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Recovery of Ground-Water Levels From 1988 to 2003 and Analysis of Potential Water-Supply Management Options in Critical Area 1, East-Central New Jersey

Scientific Investigations Report 2007-5193

U.S. Department of the Interior
U.S. Geological Survey

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By Frederick J. Spitz, Martha K. Watt, and Vincent T. dePaul

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.646317	million gallons per day (Mgal/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	365.25	million gallons per year (Mgal/yr)
million gallons per day (Mgal/d)	0.0006944	gallons per minute (gal/min)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Recovery of Ground-Water Levels From 1988 to 2003 and Analysis of Potential Water-Supply Management Options in Critical Area 1, East-Central New Jersey

By Frederick J. Spitz, Martha K. Watt, and Vincent T. dePaul

Abstract

Water levels in four confined aquifers in the New Jersey Coastal Plain within Water Supply Critical Area 1 have recovered as a result of reductions in ground-water withdrawals initiated by the State in the late 1980s. The aquifers are the Wenonah-Mount Laurel, the Upper and Middle Potomac-Raritan-Magothy, and Englishtown aquifer system. Because of increased water demand due to increased development in Monmouth, Ocean, and Middlesex Counties, five base and nine alternate management models were designed for the four aquifers to evaluate the effects resulting from potential reallocation of part of the Critical Area 1 reductions in withdrawals. The change in withdrawals and associated water-level changes in the aquifers for 1988-2003 are discussed. Generally, withdrawals decreased 25 to 30 Mgal/d (million gallons per day), and water levels increased 0 to 80 ft (feet).

The Regional Aquifer-System Analysis (RASA) ground-water-flow model of the New Jersey Coastal Plain developed by the U.S. Geological Survey was used to simulate ground-water flow and optimize withdrawals using the Ground-Water Management Process (GWM) for MODFLOW. Results of the model were used to evaluate the effects of several possible water-supply management options in order to provide the information to water managers. The optimization method, which provides a means to set constraints that support mandated hydrologic conditions, then determine the maximum withdrawals that meet the constraints, is a more cost-effective approach than simulating a range of withdrawals to determine the effects on the aquifer system. The optimization method is particularly beneficial for a regional-scale study of this kind because of the large number of wells to be evaluated. Before the model was run, a buffer analysis was done to define an area with no additional withdrawals that minimizes changes in simulated streamflow in aquifer outcrop areas and simulated movement of ground water toward the wells from areas of possible high chloride concentrations in the northern and southern parts of the Critical Area.

Five base water-supply management models were developed. Each management model has an objective function, decision variables, and constraints. Two of the five management models were test cases: clean slate option and reallocation from the Wenonah-Mount Laurel aquifer and Englishtown aquifer system to small volume wells for potable water use. Nine other models also were developed as part of a trade-off analysis between withdrawal amounts and constraint values. The 14 management models included current (2003) or regularly spaced well locations with variations on the constraints of ground-water head, drawdown, velocity at the 250-mg/L (milligram per liter) isochlor, and withdrawal rate.

Results of each management model were evaluated in terms of withdrawals, heads, saltwater intrusion, and source of water by aquifer. Each trade-off curve was defined by using six to nine separate management model runs. Results of the management models designed in this study indicate that a withdrawal reallocation of 5 to 20 Mgal/d within Critical Area 1 would increase the area of heads below -30 ft and the velocity at the 250-mg/L isochlor by up to 4 times that of the simulated 2003 results; the range of values are 0 to 521 square miles and 1 to 20 feet per year, respectively. The increase in area of heads below -30 ft was larger in the Middle Potomac-Raritan-Magothy aquifer than in other aquifers because that area was negligible in 2003. The range of modeled withdrawals is closely tied to management-model design. Interpretation of management model results is provided as well as a discussion of limitations.

Introduction

Ground-water development in the New Jersey Coastal Plain has occurred primarily near large population centers, creating large regional cones of depression in several New Jersey Coastal Plain aquifers. In the northern Coastal Plain, water-level measurements in the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, and the Upper and Middle Potomac-Raritan-Magothy aquifers in 1983 were as low as 196, 249, 59, and 91 ft below NGVD 29, respectively (Eckel and Walker, 1986). The continued decline of water levels in these confined aquifers posed the threat of serious adverse effects to the water supply in some areas, including the depletion of ground-water supplies, saltwater intrusion, and reduction of ground-water flow to streams (N.J. Department of Environmental Protection, 1996). In response to these water-resource threats, the N.J. Department of Environmental Protection (NJDEP) designated two water supply **Critical Areas**[1] where excessive withdrawals create undue stress or long-term adverse effects on the water supply (Hoffman and Lieberman, 2000).

The criteria upon which the NJDEP designates a critical water-supply area include one or more of the following hydrologic conditions: (1) shortage of surface water due to diversions from surface- or ground-water sources that leaves insufficient surface water for permitted, certified, or registered diversions or for environmental protection purposes within a drainage area of at least 10 mi^2; and (2) shortage of ground water due to diversions exceeding the long-term, safe, or dependable yield of an aquifer in an area of at least 10 mi^2 (New Jersey Administrative Code, 2005). The NJDEP may demonstrate such a shortage by a verified mathematical ground-water model, or if such a model is unavailable, by one or more of the following: (a) a progressive lowering of ground water to the extent that existing wells of 50 feet or more in depth are threatened by declining water levels or rendered inoperative and (b) a reduction of the average potentiometric surface in a confined aquifer such that the 30-foot contour below NGVD 29 is within 5 miles of saltwater or intersects the 250-mg/L **isochlor**.

On the basis of the low water levels measured in 1983 by the U.S. Geological Survey (USGS), the NJDEP determined that four aquifers, namely—Wenonah-Mount Laurel aquifer, Englishtown aquifer system, Upper Potomac-Raritan-Magothy aquifer, and Middle Potomac-Raritan-Magothy aquifer—were depleted in east-central New Jersey such that designation of an area of critical water supply concern was warranted. Specifically, it was determined that adverse conditions existed and that special measures were required to ensure the integrity and viability of the water supply. Therefore, in July 1985 and June 1990, by administrative order, the NJDEP designated Water Supply Critical Area 1 in Middlesex, Monmouth, and Ocean Counties (fig. 1). The boundary of the **depleted zone** of Critical Area 1 corresponds to the average 1983 potentiometric contour 30 feet below NGVD 29 for each affected aquifer, as published in Eckel and Walker (1986). The extent of Critical Area 1 is a "composite" that includes the largest surface extent of the depleted zones and threatened margins for all four aquifers. The **threatened margin**, consisting of a 3-mile wide area, surrounds the depleted zone of each aquifer (Hoffman and Lieberman, 2000).

In an effort to improve the management of ground-water resources in the confined aquifers within Critical Area 1, the NJDEP set out alternate water-supply plan procedures starting in 1986. Actual reductions in withdrawals were implemented starting in 1989. Within Critical Area 1, ground-water withdrawals from production wells in the depleted zone were reduced by 50 percent of 1983 rates in the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, and Middle Potomac-Raritan-Magothy aquifer, and by 40 percent of 1983 rates in the Upper Potomac-Raritan-Magothy aquifer. Withdrawals in the threatened margin were limited at 1983 rates. Purveyors had the opportunity to interconnect with alternative water sources—shallower non-restricted aquifers, ground-water sources outside the Critical Area, other purveyors, or surface-water supplies. New withdrawal allocations (with the exception of temporary construction dewatering and ground-water remediation activities) were prohibited by the New Jersey Water Supply Management Act (New Jersey Statutes Annotated, 1981). After designation of the Critical Area, withdrawal reductions resulted in water-level recovery in the affected aquifers from 1988 to 2003 and accompanying changes in the ground-water-flow system. Outside of the Critical Area, development of water supply is less regulated, and water quantity and quality concerns may occur. For example, the NJDEP has denied allocation requests when new or increased withdrawals outside of the Critical Area divert water from an affected aquifer and adversely affect the aquifers within the Critical Area (Fred Sickles, New Jersey Department of Environmental Protection, written commun., 2007).

In response to the changes in the ground-water-flow system and demands for additional water supply, the NJDEP is reevaluating allocations within the Critical Area and the effects of possible changes in allocations on the ground-water resources. During 2005-06, the USGS, in cooperation with the NJDEP, used an existing regional ground-water-flow model and a formal **optimization** technique to evaluate effects of several water-supply **management options** to provide needed information on additional withdrawals to water managers. These techniques were selected over standard trial and error withdrawal scenarios for cost and time efficiencies and applicability to the specific concerns in Critical Area 1. Such an approach is particularly beneficial for a regional-scale study of this kind because of the large number of wells to be evaluated.

A buffer analysis was conducted prior to the optimization to define an area of no additional withdrawals that minimizes changes in simulated streamflow in aquifer outcrop areas and simulated movement of ground water from areas that may have high chloride values in the northern and southern parts of the Critical Area. The revised USGS Regional Aquifer-System Analysis (RASA) flow model of the New Jersey Coastal Plain (Voronin, 2004) was used with the new Ground-Water Management Process (GWM) for MODFLOW (Ahlfeld and others, 2005) to analyze the ground-water-flow system. Model runs that incorporate proposed changes in allocations and recent changes in development outside the Critical Area were used to quantify the effects of such changes.

This approach used in this study is applicable to other studies of the Atlantic Coastal Plain because of similar hydrogeology and water-resource concerns (for example, water-level declines and saltwater intrusion). The approach also is applicable to optimization studies that use redefined **constraints**. The development of an upper bound on the gradient constraint in this study is applicable to optimization studies of contaminant movement where setting a lower bound is not an option.

[1]Words in bold are defined in the glossary at the end of the report.

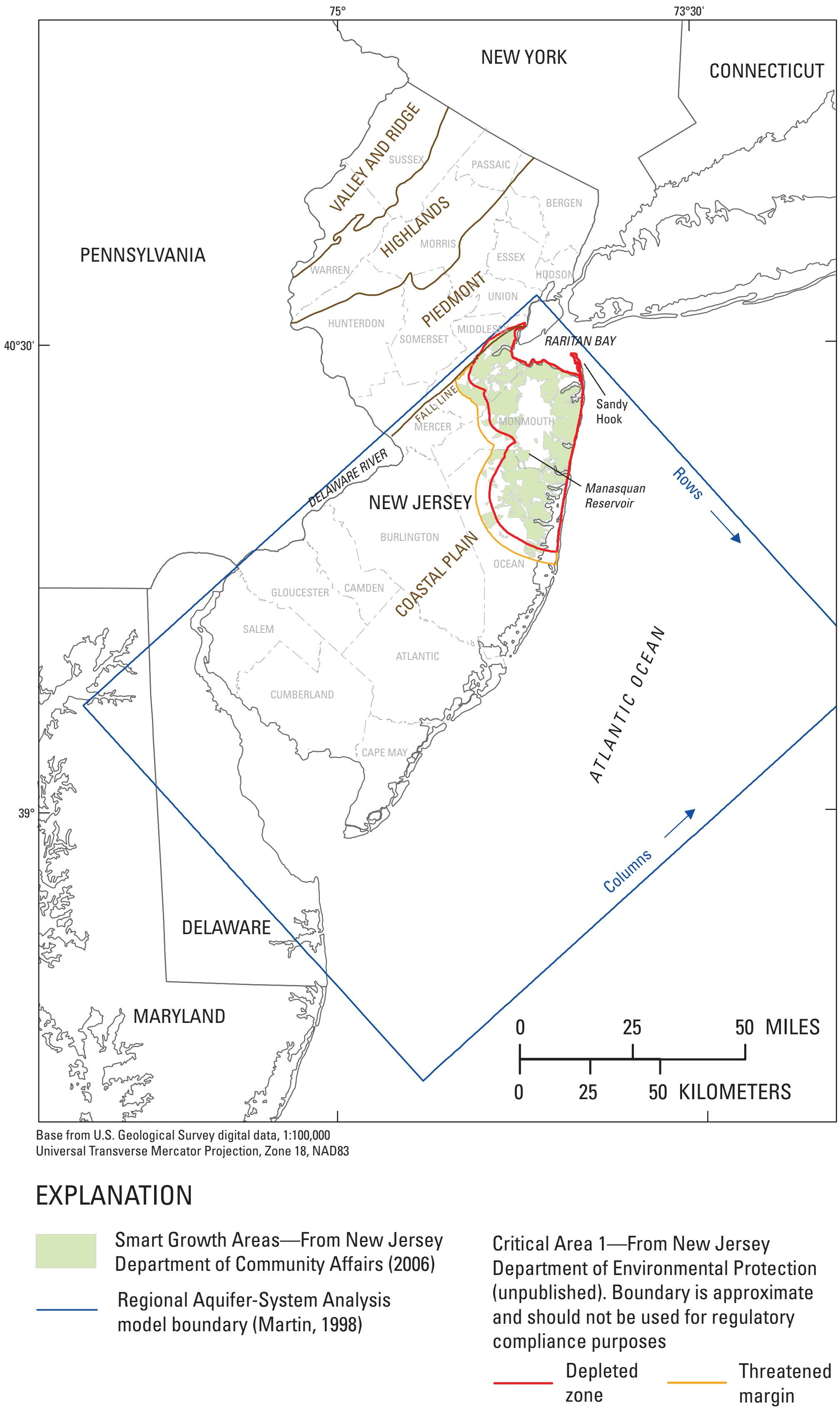

Figure 1. Location of Water Supply Critical Area 1, east-central New Jersey.

Purpose and Scope

The purpose of this report is to present the results of an analysis of the effects of an increase in water allocations that were reduced with the implementation of Critical Area 1 in east-central New Jersey. This report describes the hydrogeology of the study area and the recovery of the ground-water levels in the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, Upper Potomac-Raritan-Magothy aquifer, and Middle Potomac-Raritan-Magothy aquifer from 1988 to 2003. The model and software used to simulate the additional water-supply allocation also are described.

In this report (1) the effects of proposed changes in withdrawals within the Critical Area are quantified; (2) the hydrologic constraints modeled within the Critical Area are defined; and (3) the optimal amount and distribution of additional withdrawals that result from the simulation, subject to the constraints, are presented. This report documents the formulation of 14 management models that demonstrate the effects of withdrawal locations and volumes on head, drawdown, location of the 250-mg/L isochlor, and withdrawal rate. Landward movement of the 250-mg/L isochlor is used to define saltwater intrusion.

Description of Study Area

Critical Area 1 is located in the northern Coastal Plain and includes parts of Middlesex, Monmouth, and Ocean Counties (fig. 1). The total area is approximately 906 mi^2. According to data from the U.S. Census Bureau, Middlesex, Monmouth, and Ocean Counties are the third, fourth, and seventh most populated counties in the State, respectively (New Jersey Department of Labor and Workforce Development, accessed February 19, 2006). According to data collected in 2000, these three counties accounted for 89 Mgal/d, or 22 percent, of the total ground water withdrawn in the State from production wells (Hutson and others, 2004).

The boundaries for the two areas comprising Critical Area 1, the inner depleted zone and the outer threatened margin, are shown in figure 1. The threatened margin is a 3-mile-wide area surrounding the depleted zone, except along the northern edge where the threatened margin is not indicated (the depleted zone abuts the **Fall Line**). These areas are further refined as **aquifer subareas**. (See section "Water-Supply Management Models") Regulation of withdrawals in Critical Area 1 was implemented using the boundaries for individual aquifers, not the composite boundary (Hoffman and Lieberman, 2000, p. 25).

