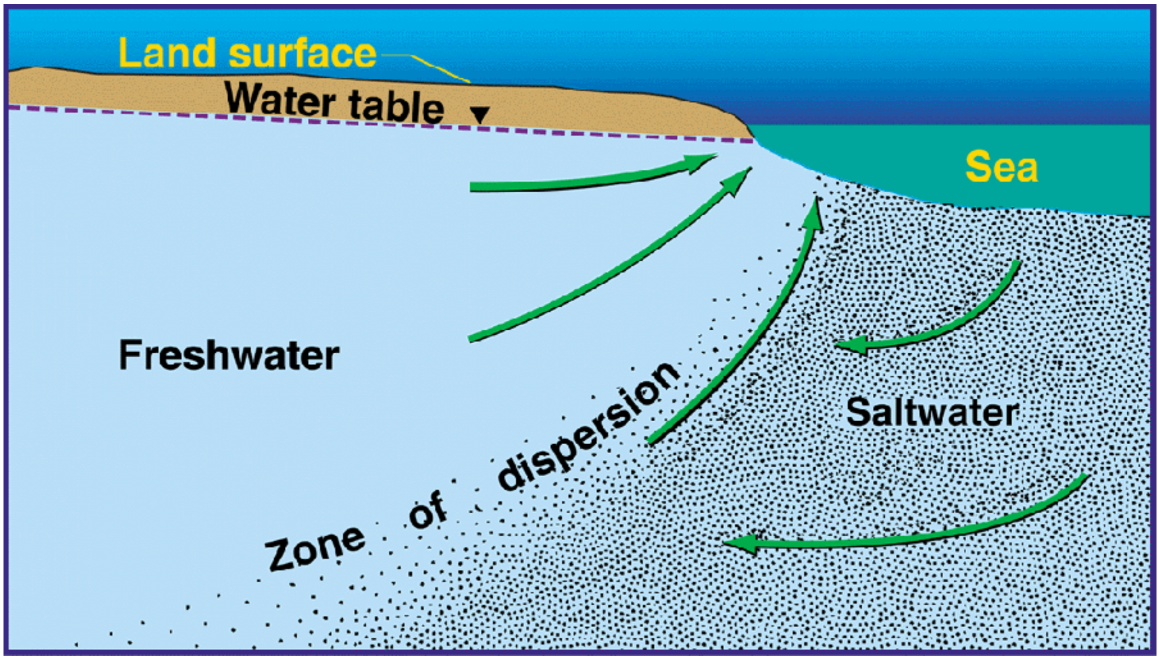

Figure 1: Groundwater/Seawater Interaction (Source: USGS)

For coastal New Jersey, saltwater intrusion has already begun to create problems. Over 120 water supply wells in Cape May County have been abandoned since 1940 (USGS 2000, 2). For communities on the Delaware Estuary, however, the threat is less clearly defined. While there have been studies have examined the potential for saltwater intrusion in the Estuary, none have examined the various ramifications of such intrusion upon estuary communities.

The principle aquifer system in the region is the Potomac-Raritan-Magothy (PRM) system, and it is the most likely candidate for saltwater intrusion (Hull et al. 1986, 20). The system rests above bedrock and is confined by clay above. It is exposed to the

Delaware River extensively between Wilmington, Delaware, and Trenton, New Jersey, and is particularly well connected hydraulically above River Mile (RM) 98 (ibid, 22).

Many communities throughout this region rely on the PRM aquifer system for their groundwater needs, and the system supplies approximately 28 percent of New Jersey's groundwater withdrawals (NJGS 2004), and 100 percent of total water supply for Camden, Cape May and Cumberland Counties (Hoffman 2002, 2). The reliance on the PRM system as a source of groundwater causes wells adjacent to rivers and streams to reverse the flow of groundwater. Groundwater travels downhill, feeding the river with water. Wells, however, lower the water table immediately around them, forming what is known as a cone of depression. When the cone of depression grows deep enough to intersect with the river bed, the aquifer begins to draw water from the river.

When aquifers begin to draw water from adjacent rivers, they take on that river's water quality issues as well. The water quality of the PRM aquifer system is directly correlated with the water quality of the Delaware. Therefore, increasing salinity of the Delaware Estuary means an increase in groundwater salinity as well. The Delaware River's 1961-65 drought of record proved the truth of this principle. During the drought, freshwater flows were reduced and saltwater from the ocean migrated upriver. The point at which the river's water becomes too saline to be potable, known as the salt line or salt front, shifted nearly 30 miles upriver from its general location at the Delaware Memorial Bridge, nearly threatening the City of Philadelphia's Torresdale drinking water intake. The increased salinity levels induced by the drought left measurable impacts on wells adjacent to the river, resulting in chloride levels measured at over twice their base value, and which would remain elevated for nearly 10 years (Hull et al. 1986, 24).

