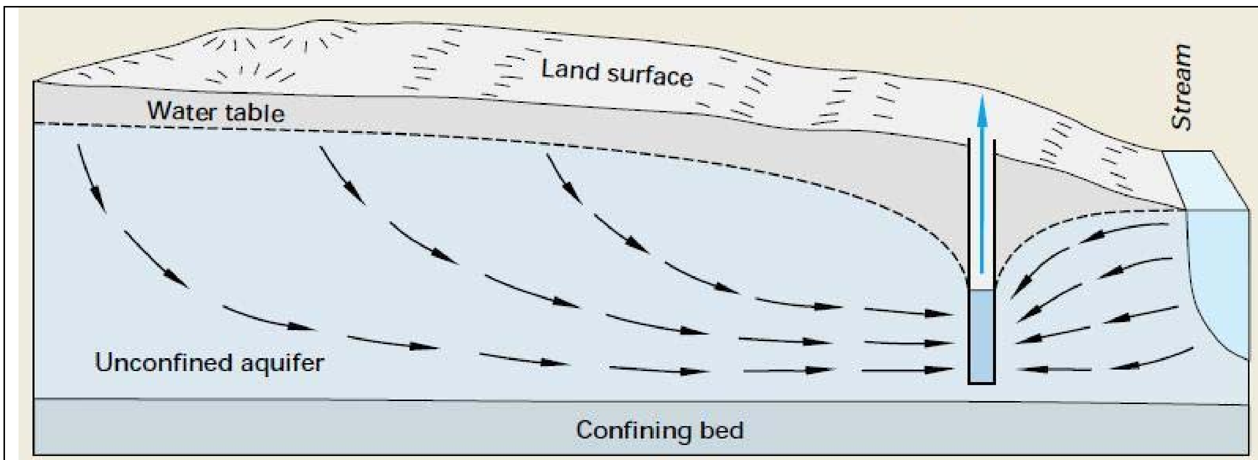
NEW JERSEY GEOLOGICAL SURVEY

Technical Memorandum 09-1

Potential Rate of Stream-Base-Flow Depletion from Groundwater Use in New Jersey



New Jersey Department of Environmental Protection

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NEW JERSEY GEOLOGICAL SURVEY

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On the cover:
A representation of induced stream leakage due to ground-water pumping in a water-table aquifer near a stream. After figure 13 of Alley and others (1999).

Epigram:
Understanding the interaction of groundwater and surface water is essential to water managers and water scientists. Management of one component of the hydrologic system, such as a stream or an aquifer, commonly is only partly effective because each hydrologic component is in continuing interaction with other components. (Winter and others, 1998)

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Potential Rate of Stream-Base-Flow Depletion from Groundwater Use in New Jersey

by

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Introduction

This report is an overview of the potential impacts of groundwater withdrawals on stream base flow. The New Jersey Department of Environmental Protection (NJDEP) must evaluate these impacts before issuing a permit for new withdrawals. This report reviews New Jersey-specific studies and presents data supporting the current regulatory approach that 90% of unconfined groundwater withdrawals is compensated for by nearby decreases in streamflow.

Groundwater withdrawn from an unconfined aquifer must be supplied by one of three mechanisms -- decreasing aquifer discharge, increasing aquifer recharge, or releasing water from storage. At steady state, when water levels have come to equilibrium and no more water is coming out of storage, all withdrawals are supplied by discharge decreases and/or recharge increases (Alley and others, 1999).

Groundwater withdrawals near streams can decrease stream flow by intercepting water that otherwise would have discharged to the surface (a decrease in aquifer discharge, called 'interception') or by pulling water directly from the stream (an increase in aquifer recharge, called 'induced leakage') (Winter and others, 1998). Both of these have the effect of decreasing streamflow. This is most noticeable at low streamflows when base flow, not overland storm runoff, is the primary component of streamflow. For this reason, the decrease in streamflow due to groundwater withdrawals is often called stream-base-flow depletion.

A number of groundwater modeling studies in New Jersey over the past 20 years provide information on stream-base-flow depletion (table 2, fig. 5). These modeling studies show that stream-base-flow depletion is generally between 80% and 100% of the groundwater withdrawal rate. A field study of streamflow on the Ramapo River in northern New Jersey near two major well fields confirms this range.

How Groundwater Pumpage Affects Stream Flow

Groundwater withdrawals from an unconfined aquifer can affect surface water through one of two mechanisms, interception or induced leakage. If the groundwater withdrawal is great enough, both mechanisms may occur.

Figure 1 shows a hypothetical situation with groundwater discharge to a stream. This discharge will naturally be greater when groundwater levels are higher, and lesser then groundwater levels are lower.

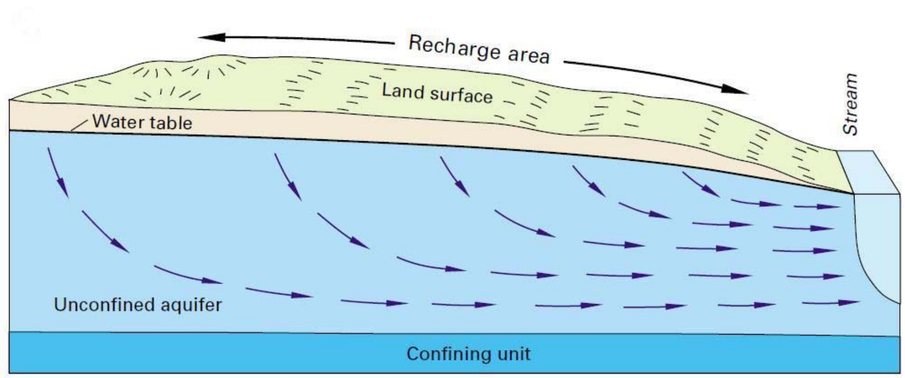

Figure 1. Example of pre-pumpage groundwater flow, with discharge to a stream. (After figure 13a of Alley and others [1999].)