Hydrogeology

The New Jersey Coastal Plain is a seaward-dipping wedge of unconsolidated sediments that range in age from Cretaceous to Holocene (Zapecza, 1989, table 2). These sediments consist mainly of clay, silt, sand, and gravel and are divided into different hydrogeologic units. In Critical Area 1, the total thickness of the sediments increases from about 150 ft at the outcrops in Middlesex County to about 1,800 ft near the barrier islands in Ocean County. The sediments crop out at land surface in northeast-southwest trending bands (strike) and dip to the southeast at 10 to 60 ft/mi (fig. 2). Hydrogeologic units that are mostly sand and gravel are permeable and are considered aquifers, and those that are mostly silt and clay are relatively impermeable and are considered confining units (fig. 2). A detailed discussion of the hydrogeology of the New Jersey Coastal Plain is found in Zapecza (1989).

The regulated aquifers in Critical Area 1, in order of increasing depth, are the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, Upper Potomac-Raritan-Magothy aquifer, and Middle Potomac-Raritan-Magothy aquifer. The Wenonah-Mount Laurel aquifer consists of the coarse-grained part of the Wenonah Formation and the Mount Laurel Sand; it is 60 to 80 ft thick in Monmouth and Ocean Counties (Zapecza, 1989). The aquifer is used most heavily in southeast Monmouth and northeast Ocean Counties because of its uniform thickness and good water quality (Jablonski, 1968). The Wenonah-Mount Laurel aquifer is in good hydraulic connection with the underlying Englishtown aquifer system because of the leaky confining unit that separates them (Zapecza, 1989, p. B14).

The Englishtown aquifer system is composed of fine- to medium-grained sand of the Englishtown formation and ranges in thickness from 40 ft near the outcrop in Monmouth County to greater than 140 ft near the barrier islands in Monmouth County. The Englishtown aquifer system is underlain by the Merchantville-Woodbury confining unit, which is the most extensive confining unit in the Coastal Plain. In Monmouth County this confining unit reaches thicknesses of greater than 100 ft and forms an effective impediment to flow between the Englishtown aquifer system and the Upper Potomac-Raritan-Magothy aquifer below.

The Potomac-Raritan-Magothy aquifer system contains the most productive aquifers in the Coastal Plain and is divided into three aquifers—the upper, middle, and lower. The Upper Potomac-Raritan-Magothy aquifer is the most extensive hydrogeologic unit of the three. In the northeastern Coastal Plain, the Upper Potomac-Raritan-Magothy aquifer corresponds to the Old Bridge Sand Member of the Magothy Formation. In Monmouth and Ocean Counties, the Upper Potomac-Raritan-Magothy aquifer is greater than 200 ft thick and consists mainly of permeable coarse-grained sediments with thin localized clay beds. In the northeastern Coastal Plain, the Middle Potomac-Raritan-Magothy aquifer corresponds to the Farrington Sand Member of the Raritan Formation. The thickness of the Middle Potomac-Raritan-Magothy aquifer is less than 50 ft near the outcrop area to more than 150 ft near the junction of Mercer, Middlesex, and Monmouth Counties. Although the top of the Middle Potomac-Raritan-Magothy aquifer can be traced into northern Ocean County, it is not possible to separate it from underlying sediments. The

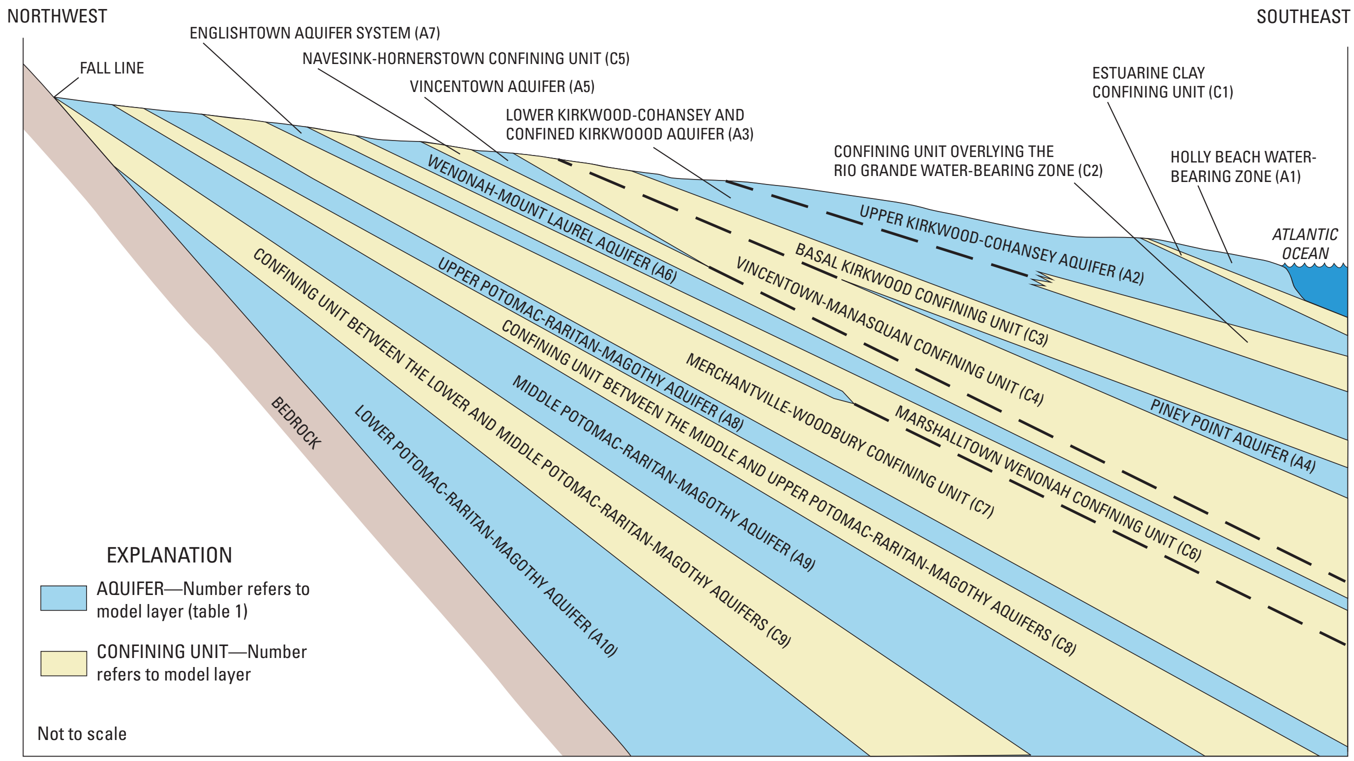

Figure 2. Generalized hydrogeologic section through the New Jersey Coastal Plain.

Lower Potomac-Raritan-Magothy aquifer is not present in the northeastern Coastal Plain.

Previous Investigations

Various regional studies describe the hydrogeologic framework of, and ground-water flow in, the New Jersey Coastal Plain. Zapecza (1989) describes the hydrogeologic framework. Synoptic water-level studies have been done for each of the major confined aquifers every 5 years since 1978 by the USGS. For each synoptic study, water levels were measured during the fall and represented annual average conditions. The most recent published work is the 1998 synoptic study by Lacombe and Rosman (2001) that comprises a series of maps showing water levels in the aquifers. Water levels from the 2003 synoptic study are on file at the USGS office in West Trenton, N.J. (V.T. dePaul, U.S. Geological Survey, written commun., 2007). The maps show the areas of decline (1978 to 1988) and recovery (1988 to 2003) of water levels in the aquifers underlying Critical Area 1. In addition, Martin (1998) and Voronin (2004) describe simulated ground-water flow in the New Jersey Coastal Plain (discussed farther on).

County-wide water-resource studies for Middlesex, Monmouth, and Ocean Counties were done by Barksdale and others (1943), Jablonski (1968), and Anderson and Appel (1969), respectively. Barlow and Dickerman (2001) and Granato and Barlow (2005) describe simulations related to water-supply management; these two studies were conducted in areas outside of New Jersey.

Recovery Of Ground-Water Levels

The ground-water flow system, changes in ground-water withdrawals, and changes in water levels in the study area during 1988-2003 are described in this section. Within Critical Area 1, withdrawal reductions initiated in 1985 and 1990 have resulted in increased water levels and other changes in the ground-water-flow system.

Ground-Water-Flow System

A detailed discussion of ground-water flow in the New Jersey Coastal Plain is found in Martin (1998). Flow in New Jersey Coastal Plain aquifers is affected by the hydraulic properties of the saturated sediments, the amount of recharge, and the locations of recharge and discharge.

Prior to water-supply development, water flowed through the aquifers from recharge areas to discharge areas. The aquifers were recharged by precipitation that fell on aquifer outcrop areas. Infiltration that reached the shallow ground-water system discharged to a local stream or pond. Infiltration also may have traveled vertically into deeper underlying hydrogeologic units and eventually discharged to larger rivers or Raritan Bay. In Critical Area 1, predevelopment flow paths indicate ground water flowed from areas of high ground-water levels in Middlesex County and Monmouth County toward topographic low points—Raritan Bay and the Atlantic Ocean (Schaefer and Walker, 1981).

After water-supply development, the location and the amount of ground-water withdrawals controlled ground-water-flow paths. Withdrawals lowered ground-water levels creating cones of depression, redistributed recharge and discharge areas by reversing flow direction, reduced ground-water discharge to streams and induced ground-water recharge from streams, and changed flow between aquifers. In the Upper Potomac-Raritan-Magothy aquifer in northern Monmouth County, increased withdrawals lowered ground-water levels to below NGVD 29. As a result, the ground-water-flow direction has reversed, converting previous discharge areas into recharge areas. In areas where the Upper Potomac-Raritan-Magothy aquifer is in good hydraulic connection with Raritan Bay, seawater is now able to recharge the aquifer (Pucci and others, 1994).

Changes in Withdrawals and Water Levels from 1988 to 2003

Since the early 1900s withdrawals in the northern New Jersey Coastal Plain have increased steadily. By the late 1950s, ground-water withdrawals created regional cones of depression in both the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers along the coastline of Raritan Bay and near the Raritan River, respectively (Farlekas, 1979). In the 1970s and 1980s withdrawals leveled off, but water levels continued to decline. Total withdrawals in the depleted zone of Critical Area 1 for the four aquifers of interest equaled 76.7 Mgal/d in 1983.

During 1983-88, total withdrawals in Critical Area 1 increased by only 2 percent; however, water levels continued to decline as much as 52 ft and 34 ft in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system, respectively (Rosman and others, 1995). Water levels declined 2 to 3 ft in the Upper Potomac-Raritan-Magothy aquifer in Middlesex and Monmouth Counties, 14 ft on average in the Middle Potomac-Raritan-Magothy aquifer in Monmouth County, and as much as 20 ft in Ocean County. Cones of depression within the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers broadened and deepened. In 1988, the lowest observed water levels were 200 ft, 220 ft, 40 ft, and 100 ft below NGVD 29 in the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, Upper Potomac-Raritan-Magothy aquifer, and Middle Potomac-Raritan-Magothy aquifer, respectively.

During 1988-93, withdrawal reductions in Critical Area 1 initiated by NJDEP went into effect. The total reduction in withdrawals in the depleted zone of Critical Area 1 was about 34 Mgal/d. Compliance by individual purveyors depended on when they could obtain an alternative water source. For example, the Manasquan Reservoir, a regional surface-water alternative source, was not available until July 1990 (Jan Gheen, N.J. Department of Environmental Protection, oral commun., 2006). The first year that most of the purveyors were in compliance with Critical Area 1 regulations was 1991.

Potentiometric surfaces in each of the four aquifers along cross section A-A’ through the New Jersey Coastal Plain at 5-year intervals from 1988 to 2003 are shown in figures 3 to 6. Ground-water withdrawals in the depleted zone from 1980 to 2003 and the total change in water levels from 1988 to 2003 also are shown. The cross section is the same as that used in the prior synoptic studies of water levels in the confined aquifers of the New Jersey and Delaware Coastal Plain (V.T. dePaul, U.S. Geological Survey, written commun., 2007). The cross section does not necessarily pass through the deepest parts of the cones of depression; therefore, some of the lowest water levels are not shown on the figures.

A cross section depicting water-level altitudes in the Wenonah-Mount Laurel aquifer is shown in figure 3a. Withdrawals in the Wenonah-Mount Laurel aquifer were small, about 2 Mgal/d in 1988, and less than 0.5 Mgal/d by 1991 (fig. 3b). Withdrawals after 1991 remained relatively stable through 2003. Water levels in the Wenonah-Mount Laurel aquifer recovered more than 50 ft during 1988-93 (Lacombe and Rosman, 1997). The cone of depression along the coastline in southern Monmouth and northern Ocean Counties decreased in extent. Water levels continued to rise in the cone of depression by as much as 50 ft during 1993-98 (Lacombe and Rosman, 2001), then remained fairly stable during 1998-2003. The total 15-year change in water levels in the Wenonah-Mount Laurel aquifer is shown in figure 3c. Water levels recovered by more than 80 ft in a 72 mi^2 area along the coast in southern Monmouth and northern Ocean Counties. Water levels recovered over 10 ft in more than 50 percent of Critical Area 1.

A cross section depicting water-level altitudes in the Englishtown aquifer system is shown in figure 4a. Withdrawals in the Englishtown aquifer system totaled about 9 Mgal/d in 1988 and declined to about 6 Mgal/d by 1991 (fig. 4b). After 1991, withdrawals remained fairly stable through 2003. Water levels in the Englishtown aquifer system rose more than 50 ft, and the cone of depression decreased in extent during 1988-93. Water levels continued to rise in the cone of depression, up to 50 ft during 1993-98, then remained fairly stable during 1998-2003. The total 15-year change in water levels in the Englishtown aquifer system is shown in figure 4c. Water levels recovered by more than 80 ft in a 110 mi^2 area along the coast in southern Monmouth and northern Ocean Counties. Water levels rose by more than 10 ft in over 76 percent of Critical Area 1. The water-level recovery in the Englishtown aquifer system is similar to that in the Wenonah-Mount Laurel aquifer because the two aquifers are in good hydraulic connection, but the recovery was greater in the Englishtown aquifer system because most of the withdrawals that affected the two aquifers were made from this aquifer. The Englishtown aquidfer system and Wenonah-Mount Laurel aquifer also have low