The well contamination associated with 1960s drought prompted authorities to begin studying the potential impacts similar droughts could bring in the future. In 1986, the US Environmental Protection Agency and the Delaware River Basin Commission produced the report "Greenhouse Effect, Sea Level Rise and Salinity in the Delaware River Estuary" (Hull et al. 1986). The report examines the existing conditions of the estuary and the effects of the 1960s drought, projects the effects of a similar drought occurring with 2.4' and 8.2' rises in sea level, and outlines specific mitigation techniques. In 2004, the US Geological Survey revisited this issue in the report "Vulnerability of Production Wells in the Potomac-Raritan-Magothy Aquifer System to Saltwater Intrusion from the Delaware River in Camden, Gloucester and Salem Counties" (Navoy et al. 2004). The study examined the saltwater intrusion vulnerability of 122 wells located within two miles of the Delaware, each capable of withdrawing 100,000 gallons daily.

The two reports present two different conclusions as to the overall vulnerability of the region's groundwater wells. This discrepancy comes down to two methodological variances between reports. First, the EPA/DRBC report examines the combined impact of sea level rise *and* future drought on the estuary; whereas the USGS report is limited to future drought scenarios exclusive of sea level rise. Second, the USGS report considers the impact of the travel time of saltwater migrating from the river *through* the aquifer into groundwater wells, whereas the EPA/DRBC report only measures the salinity of river water *entering* the aquifer. The EPA/DRBC report, by looking at higher base salinity levels in the river due to sea level rise, concludes that water entering the PRM aquifer system will exceed potability standards, and therefore poses a threat to the water supply. The USGS report, relying on significantly lower base salinity levels (e.g. present levels), finds that due to dilution due to travel time, the salinity of water entering the aquifers would need to be significantly (600 percent) higher than that of the 1960s drought, and therefore, saltwater intrusion is not a threat to the water supply.

It would appear that there needs to be a revision of these studies which both consider the increased base estuary salinity due to sea level rise and dilution effects of travel time between river and well. Further, the reports neglect several additional considerations:

Rising temperatures

A direct result of higher surface temperatures is an increase in evaporation rates. River water will grow more saline, as freshwater evaporates from the top of the water column. Future studies should attempt to incorporate such reductions in their estimates.

Storm surge & flooding

Research off the coast of North Carolina has shown that storm surge and tidal overwash can elevate salinity levels of adjacent freshwater aquifers. The Delaware estuary regularly receives storm surge warnings of approximately 9 feet, and has the potential to see surges of approximately 17 feet. An assessment of the impacts of such storm events would appear warranted.

Recalibrated equilibriums

Several reports noted that, in addition to current sea level rise and drawdowns due to wells, the transition zone between fresh and saltwater in the Delaware Estuary is significantly lower than would be expected via existing models. Hydrologists explain this as part of a lengthy recalibration of the groundwater table as a result of sea level rise after the most recent period of glaciation. It is likely that, outside of human influences, the salt line will move far inland of its own accord.

Increased demand

As population increases in the region, greater water withdrawals will be required. If the regions dependence on groundwater persists, this will increase the cones of depression around existing wells, therefore drawing higher volumes of water from the river and increasing the rate at which the aquifers will become saline. Future studies should be calibrated for expected population growth and expected demand.

Land cover change

As more land is converted from natural areas to development, increased impervious surfaces will direct more and more rainwater directly to streams and waterways. This will result in reduced groundwater recharge and increase the share of river water being drawn by wells. Again, future studies should be calibrated to account for such reductions in aquifer recharge.

Next Steps

One of the most apparent deficits of these studies is the lack of correlation between the aquifers potentially impacted and the populations they serve. Any future study should examine not only the possibility of saltwater intrusion, but the socioeconomic effects as well. To-date, reports have offered only qualitative descriptions, broad generalizations and anecdotal examples of potential impacts. From a planning & policy perspective, a threat needs to be quantitatively assessed not only in terms of the probability of occurrence or the magnitude of effects, but the costs of mitigation as well. The following outlines a three-part procedure for evaluating the financial costs of climate change's impacts on groundwater. The study is limited to southern New Jersey as a case study, given both the region's reliance on the PRM aquifer and the extensive degree of available information on the region.

Part 1: Project Future Demand: *How much water will we be relying on in 2050/2100?*

In order to effectively evaluate the impact of climate change on groundwater resources, there needs to be an understanding of approximately how much demand will be placed on those waters at the 2050 and 2100 benchmarks. Numerous sectors contribute to overall water demand, and an effective forecast will incorporate these into the demand model as reasonable. As an example, in a 2007 study of water demand projected to 2050 for the East Central Region of Illinois, five sectors were designated contributors to overall water demand, summarized in the table below.