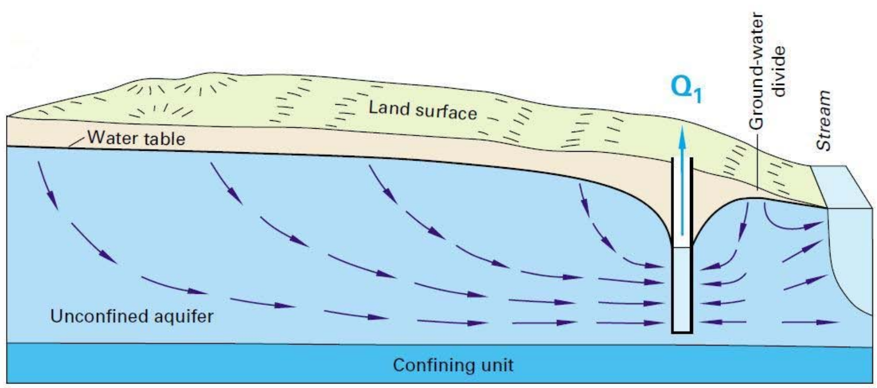

Figure 2. Example of post-pumpage groundwater flow with interception. (After figure 13b of Alley and others [1999].)

A pumping well lowers groundwater levels, modifies natural flow paths, and causes groundwater to flow towards the well. If the well pumps an unconfined aquifer, then the well will intercept some water that otherwise would have discharged to the surface (fig. 2). In this case the lower groundwater levels (called a drawdown cone) will lessen, but not totally halt, the rate at which water discharges from the aquifer into the stream.

If the well is close enough to the stream and withdraws enough water then the draw-down cone can reverse the groundwater gradient under the stream. This causes induced leakage; water flows from the stream into the aquifer (fig. 3). In this case, not only is streamflow reduced by the absence of base flow near the well, but it is also losing water to the aquifer.

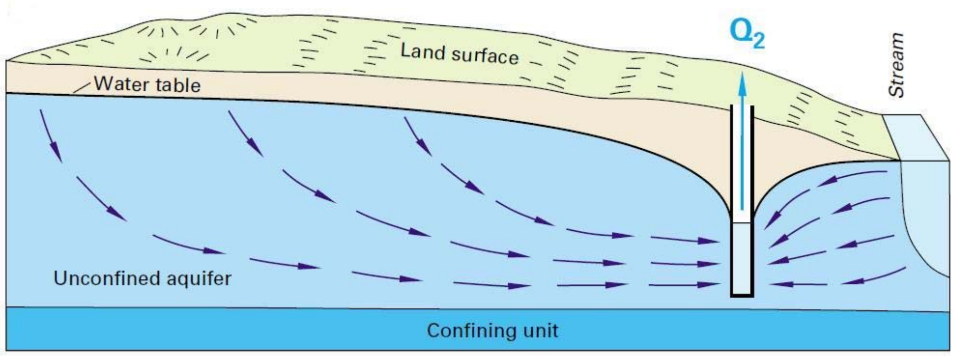

Figure 3. Example of post-pumpage groundwater flow with interception and induced leakage. (After figure 13c of Alley and others [1999].)

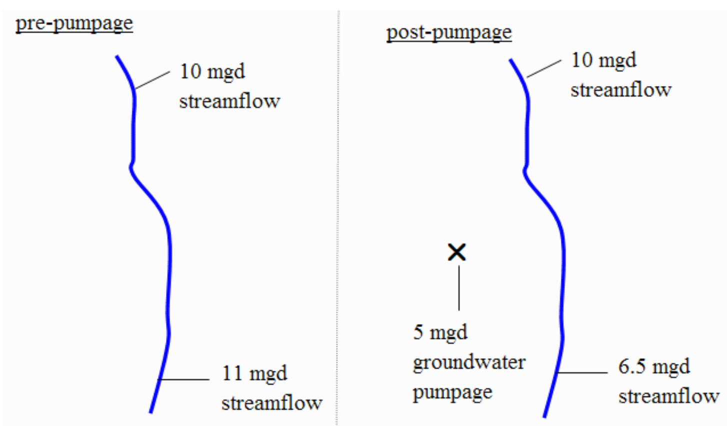

Figure 4. Hypothetical example of base flow interception and induced leakage. Pre-pumpage (left) & post-pumpage (right)

Figure 4 shows a hypothetical example. Under prepumping conditions the stream has 10 mgd flow upstream and 11 mgd downstream. It gains 1 mgd between the two monitoring points. Next, assume a 5 mgd well field is installed close to the stream. After the draw-down cone stabilizes, and under similar hydrologic conditions as the initial set of measurements, the stream has 10 mgd flow upstream and 6.5 mgd downstream. In this case the data support the conclusion that the well field has intercepted 1 mgd of water and is inducing 3.5 mgd leakage out of the stream. In short, base flow loss accounts for 4.5 mgd (90%) of the pumpage.