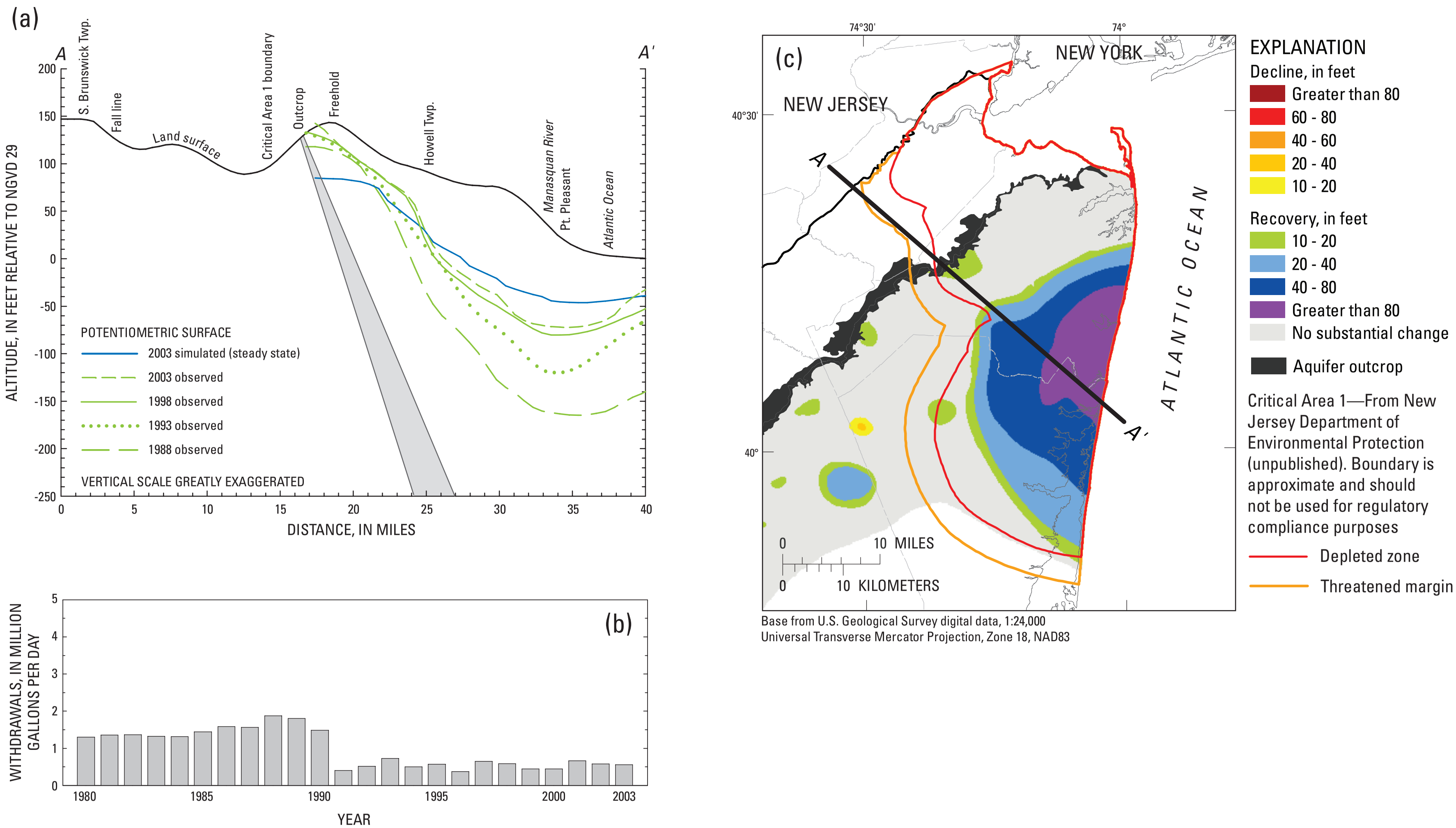

Figure 3. Wenonah-Mount Laurel aquifer (a) potentiometric surfaces along section A-A′, 1988-2003; (b) withdrawals in the depleted zone of Critical Area 1, 1980-2003; and (c) water-level changes in Critical Area 1, 1988-2003, east-central New Jersey. (Potentiometric surfaces from Rosman and others (1995), Lacombe and Rosman, (1997), Lacombe and Rosman, (2001) and V.T. dePaul (U.S. Geological Survey, written commun., 2007))

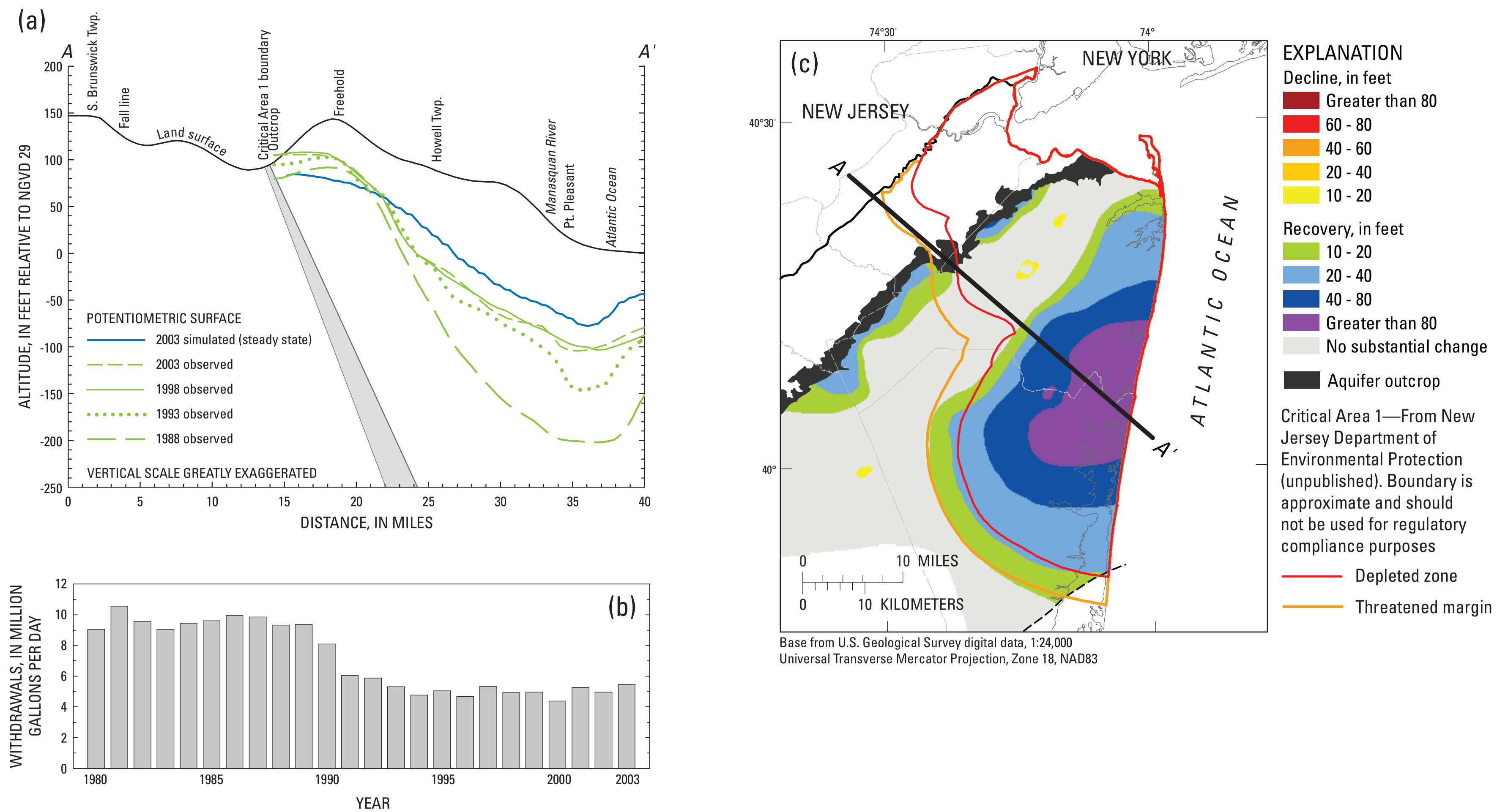

Figure 4. Englishtown aquifer system (a) potentiometric surfaces along section A-A′, 1988-2003; (b) withdrawals in the depleted zone of Critical Area 1, 1980-2003; and (c) water-level changes in Critical Area 1, 1988-2003, east-central New Jersey. (Potentiometric surfaces from Rosman and others (1995), Lacombe and Rosman, (1997), Lacombe and Rosman, (2001) and V.T. dePaul (U.S. Geological Survey, written commun., 2007))

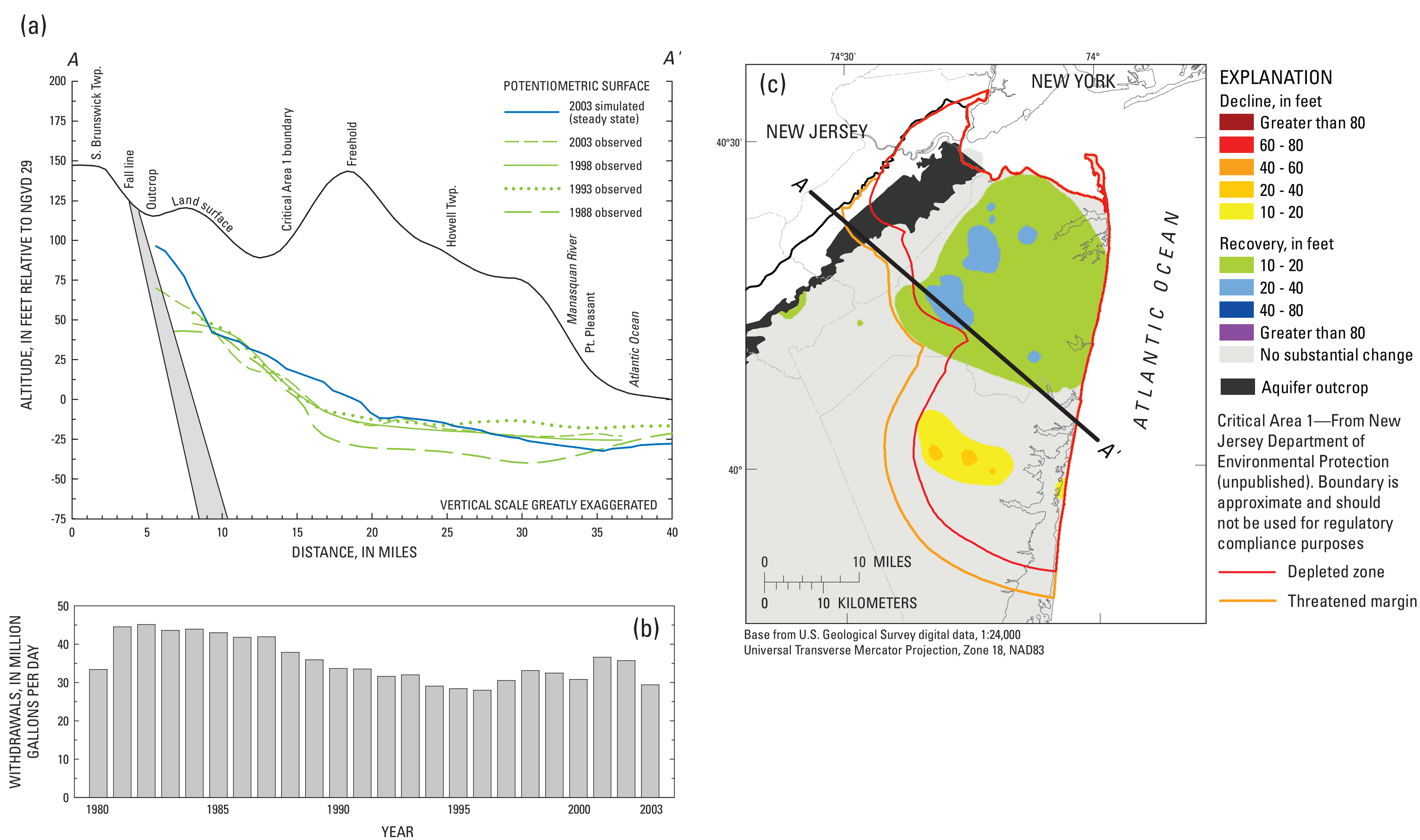

Figure 5. Upper Potomac-Raritan-Magothy aquifer (a) potentiometric surfaces along section A-A′, 1988-2003; (b) withdrawals in the depleted zone of Critical Area 1, 1980-2003; and (c) water-level changes in Critical Area 1, 1988-2003, east-central New Jersey. (Potentiometric surfaces from Rosman and others (1995), Lacombe and Rosman, (1997), Lacombe and Rosman, (2001) and V.T. dePaul (U.S. Geological Survey, written commun., 2007))

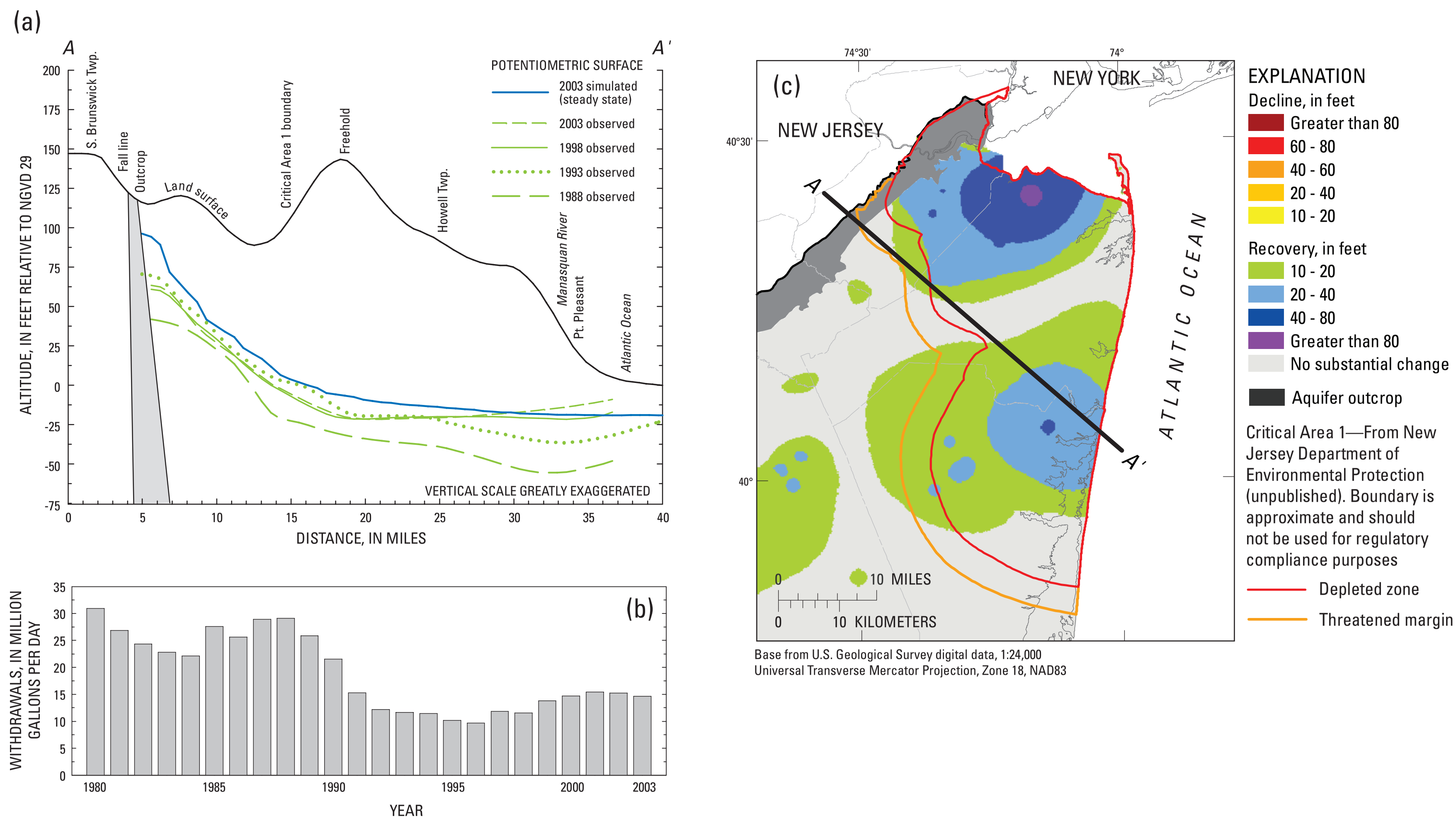

Figure 6. Middle Potomac-Raritan-Magothy aquifer (a) potentiometric surfaces along section A-A′, 1988-2003; (b) withdrawals in the depleted zone of Critical Area 1, 1980-2003; and (c) water-level changes in Critical Area 1, 1988-2003, east-central New Jersey. (Potentiometric surfaces from Rosman and others (1995), Lacombe and Rosman, (1997), Lacombe and Rosman, (2001) and V.T. dePaul (U.S. Geological Survey, written commun., 2007))

transmissivity (Martin, 1998, figs. 56-59), which contributes to a slower recovery of water levels, compared to recovery in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers.