Contributing Sectors: 2050 Water Demand Study for East Central Illinois

Sector	Approach	Driver	Variables
Public water supply	Multiple regression	Population	Employment
			Income
			Housing
			Marginal Price
			Temperature
			Precipitation
Self-supplied domestic	Per capita unit-demand	Unserved Pop	Median income
Self-supplied commercial & industrial	Multiple regression	Employment	Temperature
			Cooling degree days
			Employment in high-demand sectors
Irrigation/ Agriculture	Demand per irrigated acre/per unit of livestock	Irrigated acres/number of livestock	Biofuel capacity
			Temperature
			Precipitation
			Drought Index

Electric power generation	Demand per unit of power generation	Unit of power generation	Type of generation Type of cooling Temperature

Source: Illinois State Water Survey [*http://www.isws.illinois.edu/iswsdocs/wsp/ppt/Wittman_outreach.pdf*](http://www.isws.illinois.edu/iswsdocs/wsp/ppt/Wittman_outreach.pdf)

NJDEP maintains records of water withdrawals across the state based on the state's Watershed Management Areas (WMAs), with those most pertinent to the Delaware estuary's hydrology being 14, 17, 20, 21 and 23. Withdrawals are disaggregated by sectors roughly corresponding to those used in the Illinois study: agricultural, commercial, industrial, irrigation, mining, potable supply and power generation. Withdrawals are also disaggregated by source, either from groundwater or freshwater, although no recorded correlation exists between source and sector. Due to this lack of correlation, it is recommended that a gross, per-capita technique be utilized to calculate demand.

GIS shapefiles available from NJDEP for Water Purveyor Service Areas and Public Community Water Supply Wells can be used to identify those geographic areas reliant upon groundwater, either from public or private wells. These territories should be additionally demarcated along the state's Watershed Management Areas, as these are the recording units for groundwater withdrawals. This layer should then be used to determine the numerical portion of the population being served by groundwater within each WMA, which allows one to calculate per capita water usage for groundwater users. Using population projection and allocation techniques akin to the University of Pennsylvania 2008 Planning Studio, one can determine the population reliant on groundwater at the 2050 and 2100 benchmarks. Demand at each benchmark can be determined by multiplying per capita by the projected populations. Additional refinements may include changes in income and changes in temperature.

Part 2: Assess Vulnerability of Supply: *What will be the extent of damage to system?*

One needs to determine the extent to which a 0.5m and 1.0m sea level rise will have on a population projected to 2050 and 2100. As Navoy et al. have suggested that salinity levels in the Delaware would need to increase at least six fold before pushing aquifer salinity levels beyond water quality standards, every effort should be made to model as many parameters impacting river salinity. This should also compensate for changes in water consumption due to economic change, temperature increase, land conversion and conservation efforts.

Once having determined salinity levels for 2050 and 2100, one needs to determine the extent to which saline water will be drawn into the aquifers prior to becoming diluted within water quality standards by the time it reaches well screens. The existing literature states that those closest and with the highest withdrawal rates face the most direct threat, drawing more river water than from "natural" (i.e. via soil recharge).

In the previous step, groundwater dependent geographic areas were mapped in GIS. Using data available from NJDEP, one can ascertain the location and depth of both public and private wells within these areas, allowing one to calculate the distance between these wells and PRM aquifer outcrops under the Delaware, which can be used to calculate the proportion and concentration of saline water entering the well screen (Navoy et al), rendering total salinity for the well. Wells that exceed drinking water standards can be said to be impacted and in need of replacement.

Part 3: Evaluate Replacement Costs: *What is the cost to fix a damaged system?*

Geographically determining the demand for groundwater and the impact of saltwater intrusion allows one to determine the proportion of overall groundwater that will go unmet due to climate change. This unmet demand will need to be satisfied via alternative mechanisms: mitigation, conservation, and/or adaptation. The cost of implementation each strategy represents a potential way of determining the value of groundwater in the region. For example, going the route of mitigation could entail retrofitting existing wells with desalinization equipment, which would then be the cost of mitigation. Conservation via cutting back or abandoning saline wells can be measured as the total cost of lost economic revenue. An adaptation strategy could entail contracting alternative purveyors or constructing surface water intakes. The following table illustrates a possible way of organizing such data so as to compare different strategies for dealing with saltwater intrusion.

Contributing Sectors: 2050 Water Demand Study for East Central Illinois

Strategy	Technique	Capital Cost	Unit Cost	Lifespan
Adaptation	Desalination Units	?	?	?
Conservation	Abandonment	?	?	?
	Water Metering	?	?	?
	Stormwater BMPs	?	?	?
	Infrastructure Investment	?	?	?
Mitigation	Purveyor Purchase	?	?	?
	Surface Water Supply	?	?	?

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