Aquifers act as reservoirs. When groundwater pumping starts the water stored in the aquifer's pores buffers the stress. Water coming out of storage lessens the impact of the pumpage and delays the widening of the drawdown cone. Thus pumping impacts on a nearby stream may not start immediately when the well is turned on, and the impact may take a while to build. But once the drawdown cone has stabilized no more water is coming out of storage and all of the pumpage must be sustained by water that otherwise would have discharged to the surface.

Stream depletion refers to what degree groundwater pumpage affects stream base flow. In other words, how much stream base flow is lost for every gallon of groundwater pumped?

Three kinds of studies performed in New Jersey provide the basis for estimating how groundwater pumpage affects base-flow discharge. These are direct streamflow measurements, transient groundwater models, and steady-state groundwater models.

Streamflow measurements, taken during low flow times, provide direct knowledge of how much water a stream gains or loses. A gaining stream is one in which flow increases due to groundwater base flow entering the stream. A losing stream decreases in flow as water leaks out of it into the underlying aquifer. Streams may naturally be gaining or losing at different places or at different times. However, New Jersey is normally relatively wet and most stream reaches in the state are gaining under natural conditions. Unless site-specific hydrogeologic conditions indicate otherwise, the NJDEP assumes that natural groundwater flow is from the aquifer into the stream.

A direct measurement of base-flow depletion is done by measuring streamflow upstream and downstream of pumping wells during a dry period. The most accurate estimates of base-flow depletion come from comparing measurements made before pumping to measurements made after the drawdown cone has stabilized. The change in streamflow allows an estimate of intercepted recharge and induced leakage. If only post-pumpage measurements are available, then they allow an estimate of induced leakage.

The United States Geological Survey (USGS) and New Jersey Geological Survey (NJGS) have used numerical groundwater-flow models to evaluate the effect of pumping on base-flow discharge to streams. Transient models account for changes in input conditions, typically seasonal variations in precipitation and pumping. These models can yield information on the magnitude and timing of seasonal base-flow depletion rates, and by how much they lag input variations. Steady-state models, which use constant input conditions during the entire simulation, cannot account for seasonal variations, but still produce valuable insights into the net effect of groundwater use on stream flow.

Figure 5 shows the general locations of these studies. Table 2 summarizes the location, setting, conditions, and outcome of these studies relative to the potential impact of stream-flow depletion on surface water.

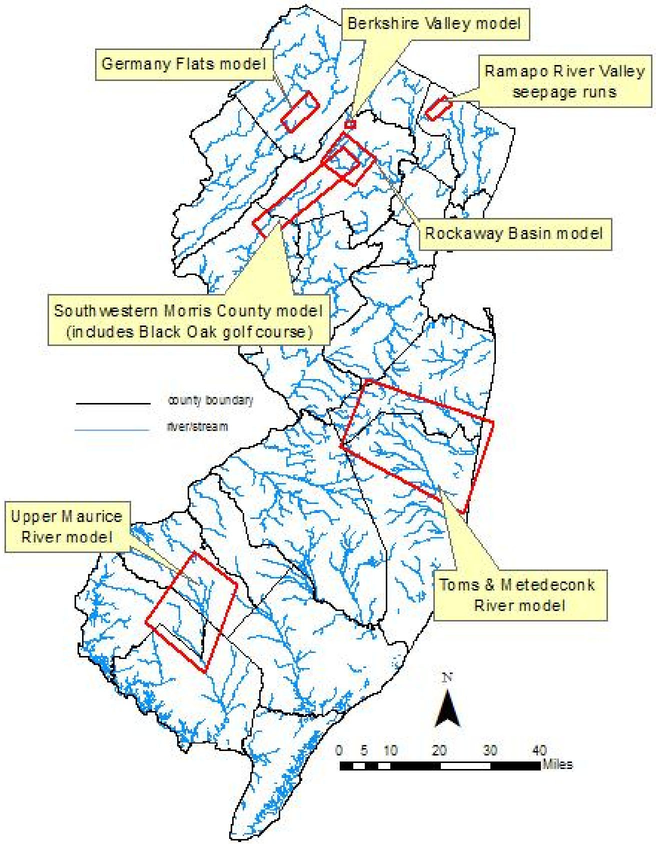

Figure 5. Study Areas

Table 1. Abbreviations and Acronyms

Abbreviation/Acronym	Meaning
BWA	Bureau of Water Allocation, NJDEP
cfs	cubic feet per second
mg	million gallons
mgd	million gallons per day
mgm	million gallons per month
mgy	million gallons per year
NJDEP	New Jersey Department of Environmental Protection
NJGS	New Jersey Geological Survey, NJDEP
USGS	United States Geological Survey