A cross section depicting water-level altitudes in the Upper Potomac-Raritan-Magothy aquifer is shown in figure 5a. Withdrawals from this aquifer were relatively stable at about 40 Mgal/d during 1981-87, then decreased during 1988-96 (fig. 5b). Withdrawals increased slightly during 1997-2002, then decreased in 2003. Water levels rose about 25 ft during 1988-93. Water levels dropped by about 10 ft during 1993-98, and then remained stable until 2003. The total 15-year change in water levels in the Upper Potomac-Raritan-Magothy aquifer is shown in figure 5c. The recovery was 10 to 20 ft, and as much as 40 ft in most of Monmouth County. Water levels declined 10 to 40 ft in a 48 mi^2 area in northern Ocean County within the composite boundary for Critical Area 1 but outside the boundary for the depleted zone of the Upper Potomac-Raritan-Magothy aquifer. No withdrawals from the Upper Potomac-Raritan-Magothy aquifer were reported for this area in the late 1980s, but withdrawals have been reported more recently. In 2003, seven wells within this area withdrew 702 million gallons.

A cross section depicting water-level altitudes in the Middle Potomac-Raritan-Magothy aquifer is shown in figure 6a. Withdrawals decreased by more than half during 1988-93. In 1988 withdrawals were about 30 Mgal/d, but by 1993 had decreased to about 11 Mgal/d. Then withdrawals remained stable until 1998, and increased slightly during 1998-2003 (fig. 6b). Water levels, which rose about 20 ft over a large part of the Critical Area during 1988-93, rose by about 15 ft in the eastern part of the Critical Area and remained stable elsewhere during 1993-98. Water levels remained stable during 1998-2003. The total 15-year change in water levels in the Middle Potomac-Raritan-Magothy aquifer is shown in figure 6c. Water levels recovered 80 ft or more in areas near Raritan Bay. Recoveries of 20 to 40 ft occurred in a 114 mi^2 area along the Monmouth and Ocean County border, but most of the recovery was 10 to 40 ft.

Evaluation Of Water-Supply Management Options

The Wenonah-Mount Laurel aquifer, Englishtown aquifer system, Upper Potomac-Raritan-Magothy aquifer, and Middle Potomac-Raritan-Magothy aquifer are hydraulically connected both horizontally and vertically to aquifers and confining units beyond the extent of Critical Area 1. Thus, to examine the effect of withdrawals on these specific aquifers, the larger hydrologic system and associated stresses must be simulated. Accordingly, a regional ground-water-flow model was used in this study that involves the entire New Jersey Coastal Plain.

The existing ground-water-flow model of the New Jersey Coastal Plain was used to simulate flow in and around Critical Area 1. Results from the RASA model have been used to understand the regional flow system and the source of water to wells in the major aquifers of the Coastal Plain. The input data for the RASA model were formatted for use with MODFLOW (Harbaugh and McDonald, 1996), a modular finite-difference ground-water-flow model. The original version of this model was constructed and calibrated as part of the USGS RASA program (Martin, 1998). The model was revised by Voronin (2004) to improve simulation capabilities. For a detailed discussion of the model design, calibration, and boundaries of the original and revised RASA models, refer to Martin (1998) and Voronin (2004). The RASA model has been shown to be an effective tool for simulating ground-water flow in the New Jersey Coastal Plain based on its wide use and the reasonable estimates it provides of the source of water to wells (for example, Gordon, 2007). The extent of the RASA model is shown in figure 1.

The current study combines optimization along with the ground-water flow modeling to determine optimal withdrawals at the optimal locations. This approach includes setting hydrologic constraints and evaluating the resulting model-calculated withdrawals, whereas the traditional model scenarios involve setting withdrawals and evaluating the resulting model-calculated hydrologic conditions. The water-supply management models used in the current study were developed using the Ground-Water Management Process (GWM) for MODFLOW (Ahlfeld and others, 2005). Several water-supply management options were simulated to evaluate the effects of proposed changes in the withdrawal allocations within Critical Area 1. These options included using current well locations, regularly distributed well locations, and variations of these such as **clean slate** and **reallocation**. A buffer analysis is described below that was done to limit the number and type of the constraints used in the optimization. Comparisons of results of all the simulations are provided in the following sections, and limitations of the water-supply management modeling also are discussed.

Ground-Water-Flow Model

For this study, the revised version of the RASA model (Voronin, 2004) was used to evaluate the effects of pumping optimal withdrawal amounts at optimal locations on mandated hydrologic conditions within Critical Area 1. This revised model simulates flow in the hydrogeologic units that comprise the New Jersey Coastal Plain and includes (1) a rediscretization of the RASA model parameters with a finer grid cell size, (2) updated boundary fluxes, (3) a spatially variable recharge rate that is based on recharge rates determined as part of recent studies of the surficial aquifers in the Coastal Plain, and (4) updated ground-water withdrawal data from 1981-98.

The grid in the revised model consists of 135 rows and 245 columns with a cell size of 0.25 mi^2 over most of Critical Area 1, 0.31 mi^2 elsewhere in the Coastal Plain, and up to 3.16 mi^2 in offshore areas. The ratio of the number of new cells to the original number of cells is 25 to 1 in onshore areas. One benefit of rediscretization is that it allows modeled withdrawals to be located more accurately. (Withdrawals are simulated as a net sink that occurs throughout the model cell closest to each well location.) Revisions to stress periods in the RASA model were made to incorporate updated withdrawal data in the revised model. The Coastal Plain hydrogeologic units were discretized into 10 aquifers and 9 intervening confining units as in the RASA model. All of the units were modeled as confined with a constant saturated thickness. Certain aquifers, such as the Wenonah-Mount Laurel aquifer and Englishtown aquifer system, are not continuous throughout the Coastal Plain. The limit of these aquifers in the southeast is modeled as a no-flow boundary. In the case of the Englishtown aquifer system, its absence resulted in vertical hydraulic connection between confining units.

The model boundaries in the revised model are the same as those used in the original model. The northwestern limit of the Coastal Plain is the Fall Line, which is modeled as a no-flow boundary. Flows at the northeast and southwest limits are computed from simulated flows from larger areal models (Leahy and Martin, 1993; Pope and Gordon, 1999). Flows in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers at the southwest boundary between Delaware and New Jersey were estimated on the basis of water-level declines to account for the large increases in withdrawals in Delaware during 1988-98 that were not included in the larger areal models. The southeastern boundary in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers is a no-flow boundary, representing the downdip limit of freshwater.

Most of the Coastal Plain hydrogeologic units have outcrop areas that receive recharge from precipitation and are in direct contact with streams. The upper boundary in model cells that contain stream reaches is a head-dependent flow boundary. For the revised model, streams were modeled using the River and Drain packages of MODFLOW. The upper boundary in remaining onshore areas is a specified recharge. A spatially variable recharge rate was applied to these cells. The rate is equal to long-term precipitation minus long-term evapotranspiration and surface-water runoff. The upper boundary in offshore areas is a constant equivalent freshwater head. The lower boundary is crystalline bedrock and was modeled as a no-flow boundary.

Subsequent minor changes have been made to the revised model. The vertical conductance of the Vincentown-Manasquan confining unit was modified to improve the representation of the geohydrologic framework. Also, the model was updated from 1998 to 2003 to include the most recent withdrawal data, and flow in the hydrogeologic units was simulated using a newer version of MODFLOW (Harbaugh and others, 2000). No additional calibration or sensitivity analysis was done.

To simplify the modeling process, a steady-state RASA model was used. In this case, steady-state conditions are those that occur when there is no further change in simulated heads with time as a result of applied stresses, such as withdrawals for 2003. In the cones of depression in Critical Area 1, heads simulated by a steady-state RASA model using withdrawal conditions for 2003 were higher than heads simulated by the transient RASA model using 2003 data. (Heads from the steady-state RASA model are higher than observed water levels for 2003 shown in figures 3-6.) The difference between simulated steady-state heads and observed water levels is approximately 30 ft in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system. The difference between the steady-state and transient models is due to aquifer storage effects; the difference between the steady-state model and observed data is due to coarse model grid size. Given that a simulation period of more than 40 years was necessary to reach steady-state conditions in these aquifers in the New Jersey Coastal Plain after applying a withdrawal stress (A.D. Gordon, U.S. Geological Survey, written commun., 2006), the steady-state RASA model may overestimate heads for transient periods of shorter duration.

Buffer Analysis

To minimize the effects of **managed withdrawals** on simulated streamflow in aquifer outcrop areas and minimize increases in simulated landward ground-water flow in areas near the 250-mg/L isochlor in Raritan Bay, a **buffer area** was defined in the northern part of the Critical Area for the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers. A buffer area was determined to be unnecessary for the Wenonah-Mount Laurel aquifer and Englishtown aquifer system because withdrawals from these aquifers are not as great as those from the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers, and streamflow depletion and saltwater intrusion are less of a concern in these aquifers. In the northern part of the Critical Area, it was determined, on the basis of the most recent (2003) chloride data, that there is no measurable saltwater intrusion in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system. A single well in the Englishtown aquifer system at Sandy Hook was found to have elevated chloride concentrations (15,100 mg/L), however.

To determine the width of the buffer area for the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers, 11 transects were developed—6 perpendicular to the coastline of Raritan Bay and 5 perpendicular to each aquifer's outcrop area (fig. 7). An origin point (0 miles) was designated near the coastline of Raritan Bay and at the downdip extent of each aquifer's outcrop area. For each steady-state simulation with 1998 withdrawal conditions, locations of additional withdrawals of 1 Mgal/d from the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers were placed along each transect at 1, 6, or 11 miles from the origin point. The total additional withdrawals in each of these simulations was 22.3 Mgal/d in Critical Area 1 based on data supplied by NJDEP (Jan Gheen, N.J. Department of Environ-

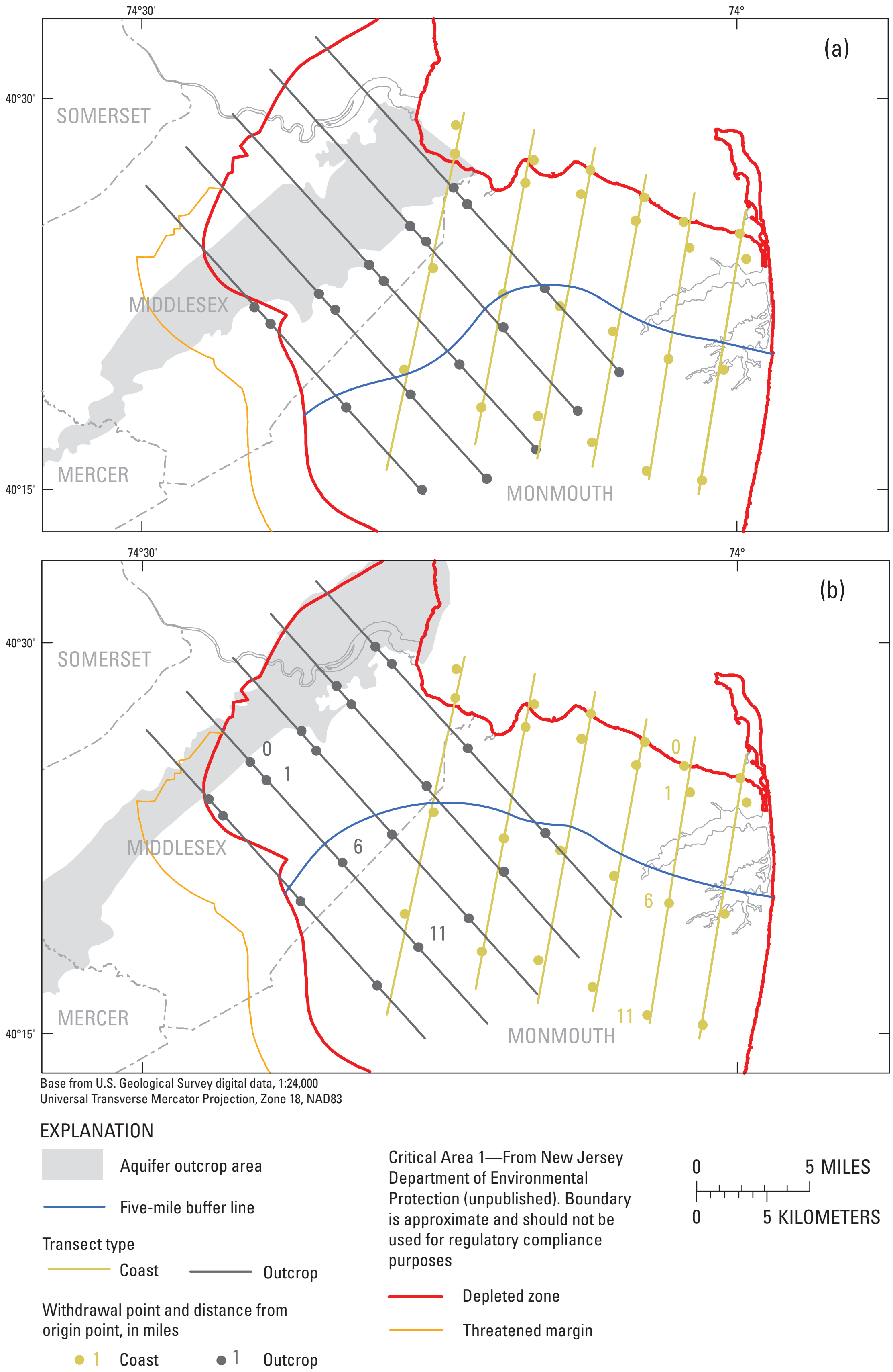

Figure 7. Transects and withdrawal points used in the buffer analysis for the (a) Upper and (b) Middle Potomac-Raritan-Magothy aquifers in Critical Area 1, east-central New Jersey.

mental Protection, written commun., 2004). To reduce well interference, simulations of withdrawals along the outcrop transects and along the coastal transects were run separately. Head and drawdown along each transect, and horizontal and vertical flow at the origin points, were evaluated for changes from the base 1998 steady-state simulation. Results indicated that the largest change in horizontal flow occurred between 1 and 6 miles from the origin point for all transects.

A water-budget analysis was done using the computer program Zonebudget (Harbaugh, 1990) to evaluate changes in vertical flow to streams and horizontal flow in the outcrop areas in more detail. Results indicated that the percent change in vertical flow to streams in the outcrop area was most affected by withdrawals located at 1 mile from the origin point. Decreases in streamflow in the Upper Potomac-Raritan-Magothy aquifer were more than twice that in the Middle Potomac-Raritan-Magothy aquifer at this distance. This may have occurred because (1) more streams are located in the outcrop area of the Upper Potomac-Raritan-Magothy aquifer than in the outcrop area of the Middle Potomac-Raritan-Magothy aquifer, (2) the Upper Potomac-Raritan-Magothy aquifer is thinner in its updip area and is affected more by losses in horizontal flow due to withdrawals than the Middle Potomac-Raritan-Magothy aquifer, and (3) the Upper Potomac-Raritan-Magothy aquifer is subject to increased vertical flow to the Middle Potomac-Raritan-Magothy aquifer due to withdrawals in the Middle Potomac-Raritan-Magothy aquifer.

Because the largest change in heads and flow occurred from 1 to 6 miles from the origin point and the largest change in flow to streams in the outcrop area occurred at 1 mile from the origin point, a 5-mile-wide buffer area was defined from the downdip boundary of the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy outcrop areas and from the coast of Raritan Bay (fig. 7). No withdrawals were managed in this buffer area, so the presence of the buffer further limited the area of managed withdrawals.