Table 2. Estimates of stream-base-flow reductions due to groundwater pumpage

Study area	Aquifer	Method of investigation	Reference	Pumping rate (mgd)	Base-flow reduction (mgd)	Base-flow reduction (percent of pumping rate)	Comments
Ramapo River Valley	Glacial valley fill	Streamflow study	Hill and others (1992)	1.90	1.68	88%	Mahwah's Ford well field
				1.49	1.88	126%	Oakland's Soons well field.
Rockaway River Basin	Glacial valley fill	Transient groundwater model, 2 years	Gordon (2002)	9.70	9.4	96%	September 1997
				9.0	8.9	98%	October 1997
		Transient groundwater model	Canace, Boyle, and Roman (2001)	0.30	0.19	63%	Berkshire Valley golf course. Interception only, no estimate of induced leakage. July estimates only. Lag effect not included.
Long Valley in Southwestern Morris County	Carbonate bedrock and valley fill	Steady state groundwater model	Nicholson and others (1996)	5.7	5.2	91%	Numbers are changes in pumpage and base-flow reduction. Interception only, no estimate of induced leakage.
				4.8	4.6	96%	
			Roman and Boyle (2003)	0.23	.21	90%	Black Oak Country Club. Modification of Nicholson and others (1996). Changes in pumpage and base-flow reduction. Interception only, no estimate of induced leakage.
				.16	.14	89%	
Southwestern Morris County	Carbonate bedrock and valley fill	Transient groundwater model	Roman and Canace (2003)	0.45	0.37 (max. month)	82% (max. month)	Flanders Valley well field. Numbers are changes in pumpage and base-flow reduction. Interception only, no estimate of induced leakage.
			Roman (2005)	0.58	0.48 (max. month)	85% (max. month)	

Table 2. Estimates of stream-base-flow reductions due to groundwater pumpage (cont.)

Study area	Aquifer	Method of investigation	Reference	Pumping rate (mgd)	Base-flow reduction (mgd)	Base-flow reduction (percent of pumping rate)	Comments
German Flats, Sussex County	Carbonate bedrock and valley fill	Steady-state groundwater model	Allan and Nicholson (2005)	0.365	0.336	92%	Sussex and Warren Holding Co.
Upper Maurice River Basin	Unconfined Kirkwood-Cohansey	Transient groundwater model	Cauller and Carelton (2005)			93%	Stream base flow depletion in Maurice River at Norma under full allocation withdrawals in August 1995.

Hydrologic Studies That Provide Information on Stream-Base-Flow Depletion

Streamflow measurements

Streamflow can be a major source of recharge to wells in unconfined aquifers. In some cases induced leakage from streams is sufficient to supply most of the pumpage of entire well fields. This induced leakage can significantly lessen streamflow, especially during dry periods.

Hill (1992) provides a good example of induced leakage in the Ramapo River Basin in northeastern New Jersey (figs. 6 and 7). Vecchioli and Miller (1973) determined that the Ramapo River here was a major source of water for withdrawals from the unconfined wells of the nearby Mahwah Township's Ford well field and Oakland Borough's Soons well field. Hill (1992) made detailed measurements of streamflow near these well fields in September 1983.

Figure 6 shows the location of stream measurement stations in the Ramapo River near Mahway's Ford well field. The hydrogeology of the well-field area suggests that the Ramapo would gain water in a downstream direction if there were no pumpage (Hill, 1992). However, streamflow upstream of the well field (13.8 cubic feet per second (cfs) was greater than just downstream (11.2 cfs). This loss of 2.7 cfs represented induced leakage caused by well field pumpage. During this time the wells were pumping at 2.9 cfs. Induced leakage thus accounts for about 89% of water pumped from the wells. The remaining water came out of aquifer storage or represents interception.

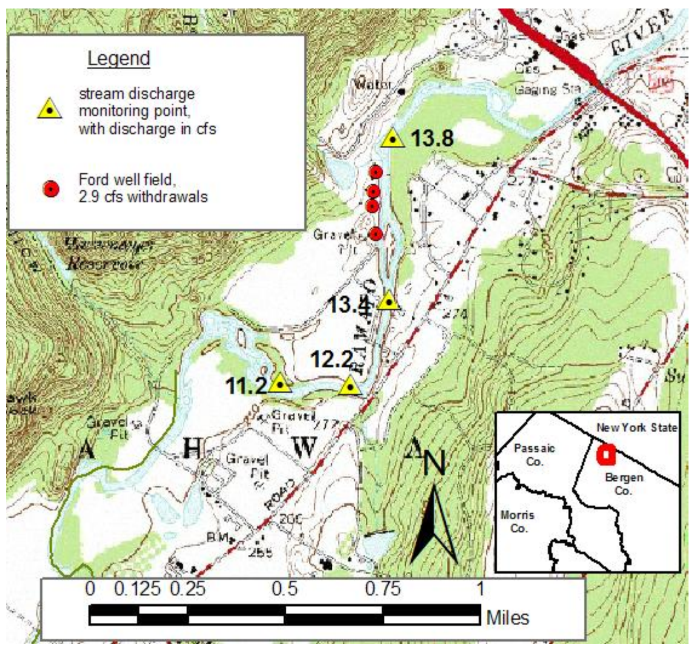

Figure 6. Observed streamflows near Mahwah Township's Ford well field, September 1983

Streamflow measurements of the Ramapo River at Oakland Borough's Soons well field yield similar results. Figure 7 shows that a loss of 2.9 cfs (1.87 mgd) was experienced between the measurement upstream of the well field (13.9 cfs) and the downstream measurement (11.0 cfs). The wells were pumping at an average rate of 2.3 cfs during this time. Thus, streamflow loss exceeded groundwater pumpage. This discrepancy may be due to delayed losses from previous pumping or losses due to other pumping in the area. In order to identify the percentage of stream base flow loss attributable solely to the Soons well field pumpage the streamflow measurements would have to be redone when the well field was not pumping and all other transient effects had been eliminated. Nonetheless, these measurements also suggest that groundwater pumpage significantly depletes stream flow in this hydrogeologic setting.

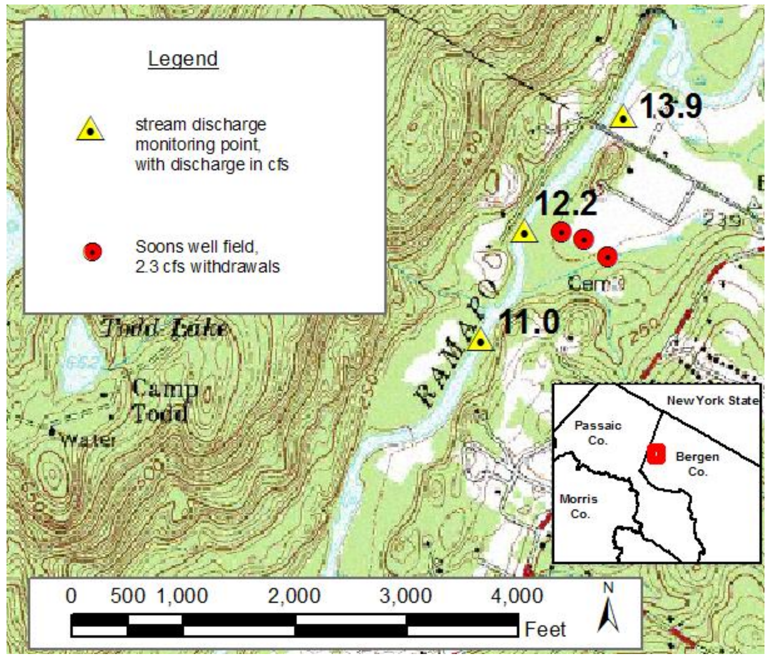

Figure 7. Observed streamflows near Oakland Borough's Soons well field, September 1983

In this area the unconfined sediments in the Ramapo River basin contain discontinuous layers of clay and silt. These less-permeable layers separate upper and lower zones of water-bearing material. Wells pumping from the lower zone may not significantly reduce streamflow at the well site but instead at a distance where the clay layer pinches out and no longer shields the stream from induced leakage. This effect can complicate determination of exactly where a well may affect streamflow.

Groundwater models

Groundwater-flow models are a numerical tool that can simulate a hydrologic system and determine its response to stress, such as groundwater pumpage. The results of several of these models provide insights into the impact of groundwater use on steam base flow.

- Rockaway River Basin groundwater model

Gordon (1993) presents a steady-state numerical groundwater model of the glacial valley-fill aquifer system in the Rockaway River Basin of Morris County. The aquifer system here consists of upper and lower sand-and-gravel aquifers separated by a semiconfining discontinuous silt-and-clay layer. Where the semiconfining layer is absent the upper and lower aquifers are in direct contact. The simulation of unstressed conditions shows that before withdrawals started the mainstem Rockaway River was a gaining stream.

Gordon (2002) expands this model to handle transient conditions for the period April 1994 to September 1998. This allows a more accurate simulation of monthly recharge and pumpage rates and how this variability affects month-by-month groundwater-surface water interactions. The transient modeling approach also allows the assignment of pumping rates that more accurately simulate actual seasonal changes in water use.

The transient model was calibrated to current water levels and base flow in the Rockaway River. Monthly aquifer recharge varies based on observed precipitation at a nearby climate station. Each month's portion of the average annual recharge is based on a previous groundwater model in the same watershed (Vronin and Rice, 1996).

As part of a simulation of hypothetical withdrawals, the model was first run without any pumpage to generate a baseline condition. Next, monthly recharge and pumping rates were introduced to simulate current conditions. Comparing the calibrated transient model to the baseline scenario allows an estimation of the effect of pumpage on base flow. For example, in September 1997 the 9.7 mgd withdrawn from the valley-fill aquifer intercepted 6.9 mgd of water that would have discharged to the stream and induced 2.4 mgd of leakage from the Rockaway River. Thus 96% of the pumpage is supplied by a decrease in stream base flow; water coming out of storage supplied the rest of the withdrawals. In October 1997 99% of the 9.0 mgd pumpage rate is supplied by a decrease in stream base flow. Gordon (2002) concludes "month-to-month increases in ground-water withdrawals from the valley-fill aquifers correspond to decreases in ground-water discharge to the Rockaway River that are approximately equal to withdrawals."

An increase in groundwater withdrawals may not cause an immediate reduction in stream flow. As pumping increases water comes out of storage in the aquifer. This is seen by a deepening of the drawdown cone close to the well to meet immediate demands. The cone expands outwards and may induce more leakage from nearby streams. This effect takes time, more when the well is further away from the stream. If pumpage decreases in a specific month the induced leakage that month may not decrease by the same amount. Gordon (2002) reports a delay in the full impact of pumping from the valley-fill aquifer on base flow in the Rockaway River. Increased withdrawals from the upper aquifer close to the stream decrease stream base flow immediately but take up to 7 months to be fully supplied by decreases in streamflow. Increased withdrawals from the lower aquifer may not increase induced leakage for several months and then take up to 1.5 years to be fully supplied by decreases in streamflow. This lag means that total streamflow depletion in any month is influenced by that month's pumping in addition to residual effects from previous months' pumping. Also, the degree to which any particular well's impact on stream base flow is lagged is governed by its distance from, and hydraulic connection to, the stream.

Roman (NJGS, personal communication, 2009) modified Gordon's (2002) transient Rockaway River Basin groundwater model. He examined the effect of increased seasonal withdrawals on stream base flow as well as the lag effect Gordon (2002) reported. He increased all monthly withdrawals by 11%, the volume projected to be needed to meet population increases.