Water-Supply Management Models

The optimization of withdrawals in Critical Area 1 using the GWM process (Ahlfeld and others, 2005) for MODFLOW is described in this section. The area of managed withdrawals does not include the entire area within the Critical Area boundary (fig. 1), but rather subareas of the four aquifers within the boundary (fig. 8). For example, the area of managed withdrawals for the Wenonah-Mount Laurel aquifer and Englishtown aquifer system extends from mid-Ocean County north to their respective outcrop areas. A brief discussion of GWM (Ahlfeld and others, 2005) also is provided in this section. The formulation, solution, and applications of the water-supply management model are presented along with a comparison of results.

Ground-Water Management Process

Each management formulation of GWM consists of a set of **decision variables**, an **objective function**, a set of constraints, and a solution process. Each of these components is discussed in further detail below. GWM supports several types of decision variables; however, only flow-rate decision variables, which are managed withdrawal rates at well sites, were used in this study. Flow-rate decision variables can extend over one or more specified model cells and be active during one or more model stress periods (only one stress period is used for steady-state simulations).

GWM supports a single objective function, which is to minimize or maximize the weighted sum of decision variables. In this study, the objective function was to maximize withdrawals at the well sites. The objective function is an equation designed to identify the best possible management solution among many possible solutions.

GWM supports several types of constraints; however, only two types were used in this study—upper and lower bounds on the flow-rate decision variables and hydraulic-head based constraints, including head, drawdown, and velocity. Constraints represent limits imposed on the values of the decision variables. Typically, only a subset of constraints controls the **optimal solution**. **Binding constraints** restrict the value of the objective function because they prevent decision variables from taking on values that further improve the objective function and, therefore, bind the solution. Conversely, nonbinding constraints do not affect the optimal values of the decision variables and could be removed from the management formulation without changing the solution.

A response-matrix technique is used in GWM to solve several types of management formulations. This study involves only linear formulations. The solution process is used to determine the decision-variable values, such as withdrawal rates, that optimize the objective function while satisfying the constraints, thus resulting in the greatest allocation of withdrawals. The Response Matrix Solution (RMS) Package of GWM uses the Ground-Water Flow (GWF) Process of MODFLOW to compute the change in head at each constraint location that results from a perturbation of a flow-rate decision variable. Then, these changes are used to compute response coefficients (response functions) between the simulated wells and computed heads. The resulting matrix of response coefficients then is combined with other components of the linear management formulation, such as decision variables, to form a complete linear formulation, which is then solved by use of the simplex algorithm, which is part of the RMS Package.

GWM first calls the GWF Process for the base-condition run. The status of each constraint is determined at this point as either satisfied, not met, or **near-binding**. Next, the management formulation is converted into a form that can be solved using linear-programming techniques (that is, the simplex algorithm), the response matrix is generated by the required GWF Process runs, the linear program is solved by the simplex algorithm, and an optimal solution, if possible,

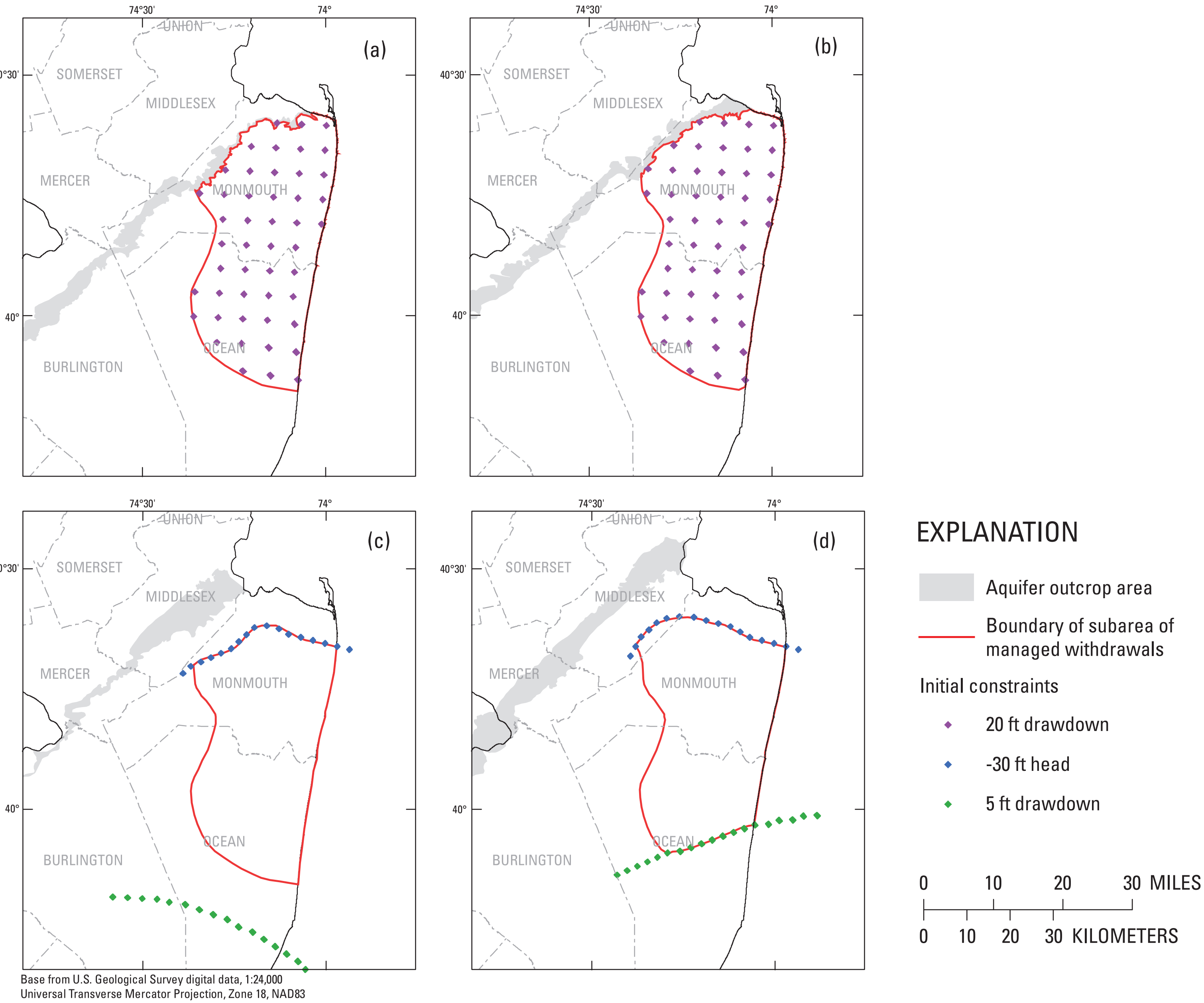

Figure 8. Aquifer subareas and management model constraints for the (a) Wenonah-Mount Laurel aquifer, (b) Englishtown aquifer system, (c) Upper Potomac-Raritan-Magothy aquifer, and (d) Middle Potomac-Raritan-Magothy aquifer in Critical Area 1, east-central New Jersey.

is obtained. At this point, the value of the objective function, the optimal values of withdrawal for each of the flow-rate decision variables, and the binding constraints are determined. The last step in a successful GWM run is a final run of the GWF Process using the optimal flow rates determined by the simplex algorithm. This run should indicate that all constraints are either satisfied or near-binding.

Formulation

The goal of the optimization is to maximize additional withdrawals (greater than 2003 withdrawals), given reasonable hydrologic constraints, in the four aquifers of concern in Critical Area 1. Comparison between 2003 withdrawals and (full) **base allocation** depends on which limits are used. Base allocation has annual and monthly limits. Using annual limits, 2003 withdrawals from most wells are comparable to base allocation (table 1). Although this difference in withdrawals can be quantified, the effect on resulting optimal withdrawals cannot be known without making additional model runs.

What constitutes a reasonable hydrologic constraint is somewhat uncertain, and therefore, an evaluation was done to determine how different constraint values affect the optimal withdrawals (that is, a tradeoff analysis). The constraints were selected in coordination with NJDEP. An implied constraint was that resulting effects (for example, low water levels) would not be as unfavorable as the effects during the time of pre-reduction withdrawal allocations.

The statement of the water-supply management problem that is solved by use of GWM is formulated as

maximize

$$\sum_{n=1}^{N} Qw_n T_{Qw_n} , \quad (1)$$

subject to

$$0 \le Qw_n \le Qw_n^u , \quad (2)$$

$$h_{i,j,k,t} \le h_{i,j,k,t}^l , \quad (3)$$

$$dd_{i,j,k,t} \le dd_{i,j,k,t}^u \text{ , and (or)} \quad (4)$$

$$\frac{(h_{i,j,k,t})_1 - (h_{i,j,k,t})_2}{\Delta x} \ge (grad_{i,j,k,t})_{1,2} , \quad (5)$$

where

- N is the total number of flow-rate decision variables;
- n represents both the location of the nth well site and the stress period (or periods) during which the well operates;
- Qw_n is the managed withdrawal rate at a well site;
- T_{Qw_n} is the total duration of withdrawal at well site n;
- Qw_n^u is the specified upper bound on the managed withdrawal rate at a well site;
- $h_{i,j,k,t}$ is the model-calculated head in cell i,j,k at the end of stress period t;
- $h_{i,j,k,t}^l$ is the specified lower bound on head at location i,j,k at the end of stress period t;
- $dd_{i,j,k,t}$ is the model-calculated drawdown in cell i,j,k at the end of stress period t;
- $dd_{i,j,k,t}^u$ is the specified upper bound on drawdown at location i,j,k at the end of stress period t;
- $(h_{i,j,k,t})_1$ is the model-calculated (higher) head in cell i,j,k at the first location at the end of stress period t;
- $(h_{i,j,k,t})_2$ is the model-calculated (lower) head in cell i,j,k at the second location at the end of stress period t;
- Δx is the distance between two well locations; and
- $(grad_{i,j,k,t})_{1,2}$ is the specified lower bound on gradient between well locations 1 and 2 (discussed in more detail below).

The total number of flow-rate decision variables used in this study depends on the management option tested. Four types of initial constraints were used in the water-supply management models (also see fig. 8):

Constraint number	Description
1	Maximum allowable withdrawal rate
2	Maximum allowable drawdown of 20 ft throughout the Wenonah-Mount Laurel aquifer and Englishtown aquifer system
3	Minimum allowable head of -30 ft along the northern buffer in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers
4	Maximum allowable drawdown of 5 ft along the downdip 250-mg/L isochlor in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers

Constraint 1 was set equal to 500 gal/min (0.72 Mgal/d) for management models involving **regularly spaced well locations**. This value represents a typical specific capacity for a large well and can represent multiple wells in a model cell. Constraint 1 was set equal to the specific capacity of the well minus it’s current (2003) withdrawals for management models

Table 1. Withdrawals from and model locations of production wells in the depleted zone of Critical Area 1, east-central New Jersey.

[NJDEP, New Jersey Department of Environmental Protection; USGS, U.S. Geological Survey; BWA, Bureau of Water Allocation; MM05, management model 05; ft, foot; Mgal/d, million gallons per day; WD, Water Department; WC, Water Company; WU, Water Utililty; MUA, Municipal Utilities Authority; NJ, New Jersey; Co, Company; ---, not available or not applicable; model locations in **bold** contain more than one well]

					NJDEP			USGS					
									Model location			[4]Withdrawal (Mgal/d)	
Well owner	Local well name	Well depth (ft)	Depth to top of open interval (ft)	Depth to bottom of open interval (ft)	BWA permit number	Well permit number	[1]Allocation (Mgal/d)	Local well number[2]	Layer[3]	Row	Column	2003	[5]MM05
Atlantic Highlands Borough WD	Atlantic Highlands PW 6	251	198	248	5325	29-25383	0.54	250714	7	36	232	0.194	---
Avon By The Sea Borough WD	Avon PW 1	504	424	504	5132	49-00017	0.16	250014	**6**	**59**	**213**	---	0.035
	PW 2	501	419	501	do.	49-00018	---	250011	**6**	**59**	**213**	---	0.035
Belmar Borough WD	2 Elec(10)	581	---	---	5138	49-00023	0.48	250018	**7**	**60**	**211**	---	0.014
	Belmar 3 Elec(12)	594	563	594	do.	29-00045	---	250016	**7**	**60**	**211**	---	0.014
	4 Elec(11)	679	601	671	do.	49-00024	---	250026	7	61	213	---	0.014
	7 Sub	648	---	---	do.	49-00022	---	250015	**7**	**60**	**211**	---	0.014
	PW 13	605	555	605	do.	29-06956	---	250023	**7**	**60**	**211**	0.225	0.014
	PW 14	550	---	---	do.	29-10462	---	250497	**7**	**60**	**211**	---	0.014
Brick Township MUA	Forg Pond 9-73	1,779	1,441	1,779	5172	29-06841	1.88	290045	9	63	193	0.191	---
	Fp 10	1,832	1,607.25	1,827	do.	29-07791	---	290046	**8**	**63**	**193**	0.221	---
	Fp 11	1,800	1,565	1,800	do.	29-08356	---	290595	8	64	193	0.722	---
	PW 12	1,860	1,700	1,860	do.	29-12006	---	290779	**8**	**63**	**193**	0.835	---
Brielle Borough WD	Brielle PW 2	750	690	750	5279	29-00069	0.23	250030	7	64	203	0.139	0.041
	Brielle PW 3	820	770	820	do.	29-05292	---	250028	7	64	201	0.105	0.041
Englishtown Borough WD	Englishtown PW 2	384	363	384	5191	28-05400	0.25	250056	8	25	196	0.181	---
Farmingdale Borough WD	Farmingdale PW 3	460	420	460	5126	29-04386	0.16	250063	**7**	**48**	**202**	---	0.041
	PW 4	470	410	470	do.	29-06088	---	250064	**7**	**48**	**202**	---	0.041
Freehold Borough WD	PW 3	567	468	567	5059	29-04419	1.07	250099	8	32	200	0.220	---
	PW 6	943	835	943	do.	29-11217	---	250503	9	31	200	0.190	---
	PW 7	884	771	884	do.	29-13480	---	250561	9	32	200	0.300	---
	WaterWorks Rd 8	229	136	224	do.	29-25736	---	250730	7	32	200	0.358	---
Freehold Township WD	PW 3	212	150	212	5009	29-05302	1.87	250105	**7**	**31**	**200**	0.299	---
	10 Jackson Mill Rd	697	633	691	do.	29-14513	---	250722	8	39	195	0.182	---
	Jackson Mills T Plant 11	1,002	918	997	do.	29-24426	---	250725	9	39	195	0.422	---
	Koenig Lane T Plant 13	680	584	673	do.	29-24703	---	250726	8	37	198	0.118	---
	Edwards Dr Plant 12	211	149	206	do.	29-24425	---	250727	**7**	**31**	**200**	0.152	---
	PW 14	993	927	988	do.	29-33928	---	250774	**8**	**38**	**195**	1.110	---
	PW 15	983	918	978	do.	29-33929	---	250775	**8**	**38**	**195**	0.320	---
Gordons Corner WC	Gordons PW 5	670	580	670	5185X	29-06353	2.20	250230	**9**	**24**	**203**	0.279	---
	PW 6	712	592	708	do.	29-07402	---	250231	**9**	**24**	**203**	0.387	---
	Gordons PW 7	594	524	594	do.	29-05790	---	250244	8	30	206	0.162	---
	PW 4	810	741	810	do.	29-05548	---	250249	**9**	**27**	**202**	0.175	---
	PW 10	800	740	800	do.	29-10864	---	250452	**9**	**27**	**202**	0.456	---
	PW 11	576	479	576	do.	29-12877	---	250564	8	29	206	0.187	---
Jackson Township MUA	PW 1	557	511	557	5075	29-03574	0.72	290229	7	50	188	---	0.041
	PW 3	559	513	559	do.	29-03797	---	290228	7	48	175	---	0.041
	Jackson PW 8	1,462	1,276	1,462	do.	29-08936	---	290576	**9**	**48**	**185**	0.669	---
	PW 9	1,430	1,276	1,430	do.	29-08937	---	290575	**9**	**48**	**185**	0.331	---
Lakehurst Borough WD	Lakehurst Boro Tw14/PW15	1,029	937	1,024	5262	29-42955	0.33	291380	8	56	172	0.396	---
Lakewood Township MUA	Lakewood PW 1	817	752	817	5079	29-05721	0.66	290430	7	63	185	---	0.027
	PW 2	762	680	762	do.	29-04116	---	290431	7	63	188	---	0.027
	Lakewood PW 3	741	673	741	do.	29-05110	---	290433	7	62	187	---	0.027
	Lakewood PW 7	1,625	1,410	1,620	do.	29-09259	---	290588	9	59	190	0.444	---
Lavallette Borough WD	PW 3	1,808	1,120	1,180	5136	33-00001	0.06	290452	7	77	188	---	0.065
Manchester Township WU	Manchester PW 10	1,189	1,013	1,184	5043	29-23401	1.68	291040	**8**	**61**	**178**	0.212	---
	PW 12	1,146	997	1,141	do.	29-23400	---	291041	**8**	**61**	**178**	0.699	---
	11 Util Easement	1,146	991.33	1,141	do.	29-25969	---	291101	**8**	**61**	**178**	0.318	---