The model shows that the largest base flow depletion rates occur in the month of most groundwater pumpage (typically June, July or August). The model shows that 80% of the increase in withdrawals between June and July is compensated for by decreases in base flow in July. The remaining 20% of increases comes out of aquifer storage immediately and causes a decrease in base flow in later months.

The impact of peak withdrawals continues to affect streamflow in following months. For some months in early fall, when withdrawals have decreased but the lagged impact of greater summer withdrawals is still being felt, total base flow depletion is greater than that month's pumpage.

- Berkshire Valley

Canace, Boyle and Roman (2001) report on a transient groundwater flow model of the upper Berkshire Valley along the Rockaway River in Jefferson Township, Morris County. The model simulates the effect of a proposed 11.2 mgm withdrawal at the Berkshire Valley golf course.

The proposed withdrawal is from the glacial valley-fill aquifer. The model consists of two layers, an upper aquifer (glacial sand and gravel) and a lower (bedrock) aquifer. The aquifers are simulated as isotropic and homogenous. Recharge rates are from a streamflow hydrograph separation analysis on the Rockaway River near the site and varied seasonally. The model uses 12 monthly periods to simulate seasonal variations in recharge and pumpage.

Model results show that during the 5-month irrigation season (May - September) decreases in base flow to streams in the modeled area supply between 62% and 70% of each month's withdrawals. July is the month with the greatest withdrawal rate, 0.30 mgd. This is also the month with the greatest loss of base flow discharge, 0.19 mgd cfs (63% of withdrawals). The water not supplied by intercepted base flow comes from groundwater that would have flowed laterally out of the study area. This intercepted water may have discharged to the stream outside of the modeled area. This value represents only intercepted groundwater. The model did not simulate induced leakage from the stream.

- Southwestern Morris County

Nicholson and others (1996) report on a steady-state groundwater model of the glacial-valley-fill and carbonate-bedrock aquifers in Long Valley in southwestern Morris County. The valley-fill sediments are a sequence of stratified drift, till, alluvium, colluvium and lake-bottom material of various ages. The valley-fill aquifer system consists of an upper and a lower aquifer. It overlies, and is in hydrologic communication with, a prolific bedrock aquifer that consists of fractured, weathered carbonate. The aquifers are bounded laterally by Precambrian gneiss, which, because of its much lower permeability, is simulated as a no-flow hydrologic boundary in the model.

The model examines the impact of major groundwater diversions and determines the source of water to major wells over the period 1988-1989. Nicholson and others (1996) used it to estimate changes in stream leakage and base-flow discharge due to future increases in withdrawals.

In one scenario, 5.7 mgd additional withdrawals is assigned to a new pumping center. This pumping rate is equivalent to the projected increase in groundwater use among major users in the entire study area for the year 2040. The second scenario consisted of increasing pumping by 4.8 mgd but spread out over existing well fields. The model showed decreases in stream base flow over a wide area of stream reaches under both scenarios. At steady state 91% of increased withdrawals in the first scenario was compensated for by a decrease in base flow discharge. For the second scenario 96% of the pumpage came from a decrease in base flow.

- Flanders Valley well field

Roman and Canace (2003) modified the Nicholson and others (1996) model in order to analyze proposed pumping increases from the carbonate-bedrock aquifer at the Morris County Municipal Utilities Authority's Flanders Valley well field. The modified model is a transient groundwater model that incorporates seasonal changes in recharge and pumpage.

Roman and Canace (2003) ran a two-year simulation of two scenarios: (1) A baseline scenario with current pumping from the Flanders well field at 58 mgm (1.87 mgd); and (2) A growth scenario with Flanders well field pumpage increased to 72 mgm (an increase of 14 mgm or .45 mgd). They compared the results from the two scenarios in order to estimate potential base flow changes due to the increased pumpage. This comparison showed that, on an average annual basis, 73% (0.33 mgd) of the increased pumpage comes from a decrease in stream base flow. The remainder of the water may come from lateral groundwater flow from a neighboring watershed not included in this model.

There is some variation in monthly impacts. The maximum decrease of monthly base flow is 0.37 mgd (81%). The decrease in aquifer discharge to streams varies from month to month due to seasonal recharge variations and a lag time between the months of greatest pumping and decline in base flow.

Roman (2005) further expands the Flanders well field model by adding a third scenario that increases the maximum monthly pumping rate from 72 mgm (the second scenario) to 90 mgm (an increase of 18 mgm or .58 mgd). This scenario shows that on an average annual basis, 74% of the increased pumpage comes from a decrease in stream base flow. In the most impacted month 83% of that month's increased withdrawals is supplied by base flow reductions.

- Black Oak golf course

Roman and Boyle (2003) modified the Nicholson and others (1996) groundwater model to simulate the steady-state effects of proposed bedrock withdrawals at the Black Oak Golf Club in Washington Township, Morris County. The original proposal requested 35.2 million gallons (mg) over a 5-month period. A second proposal reduced this volume to 23.6 mg. The revised model simulates both withdrawal volumes, assuming a steady pumping rate over the 5-month demand period. Model results show that of the requested volumes, 90% (of the 35.2 mg) or 89% (of the 23.6 mg) is supplied by a decrease in aquifer discharge to surface water.

- Germany Flats

Nicholson (1995) created a steady-state groundwater flow model of the hydrogeology of the Germany Flats carbonate-bedrock/glacial-valley-fill aquifer system in Sussex County. The model encompasses approximately 12.2 square miles, about two-thirds of which is in the East Branch Paulins Kill watershed and the remainder in the headwaters of the Pequest River. The NJGS has used this model several times to examine the impacts of proposed major groundwater withdrawals.