Table 1. Withdrawals from and model locations of production wells in the depleted zone of Critical Area 1, east-central New Jersey.—Continued

[NJDEP, New Jersey Department of Environmental Protection; USGS, U.S. Geological Survey; BWA, Bureau of Water Allocation; MM05, management model 05; ft, foot; Mgal/d, million gallons per day; WD, Water Department; WC, Water Company; WU, Water Utililty; MUA, Municipal Utilities Authority; NJ, New Jersey; Co, Company; ---, not available or not applicable; model locations in **bold** contain more than one well]

					NJDEP			USGS					
									Model location			Withdrawal (Mgal/d) [4]	
Well owner	Local well name	Well depth (ft)	Depth to top of open interval (ft)	Depth to bottom of open interval (ft)	BWA permit number	Well permit number	Allocation [1] (Mgal/d)	Local well number [2]	Layer [3]	Row	Column	2003	MM05 [5]
Marlboro Township MUA	1-Prod	716	647	716	5055	29-06360	0.77	250269	**9**	**26**	**210**	0.500	---
	4A-Prod	720	638.5	720	do.	29-12777	---	250543	**9**	**26**	**210**	0.412	---
	3-Prod	710	624.2	710	do.	29-11251	---	250549	9	25	211	0.235	---
NJ American WC	1 Gondola Rsvr	1,154	999	1,149	5018X	29-15170	2.13	250721	8	55	208	0.246	---
	Swimming R Res Tp 2	655	575	655	do.	29-21611	---	250729	8	40	218	0.116	---
	Jumping Br 6	1,080	1,000	1,075	do.	29-11335	---	250501	8	55	211	0.811	---
NJ American WC	Bay Head 5	834	750	834	5062X	49-00002	0.46	290005	**7**	**70**	**200**	---	0.041
	Bay Head 6	818	778	818	do.	29-00087	---	290006	7	70	200	0.131	0.041
	Monterey 16	1,496	1,375	1,495	do.	33-01159	---	290070	8	76	191	0.487	---
NJ American WC	1-1975/Yellow Brk Well	860	---	---	5078X	29-07784	2.48	250493	8	46	201	0.243	---
	Aldrich PW 2	440	354	440	do.	29-03105	---	250168	6	48	195	0.214	0.027
	Aldrich Wc 3/Htmua	396	336	396	do.	29-04381	---	250166	6	47	194	---	0.027
	Aldrich Wc 4/Htmua 4	550	363	550	do.	29-05346	---	250165	7	50	193	0.375	0.027
	Lakewood PW 6	582	520	582	do.	29-03324	---	290450	7	53	189	0.330	0.021
	Lakewood PW 7	757	697	757	do.	29-04304	---	290434	7	59	185	0.275	0.021
	Lakewood PW 8	758	600	758	do.	29-04834	---	290438	7	56	186	0.221	0.021
	Lakewood PW 9	698	569	698	do.	29-05496	---	290449	7	56	191	0.275	0.021
	Lakewood PW 10	1,607	1,357	1,602	do.	29-06549	---	290440	9	56	187	0.820	---
Parkway WC	Parkway 1 A	649	594	644	5184	29-16728	0.06	250710	7	59	195	---	0.062
Point Pleasant Borough WD	Pt Pleasant PW 3	798	748	798	5150	49-00075	1.13	290532	7	67	200	0.159	0.082
	Pt Pleasant PW 5	1,342	1,256	1,342	do.	29-03345	---	290531	8	67	199	0.868	---
Sea Girt Borough WD	Sea Girt PW 5	710	660	710	5237	29-04102	0.01	250374	7	64	206	---	0.011
Seaside Heights Borough WD	Seaside Heights Wd-7	1,590	1,389	1,580	5093	33-37776	0.67	291365	8	79	186	0.633	---
Spring Lake Borough	PW 1	711	631	711	5089	49-00014	0.27	250383	**7**	**63**	**208**	---	0.021
	PW 2	707	640	700	do.	49-00015	---	250384	**7**	**63**	**208**	---	0.021
	Spring Lake PW 3	705	640	705	do.	49-00016	---	250385	7	63	209	---	0.021
	PW 4	670	600	670	do.	29-04721	---	250386	7	61	210	0.138	0.021
Spring Lake Heights Borough	Spring Lake Hgts PW 2	711	660	711	5266	29-00398	0.30	250389	7	61	207	0.108	0.041
	PW 3	680	630	680	do.	29-05075	---	250388	7	62	207	---	0.041
	PW 1	600	570	600	do.	29-00180	---	250387	6	61	207	---	0.035
	Spring Lake Hgts PW 4	564	485	561	do.	29-07506	---	250391	6	62	209	---	0.035
United Water NJ	PW 42	1,342	1,198	1,337	5000X	33-32509	1.72	291221	8	67	181	0.227	---
	Toms River PW 30	1,875	1,754	1,715	do.	33-10224	---	290626	9	70	177	1.447	---
Wall Township WD	Allenwood 1	740	688.58	740.42	5149	29-02869	0.80	250428	7	60	204	0.146	0.021
	Allenwood 2	710	658	710	do.	29-02870	---	250427	7	60	203	0.196	0.021
	Imperial 2	662	627	657	do.	49-00032	---	250442	7	57	209	---	0.021
	Rt 34	649	549	649	do.	29-05289	---	250441	7	55	205	0.194	0.021
	Imperial 1	465	435	465	do.	29-02871	---	250443	**6**	**57**	**209**	---	0.021
	Rosehill 2A	456	421	451	do.	29-17963	---	250698	6	56	209	---	0.021
	Imperial 3	455	425	455	do.	29-09107	---	250465	**6**	**57**	**209**	---	0.021
	West Belmar	575	440	575	do.	29-02868	---	250440	6	60	210	---	0.021

[1] Current base allocation in depleted zone and threatened margin for all wells associated on BWA permit (Jan Gheen, NJDEP, written. commun., 2004).

[2] Number of wells associated with BWA is based on Regional Aquifer-System Analysis model data (Voronin, 2004).

[3] Layer 6 is the Wenonah-Mount Laurel aquifer, 7 is the Englishtown aquifer system, 8 is the Upper or Undifferentiated Potomac-Raritan-Magothy aquifer, and 9 is the Middle Potomac-Raritan-Magothy aquifer.

[4] Values for 2003 are actual unmanaged withdrawals; values for MM05 are the maximum managed withdrawals allowed for the well (FVMAX).

[5] Only wells in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system were simulated.

involving current well locations. In this case, the goal was to determine the additional withdrawal possible.

Constraint 2 represents a maximum allowable drawdown in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system. If no constraint was applied to these aquifers, substantial drawdown would occur in order to compensate for constraints 3 and 4 applied to the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers.

Constraint 3 represents a minimum allowable head at a 5-mile distance from outcrop areas susceptible to streamflow depletion and coastal areas susceptible to saltwater intrusion in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers. The buffer area minimizes, but does not eliminate, the effect of withdrawals on head changes and saltwater intrusion in the northern part of the Critical Area.

Constraint 4 represents a maximum allowable drawdown at the downdip 250-mg/L isochlor in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers. As mentioned previously, landward movement of the 250-mg/L isochlor is used to define saltwater intrusion. (Isochlor locations in this report are more continuous than shown.) The constraint is not based on a buffer analysis because saltwater intrusion is a regional feature in the southern part of the Critical Area, whereas saltwater intrusion is a localized feature in the northern part. Also, in the northern part, it is not known whether increased chloride concentrations are due primarily to ground-water flow or leakage from Raritan Bay. Few wells are screened in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system in the southern part of the Critical Area. Measured chloride concentrations are very low (less than 25 mg/L), given the limited number of wells. The limited amount of data on chloride concentrations precludes delineation of isochlor locations in these aquifers. Future monitoring wells might be useful in these aquifers in this area.

Input

Each GWM run includes a set of files that are added to a standard MODFLOW run. These include a GWM file (analogous to a MODFLOW name file), an objective function file (OBJFNC), a decision variables file (DECVAR), constraint files (VARCON and HEDCON), and a solution and output-control parameters file (SOLN). Details on these files are described in Ahlfeld and others (2005).

The goal for most of the GWM runs was to determine the additional withdrawals that could be obtained beyond **unmanaged withdrawals** included in the MODFLOW WEL Package. If more than one well was simulated within a model cell, the withdrawals were combined into a single well to satisfy the GWM requirement of only one well per cell.

Output

Output from GWM that was evaluated for this study includes simulated heads, optimal withdrawal values and well locations, and constraint values and locations. Geographic Information System and Fortran postprocessing plotting software were developed by D.A. Pope and M.M. Chepiga (U.S. Geological Survey, written commun., 2006). This software may be useful in future studies involving GWM. Examples of output for the first management model tested are shown in figures 9-11. The output types shown in figures 9-11 were produced and analyzed for each management model, but are not included in this report. Simulated heads are shown in figure 9; optimal withdrawal rates, locations of withdrawals, and whether certain withdrawals are binding constraints, in figure 10; and constraints, locations, and whether certain constraints are binding (based on **distance to right-hand side**), in figure 11.

Base Applications

A summary of the 14 management models is presented in table 2. The management models are designated by a two-letter prefix “MM” followed by a sequence number and (or) letter. Five base management models were run (MM01-MM05). Nine other management models (MM06-MM14) were run as part of a **trade-off analysis** between withdrawal amounts and constraint values. The management models are evaluated in terms of additional withdrawals, simulated area of heads below -30 ft NGVD in Critical Area 1, **maximum saltwater intrusion velocity** (ground-water velocity at the 250-mg/L isochlor), and number of binding constraints.

Statements about the -30 ft potentiometric contours are with respect to 2003 heads. The 1983 -30 ft contour, which defines the Critical Area boundary, has decreased in extent over time as a result of reductions in withdrawals. Thus, no change in the Critical Area boundary would need to be considered until the -30 ft contour extends beyond the 1983 -30 ft contour.

Maximum saltwater intrusion velocity was determined by solving equation 7 (shown farther on) for velocity along the 250-mg/L isochlor and recording the largest value. This value is an estimate because MODFLOW is a constant-density flow model and not a variable-density flow model, such as SEAWAT (Langevin and others, 2003), that would simulate freshwater/saltwater interactions more accurately. Estimates of travel time of saltwater to wells would require use of particle tracking software in many locations and for many model runs.

Certain constraints may be very close to binding, but as a result of GWM precision, are not identified as such. Recent conditions (2003) also are included in the table for comparison. Only substantial changes between management models listed in table 2 are noted in the text. Each management model is discussed in more detail below.

Current (2003) Well Locations (Management Models MM01 and MM02)

Reductions in allocations and development of alternative withdrawal plans were required of all purveyors in Critical Area 1; this involved several hundred wells in aquifer sub-

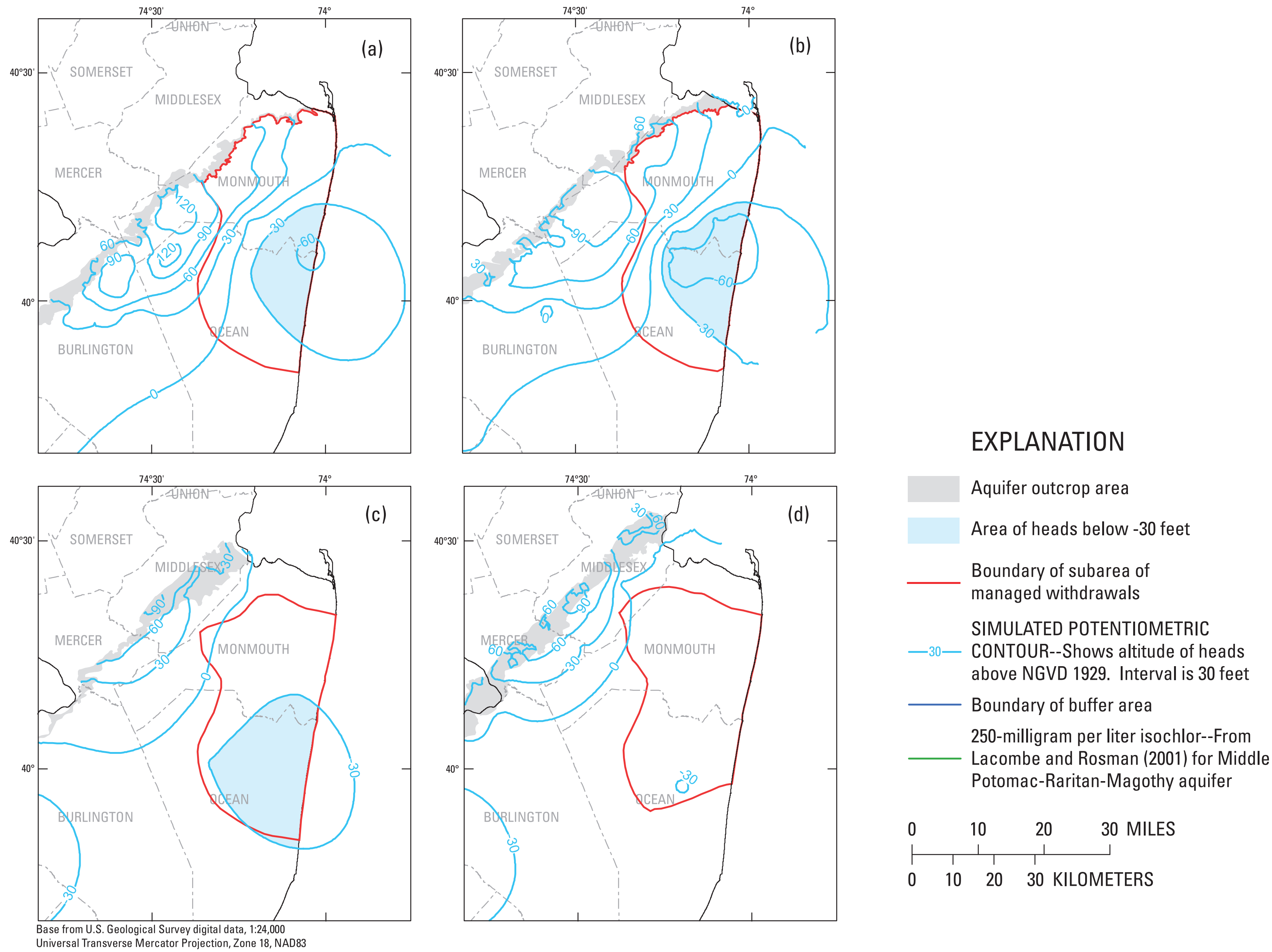

Figure 9. Simulated potentiometric surface in the (a) Wenonah-Mount Laurel aquifer, (b) Englishtown aquifer system, (c) Upper Potomac-Raritan-Magothy aquifer, and (d) Middle Potomac-Raritan-Magothy aquifer for management model MM01 in Critical Area 1, east-central New Jersey.

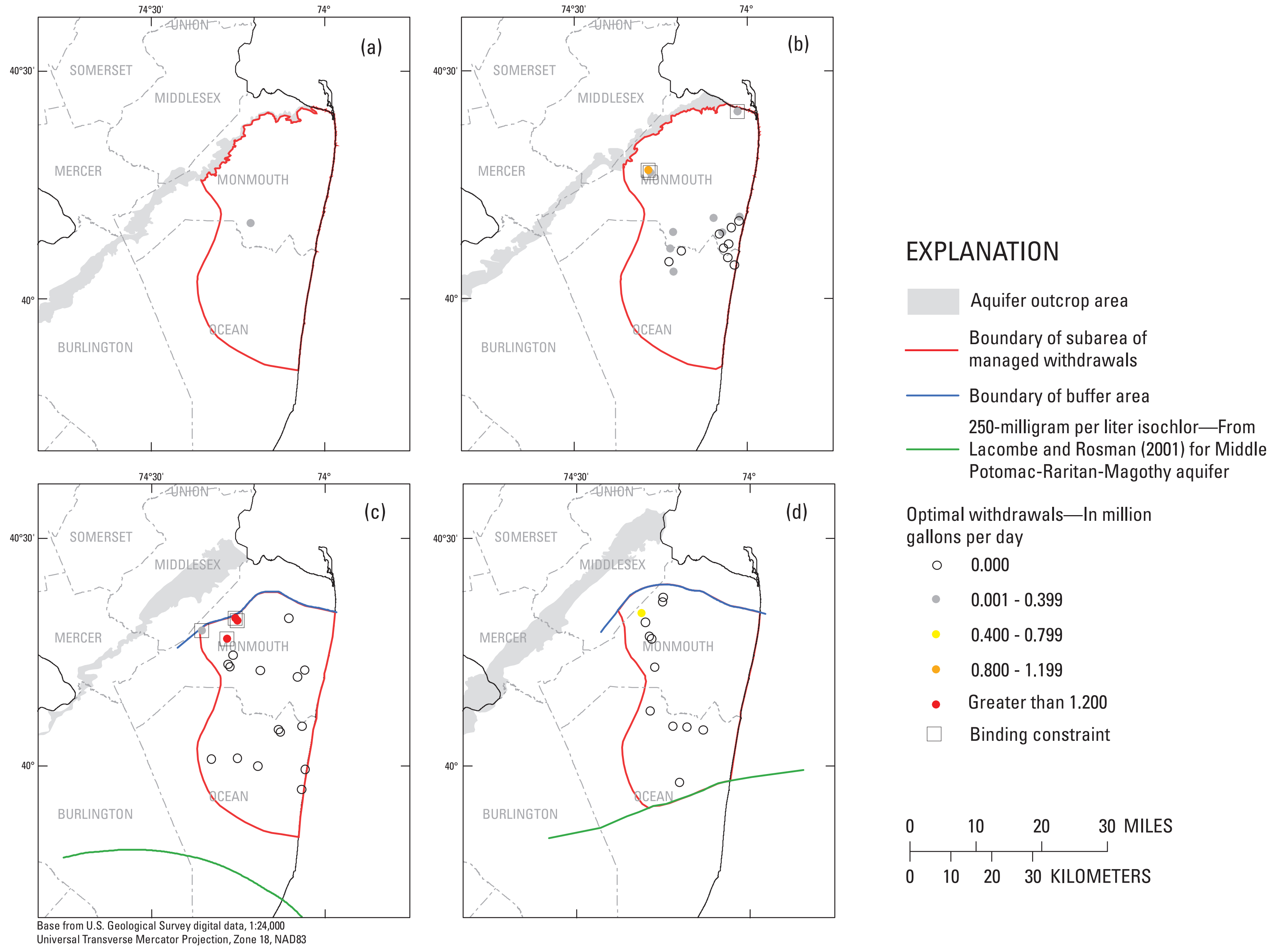

Figure 10. Simulated optimal withdrawals in the (a) Wenonah-Mount Laurel aquifer, (b) Englishtown aquifer system, (c) Upper Potomac-Raritan-Magothy aquifer, and (d) Middle Potomac-Raritan-Magothy aquifer for management model MM01 in Critical Area 1, east-central New Jersey.

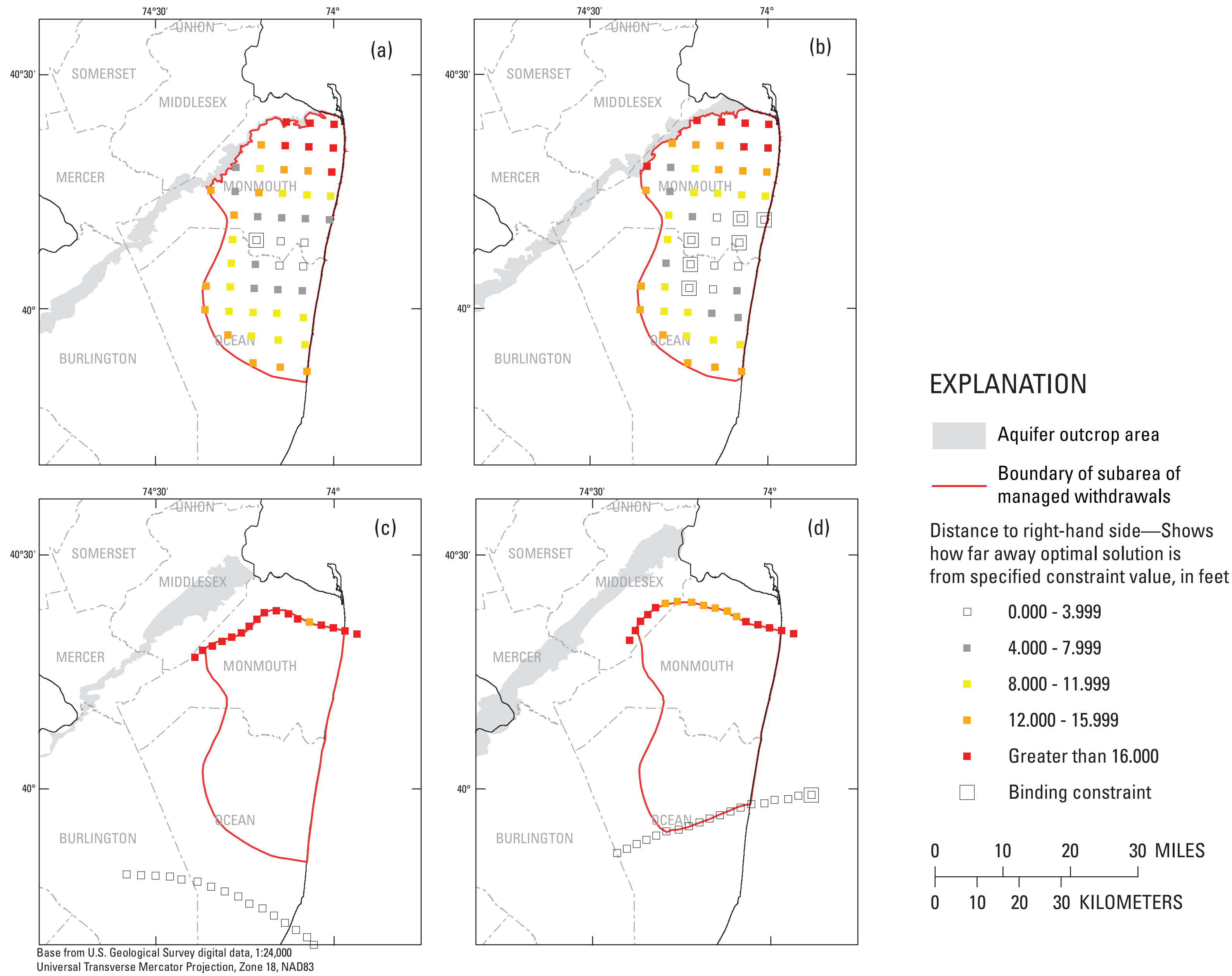

Figure 11. Simulated constraints in the (a) Wenonah-Mount Laurel aquifer, (b) Englishtown aquifer system, (c) Upper Potomac-Raritan-Magothy aquifer, and (d) Middle Potomac-Raritan-Magothy aquifer for management model MM01 in Critical Area 1, east-central New Jersey.

Table 2. Summary of water-supply management models and results in Critical Area 1, east-central New Jersey.

[MLRW, Wenonah-Mount Laurel aquifer; EGLS, Englishtown aquifer system; UPRM, Upper Potomac-Raritan-Magothy aquifer; MPRM, Middle Potomac-Raritan-Magothy aquifer; PRM, Upper and Middle Potomac-Raritan-Magothy aquifers; mi^2, square miles; CR, current; RS, regularly spaced; dd, drawdown; hd, head; vel, velocity; hd03-20, simulated head 2003 minus 20; ft; foot; ft/yr, foot per year; gal/min, gallons per minute; Mgal/d, million gallons per day; mg/L, milligrams per liter; ---, not applicable]

Management model			Constraints[1]				Withdrawals (Mgal/d)		[2]Area of heads below -30 ft in Critical Area 1 (mi^2)				Maximum velocity of 250-mg/L isochlor (ft/yr)		Number of binding constraints[3]			
Designation	Description	Well design	FVMAX (gal/min)	MLRW, EGLS	PRM north	PRM south	Unmanaged	Additional	MLRW	EGLS	UPRM	MPRM	UPRM	MPRM	Areal	Lateral	MLRW, EGLS	PRM
---	Current (2003) conditions[4]	---	---	---	---	---	23.7	---	64	118	143	0	3.3	11.5	---	---	---	---
MM01	Current (2003) well locations	CR	Cs	dd=20	hd=-30	dd=5	23.7	7.0	137	175	242	3	4.5	11.5	14	1	10	5
MM02	Within Smart Growth Areas	CR	Cs	dd=20	hd=-30	dd=5	23.7	7.0	137	175	241	3	4.7	11.5	13	1	9	5
MM03	Regularly distributed well locations	RS	500	dd=20	hd=-30	dd=5	23.7	9.7	160	192	238	3	4.5	11.3	22	1	19	4
MM04	Clean slate[5]	RS	500	hd03-20	hd=-30	hd03-20	---	(23.7+11.9)	155	194	204	2	6.5	7.8	60	0	29	31
MM05a	Reallocation to small volume wells[6]	CR	Cs		hd=-30		23.7	0.2	71	124	144	0	3.3	11.5	7	0	7	0
MM05b				dd=20	hd=-30		23.7	0.9	123	161	156	0	3.5	11.3	36	0	36	0
MM05c				dd=20	hd=-30	dd=5	23.7	0.9	123	161	156	0	3.5	11.3	36	0	36	0
MM06	Vary dd in MLRW, EGLS	CR	Cs	dd=5	hd=-30	dd=5	23.7	5.8	86	134	237	3	4.3	11.6	13	1	9	5
				dd=50			23.7	7.6	209	231	246	3	4.5	11.5	13	2	10	5
MM07	Vary dd in MLRW, EGLS	RS	500	dd=5	hd=-30	dd=5	23.7	5.7	87	135	235	3	4.5	11.5	15	2	15	2
				dd=50			23.7	12.6	255	269	242	3	4.5	11.3	17	2	4	15
MM08	Vary hd in MLRW, EGLS	RS	500	hd=-110	hd=-30	dd=5	23.7	12.3	254	260	239	3	4.7	11.3	19	1	17	3
				hd=-10			23.7	0.7	65	119	144	0	3.3	11.5	2	0	2	0
MM09	Vary dd at 250-mg/L isochlor in PRM	CR	Cs	dd=20	hd=-30	dd=1	23.7	2.6	95	140	161	0	3.5	11.5	5	2	4	3
						dd=20	23.7	17.4	175	211	510	486	11.1	11.5	20	2	9	13
MM10	Vary dd at 250-mg/L isochlor in PRM	RS	500	dd=20	hd=-30	dd=1	23.7	4.9	86	135	162	0	3.5	11.5	7	1	7	1
						dd=20	23.7	17.3	200	232	471	462	13.6	10.9	31	4	18	17
MM11	Vary vel at 250-mg/L isochlor in PRM	CR	Cs	dd=20	hd=-30	vel=9.8	23.7	8.5	174	206	403	185	9.8	9.9	12	2	6	8
						vel=20	23.7	19.3	175	211	507	499	14.7	19.9	15	2	5	12
MM12	Vary vel at 250-mg/L isochlor in PRM	RS	500	dd=20	hd=-30	vel=9.4	23.7	11.6	191	218	390	280	9.4	9.5	23	2	14	11
						vel=20	23.7	19.7	186	221	481	500	13.0	18.1	31	2	12	21
MM13	Vary FVMAX	RS	250	dd=20	hd=-30	dd=5	23.7	8.1	161	193	252	3	4.7	11.3	26	1	19	8
			2,500				23.7	10.6	148	184	227	2	4.3	11.5	11	2	11	2
MM14	Vary FVMAX for clean slate[5]	RS	250	hd03-20	hd=-30	hd03-20	---	(23.7-2.8)	157	172	0	0	0.4	3.0	63	0	32	31
			2,500				---	(23.7+32.0)	2	8	521	499	14.3	1.3	24	3	14	13

[1] Maximum withdrawal allowed for well (FVMAX) for current well design equals specific capacity (Cs) minus unmanaged withdrawal.

[2] Area of depleted zone in Critical Area 1 is approximately 740 mi^2.

[3] Areal constraints are within aquifer subarea, lateral constraints are along subarea boundary.

[4] Includes no managed withdrawals.

[5] Removal of wells extending beyond aquifer subareas to include all of Critical Area 1.

[6] Variations a and b (or c) involve a different number of wells.

areas. In this study, the number of managed withdrawals had to be reduced in order to make optimization runs feasible. Accordingly, only production wells with 2003 withdrawals greater than 0.1 Mgal/d were used. Production wells account for the largest withdrawals in Critical Area 1. Withdrawal locations of these wells are indicative of future withdrawal locations. Small wells grouped on one allocation permit having an aggregate withdrawal greater than 0.1 Mgal/d or withdrawals for other uses were not included. Other withdrawals that were not specifically managed were included as unmanaged withdrawals (23.7 Mgal/d) in the simulations. If those withdrawals were managed, minor changes would be expected in the overall additional withdrawals and well locations.

Almost 90 percent of all withdrawals were accounted for in aquifer subareas using the above criteria. Nine of the 59 wells (not identified in table 1) were located in duplicate model cells reducing the total number of wells with managed withdrawals to 50. Well locations for managed withdrawals (MM01) in the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, Upper Potomac-Raritan-Magothy aquifer, and Middle Potomac-Raritan-Magothy aquifer are shown in figure 12. Management model MM02 is a variation of MM01 and includes only wells in Smart Growth Areas (New Jersey Department of Community Affairs, accessed January 27, 2006). Smart Growth Areas are shown in figure 1. The MM02 configuration contained six fewer wells than MM01, but the results for the two management models were virtually identical. The four types of initial constraints described on page 16 were used in MM01 and MM02.