Allen and Nicholson (2005) used this model to investigate the potential impacts of a proposed withdrawal of 11.32 mgm (0.365 mgd) from wells completed in the glacial valley-fill aquifer in Andover Township. The wells are located near the surface- and groundwater divide between the Pequest and Paulins Kill watersheds. The investigation is based on comparing prepumpage base flow to a steady-state case with this additional pumpage added. Model results show that the wells would divert about 0.168 mgd of base flow from each watershed, for a total of 0.0.336 mgd. Thus 92% of the increased pumpage consists of water that would have otherwise discharged to streams or lakes in the vicinity. It is likely that the largest impacts would be felt in stream segments located closest to the pumping wells.

- Toms River, Metedeconk River and Kettle Creek Basins

Nicholson and Watt (1997) report on a transient groundwater model of the Toms River, Metedeconk River, and Kettle Creek Basins. The model is unique in that it considers recharge reductions (due to development) in addition to increased pumpage as causes of changes in groundwater levels and base flow. This model compares 1980's pumpage and development conditions to a pre-development condition.

Recharge reductions are due to increases in impervious cover as the watershed develops. The pumping increases are the result of two trends: (1) rapid population growth in southern Monmouth and northern Ocean Counties; and (2) restrictions on confined aquifer withdrawals under the state's Critical Areas program.

The model's output allows a more detailed comparison of water movement. A reanalysis of additional water budget information[1] shows that in the Toms River watershed 1980's base flow is 10.65 mgd less than pre-development conditions, a 7% decline. This is due to average pumpage of 7.93 mgd and also to an estimated 2.24 mgd reduction in recharge. These two factors account for a total of 10.16 mgd base flow reduction. The additional 0.48 base flow reduction is due to pumpage in nearby basins intercepting water that otherwise would have had discharged to Toms River. Of the total base flow reduction, 74% is due to pumpage in the basin and 5% to pumpage outside of the basin.

In the Metedeconk River watershed base flow has declined by 4.26 mgd. Pumpage averaged 1.86 mgd while decrease in recharge was 2.56 mgd. These two stresses add to 4.42 mgd, which is greater than the observed base flow decline. In this watershed some of the loss is compensated for by lateral inflow of groundwater.

In the Kettle Creek watershed the model estimates a base flow decline of .64 mgd. Pumpage averaged .16 mgd and the estimated decrease in recharge is .35 mgd, a net of .51 mgd loss. In this case, the Kettle Creek watershed, like the Toms River watershed, is supplying water to pumpage in neighboring watershed by groundwater lateral flow. Of the total base flow reduction, 45% is due to pumpage in the Kettle Creek and neighboring watersheds and 55% in this watershed.

[1] Data supplied by Robert Nicholson, U.S. Geological Survey, written communication, July 2009.

- Upper Maurice River Basin

Cauller and Carleton (2006) report on a three-dimensional groundwater flow model of the Upper Maurice Basin in southern NJ. The model simulates pre-development and current conditions, and projected pumpage based on future population growth scenarios. Regulators are concerned about documented decreases in base flows in this watershed. The model helps clarify the impacts of current withdrawals in the area, along with potential impacts of future increases.

The Kirkwood-Cohansey aquifer system consists of the coarse-grained, sandy Cohansey Formation and the finer-grained Kirkwood Formation. Both are prolific aquifers capable of sustaining public supply, industrial, and irrigation wells. The Cohansey overlies the Kirkwood and is a true water-table aquifer over most of its extent. In many places it is in direct hydrologic communication with streams and wetlands. Pumping from the Cohansey is partially sustained by leakage of surface water where the cone of depression of a well intersects the surface-water body. Even where there is no direct connection to a surface-water body, pumping from the Cohansey can intercept groundwater that would otherwise discharge to local surface-water bodies, lowering the water table under wetlands and ponds, and lessening stream flow. In places, particularly toward the Atlantic Coast, the Kirkwood Formation occurs under semi-confined conditions, partially confined by a unit composed mostly of silt and clay. This semi-confined condition isolates the Kirkwood to some degree from local surface water, but an indirect up-dip connection may still exist. Thus pumping from the Kirkwood may deplete surface water. In up-dip areas, away from the Atlantic Coast, the Kirkwood Formation tends to be in more direct communication with surface water, as it occurs at a more shallow depth and the semi-confining layer above the water-bearing sands is thinner and coarser. Such is the case in the Upper Maurice River Basin.

Cauller and Carleton (2006) compare three scenarios: pre-development, current (1995-1997) conditions, and future (increased) pumpage. The report does not go into great detail about what percentage of current pumpage is supplied by either induced leakage or interception. It does provide some information on source of water for future pumpage.

For example, in the Scotland Run watershed above Williamstown a future pumpage rate of 2.03 cfs (on a yearly average) is supplied by a reduction in base flow of 1.83 cfs. Thus, on average, 80% of the withdrawal is compensated for by a decline in base flow.

Cauller and Carleton (2006) do estimate net impacts of pumpage on base flow. This provides insight into the impact of water-table withdrawals on stream flow. For example, the simulation estimates in Scotland Run (a small headwaters stream) current pumpage reduces base flow by 62% during droughts and 28% during wet periods. The simulation also shows that if additional withdrawals are located near the Scotland Run then base flow is entirely eliminated during dry periods.

Moving simulated wells away from the stream to the surface-water divide lessened the base flow impact. Under one such scenario base-flow reduction was 48% of the pumpage during May 1995, but during June, August and September simulated flow in the stream was non-existent. Thus, the distance between the wells and the stream does affect the instantaneous impact on stream flow, but the lag effect caused by changes in groundwater storage may delay the most acute impacts.

The study also estimated base-flow reduction that might occur at a groundwater use equivalent to the maximum permitted monthly allocation during a severe drought. They found "a comparison of maximum allocation conditions with pre-development conditions indicated base flow was reduced by 93 percent during August 1995 at the Maurice River at Norma, NJ" (Cauller and Carleton, 2006, p. 46).

Summary

Groundwater withdrawals from the unconfined aquifer will decrease streamflow. The drawdown cone created by pumpage will intercept some groundwater that otherwise have discharged to the surface. This is called interception. If the drawdown cone is significant enough it may reverse the vertical hydraulic gradient and induce water to leak out of the stream into the aquifer. This is called induced leakage.

The New Jersey Department of Environmental Protection assumes that at least 90% of unconfined groundwater withdrawals are compensated for by a nearby decrease in streamflow. This conservative approach is confirmed by direct stream flow measurements and modeling results that show a decrease between 60% and 100%. All groundwater pumpage must be compensated for by a decrease in water discharge to the surface once groundwater levels have stabilized. Assuming 90% of this pumpage is compensated for by a reduction in nearby stream base flow is reasonably conservative and appropriate for regulatory analysis.

References

Allan, S. and Nicholson, L, 2005, Characterization of potential impacts to surface water for Sussex and Warren Holding Company, Water Allocation Permit number 5390: Internal NJDEP memorandum from Stephanie Allen and Laura Nicholson (NJGS) to Carolyn Olynyk (BWA), October 31, 2005, 5 p.

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of groundwater resources: U.S. Geological Survey Circular 1186, Denver, CO, 79p.

Canace, R.J., Boyle, J.T, and Roman, E.W., 2001, Berkshire Valley golf course – review of hydrogeologic report and evaluation of potential hydrologic impacts of proposed diversion: Internal NJDEP memorandum from Robert Canace, James Boyle and Eric Roman (NJGS) to Jan Gheen (BWA), May 4, 2001, 16 p.

Cauller, S.J. and Carleton, G.B., 2006, Hydrogeology and simulated effects of groundwater withdrawals, Kirkwood-Cohansey aquifer system, upper Maurice River Basin, New Jersey: U.S. Geological Survey Scientific Investigations Report 2005-5258, Reston, Va., 48 p.

Gordon, A.D., 1993, Hydrogeology of, and simulation of groundwater flow in, the valley-fill aquifers of the upper Rockaway River Basin, Morris County, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 93-4145, West Trenton, NJ, 73 p.

Gordon, A.D., 2002, Simulation of transient groundwater flow in the valley-fill aquifers of the upper Rockaway River Basin, Morris County, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 01-4174, West Trenton, NJ, 47 p.

Hill, M.C., Lennon, G.P., Brown, G.A., Hebson, C.S., and Rheaume, S.J., 1992, Geohydrology of, and simulation of groundwater flow in, the valley-fill deposits in the Ramapo River valley, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 90-4151, West Trenton, NJ, 92 p., 4 plates.

Nicholson, L.J. 1995. Ground water flow in a buried valley and effects of quarry dewatering on Howells Pond, Sussex County, New Jersey. Unpublished M.S. thesis, Drexel University.

Nicholson, R.S., McAuley, S.D., Barringer, J.L., and Godron, A.D., 1996, Hydrogeology of, and groundwater flow in, a valley-fill and carbonate-rock aquifer system near

Long Valley in the New Jersey Highlands: U.S. Geological Survey Water-Resources Investigation Report 93-4157, West Trenton, NJ, 159 p.

Nicholson, R.S. and Watt, M.K., 1997, Simulation of groundwater flow in the unconfined aquifers system of the Toms River, Metedeconk River, and Kettle Creek Basins, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 97-4066, 100 p.

Roman, E.W. and Boyle, J.T., 2003, Aquifer test analysis for the Black Oak Golf Club (BWA Permit 2545P) in Washington Township, Morris County: Internal NJDEP memorandum from Eric Roman and James Boyle (NJGS) to Carolyn Olynyk (BWA), May 14, 2003, 9 p.

Roman, E.W. and Canace, R.J., 2003, Review of Morris County MUA extended pump test on the Flanders Valley well field to analyze the proposed allocation increase to 72 million gallons per month : Internal NJDEP memorandum from Eric Roman and Robert Canace (NJGS) to Rob Hudgins (BWA), October 16, 2003, 10 p.

Roman, E.W., 2005, Morris County MUA – Permit modification for water allocation permit application no. 5058 (Flanders Valley well field): Internal NJDEP memorandum from Eric Roman (NJGS) to Rob Hudgins (BWA), September 22, 2005, 4 p.

Vecchioli, J. and Miller, E.G., 1973, Water resources of the New Jersey part of the Ramapo River basin: U.S. Geological Survey Water-Supply paper 1974, 77 p.

Vronin, L.M. and Rice, D.E., 1996, Hydrogeology and simulation of groundwater flow, Picatinny Arsenal and vicinity, Morris County, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 96-4061, West Trenton, NJ, 64 p.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.A., 1998, Groundwater and surface water, a single resource: U.S. Geological Survey Circular 1139, Denver, CO, 79 p.