Model results for each of the four aquifers are shown in figures 9-11. Results are listed in table 2. An additional 7.0 Mgal/d of withdrawals was obtained using MM01. In this management model, the largest withdrawals were from the Upper Potomac-Raritan-Magothy aquifer (3.9 Mgal/d); the smallest withdrawals were from the Wenonah-Mount Laurel aquifer (0.2 Mgal/d). Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints are listed in the table. The combined simulated area of heads below -30 ft in the four aquifers is less than double the area in 2003 (table 2).

Regularly Spaced Well Locations (Management Model MM03)

For this management model, unmanaged withdrawals were located at current production wells. Managed withdrawals were located at regularly spaced intervals in the subareas of the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, Upper Potomac-Raritan-Magothy aquifer, and Middle Potomac-Raritan-Magothy aquifer (fig. 13). The purpose of this configuration was to evaluate how much in additional withdrawals could be obtained given a regular distribution of wells. The additional withdrawals are derived only from managed withdrawals. Regularly spaced wells were used in order to demonstrate how the locations of managed wells affect the optimal solution. The resulting distribution may not represent all realistic sites, but it does represent general areas of water availability.

The number of wells used likely has an effect on the optimal solution, perhaps not on the total amount withdrawn by all wells, but on the amount of withdrawals at individual wells. Also, if too few wells are used, the allowable maximum withdrawal rates may be reached, and the maximum overall withdrawal may not be obtained. Sixty-five wells were used, allocated among the four aquifers of concern. The wells also were offset vertically to maximize withdrawal potential. The four types of initial constraints described on page 16 were used in MM03.

As expected, regularly spaced well locations result in greater additional withdrawals than current well locations (table 2). An additional 9.7 Mgal/d was obtained with MM03. The largest withdrawals are from the Englishtown aquifer system (3.9 Mgal/d); the smallest withdrawals are from the Upper Potomac-Raritan-Magothy aquifer (1.2 Mgal/d). Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints are listed in table 2. For MM03, the combined simulated area of heads below -30 ft in the four aquifers almost doubled compared to 2003 conditions (table 2).

Clean Slate (Management Model MM04)

This management model is designed to represent the development of water supply in Critical Area 1 assuming that withdrawals had been made only at regularly spaced well locations from the outset. For MM04, there were no unmanaged withdrawals in the entire Critical Area, including the threatened margin, in all four aquifers of concern. All withdrawals were managed at regularly spaced well locations inside the aquifer subareas. Management model MM04 used initial constraints 1 and 3 described on page 16, but used modifications of initial constraints 2 and 4. The maximum areal drawdown in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system, and the maximum drawdown at the 250-mg/L isochlor in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers were changed to head constraints of 20 ft below simulated 2003 heads.

Management model MM04 yields the most additional withdrawals (11.9 Mgal/d) of the five base management models (MM01-MM05). The largest withdrawals are from the Middle Potomac-Raritan-Magothy aquifer; the smallest withdrawals are from the Wenonah-Mount Laurel aquifer; actual values are not listed due to the absence of unmanaged withdrawals. The distribution of withdrawals was spread throughout the aquifer subareas. Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints are listed in table 2. For MM04, the combined simulated area of heads below -30 ft in the four aquifers less than doubled compared to 2003 conditions.

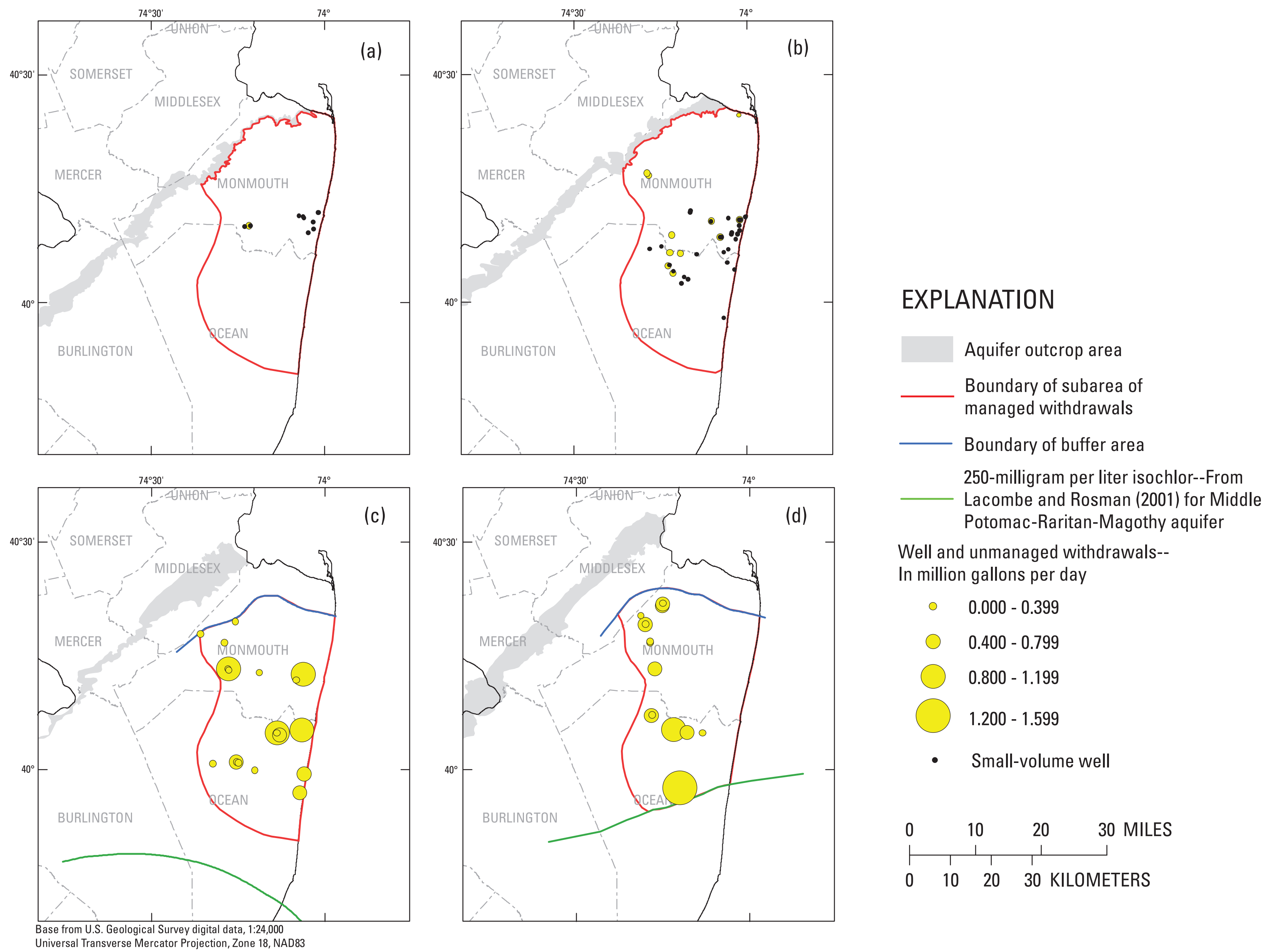

Figure 12. Current (2003) well locations and unmanaged withdrawals used in the (a) Wenonah-Mount Laurel aquifer, (b) Englishtown aquifer system, (c) Upper Potomac-Raritan-Magothy aquifer, and (d) Middle Potomac-Raritan-Magothy aquifer for management model MM01 in Critical Area 1, east-central New Jersey.

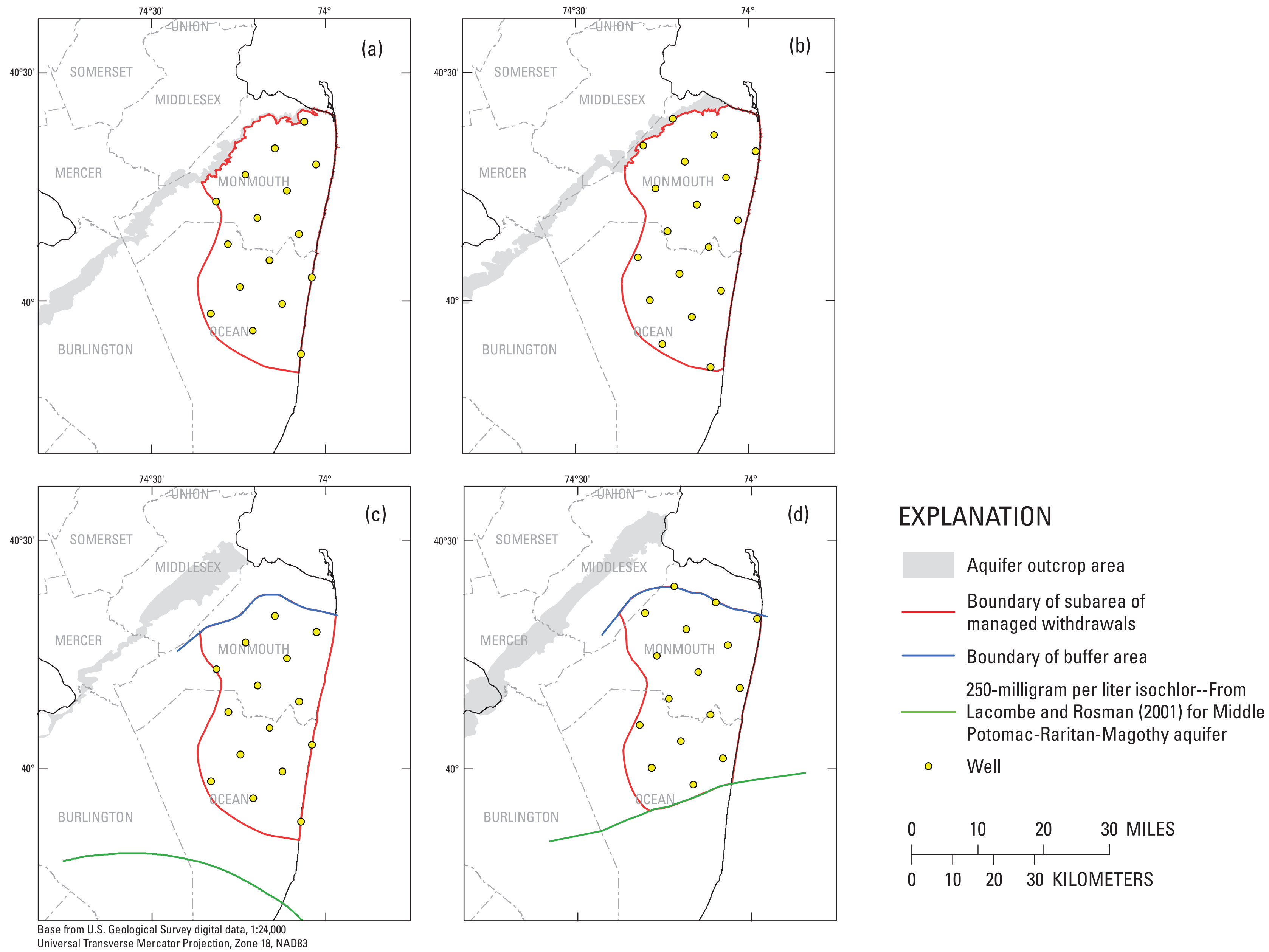

Figure 13. Regularly spaced well locations used in the (a) Wenonah-Mount Laurel aquifer, (b) Englishtown aquifer system, (c) Upper Potomac-Raritan-Magothy aquifer, and (d) Middle Potomac-Raritan-Magothy aquifer for management model MM03 in Critical Area 1, east-central New Jersey.

Reallocation to Small Volume Wenonah-Mount Laurel Aquifer and Englishtown Aquifer System Potable Users (Management Model MM05)

Management model MM05 is designed to represent managed withdrawals of up to 30 Mgal/yr for potable use at current well locations from the Wenonah-Mount Laurel aquifer and Englishtown aquifer system in the depleted zone. Locations of the small volume wells (Jan Gheen, New Jersey Department of Environmental Protection, written commun., 2006) are shown in figure 12 and listed in table 1. The maximum simulated withdrawal rate for these wells was 30 Mgal/yr or the pre-Critical Area allocation, whichever is smaller (Jan Gheen, written commun., 2006). Three variations of management model MM05 (a, b, and c) were designed with different constraints.

For MM05a, only small volume wells in areas with observed water levels above -50 ft below NGVD 29 were managed. A head constraint value of -50 ft below NGVD 29 was used for these wells. The value of head at each location was modified using the following equation to account for the difference (residual) between simulated heads and observed 2003 water levels.

$$wl_{obs} - residual = h_{sim}, \qquad (6)$$

where

- wl_{obs} is the observed water level at a location,
- h_{sim} is the simulated head at a location, and
- $residual$ is the difference between the observed water level and simulated head (both positive and negative values).

The right-hand side of equation 3 was replaced by equation 6. Only initial constraints 1 and 3 described on page 16 were applied. For MM05b, withdrawals at all small volume wells were managed, and initial constraint 2 was included. Management model MM05c is similar to MM05b, except that initial constraint 4 also was included to see whether a different result was obtained.

Results for the three MM05 simulations are listed in table 2. A maximum additional withdrawal of 0.9 Mgal/d was simulated in these runs. The largest withdrawals were evenly distributed in the Englishtown aquifer system (0.6 Mgal/d) for MM05b or MM05c. The amount of additional withdrawals simulated equals the maximum reallocation for the Wenonah-Mount Laurel aquifer and Englishtown aquifer system. Thus, the increase of 0.9 Mgal/d can be accommodated if the initial constraints are acceptable. Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints are listed in table 2. For this management model, there were no substantial changes in results compared to 2003 conditions.

Trade-Off Analysis

A trade-off analysis was done to evaluate the quantities of additional withdrawals obtained by varying the constraint values (Ahlfeld and Mulligan, 2000). A trade-off analysis is useful because it provides water managers with (1) an understanding of how hydrologic constraints affect withdrawal patterns and (2) a range of outcomes based on alternative definitions of hydrologic constraints because constraints are often difficult to define. Determination of each point on a trade-off curve or bar in a chart requires the development and execution of a separate management model run. Six to nine management model runs were constructed to define each trade-off curve. Using more management model runs could better define the trade-off curve and associated results. Approximately 60 management-model runs were made. Some trade-off curves were used to test comparable constraints (for example, drawdown compared to head) to see if results were different.

Maximum Allowable Drawdown in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system (Management Models MM06 and MM07)

For this trade-off analysis, all initial constraints described on page 16 were held constant except for constraint 2, the maximum allowable drawdown in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system, which was varied from 5 to 50 ft. Both current (MM06) and regularly spaced well locations (MM07) were tested.

The resulting trade-off curves and source of water to wells are shown in figures 14a and 14b. A maximum additional withdrawal of up to 12.6 Mgal/d was derived over this range for regularly spaced well locations; a maximum additional withdrawal of about 7.6 Mgal/d was derived for current well locations. The difference in additional withdrawals was small over the range for current well locations. Most of the source water was from the Englishtown aquifer system for regularly spaced well locations and the Upper Potomac-Raritan-Magothy aquifer for current well locations. The distribution of withdrawals was concentrated in updip areas for regularly spaced well locations; the distribution for current well locations was similar and was dictated by those wells.

Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints for MM06 and MM07 are listed in table 2 only for the simulations at the endpoints on each curve. For both well configurations and maximum allowable drawdown constraint of 50 ft, the combined simulated area of heads below -30 ft in the four aquifers more than doubled compared to 2003 conditions.

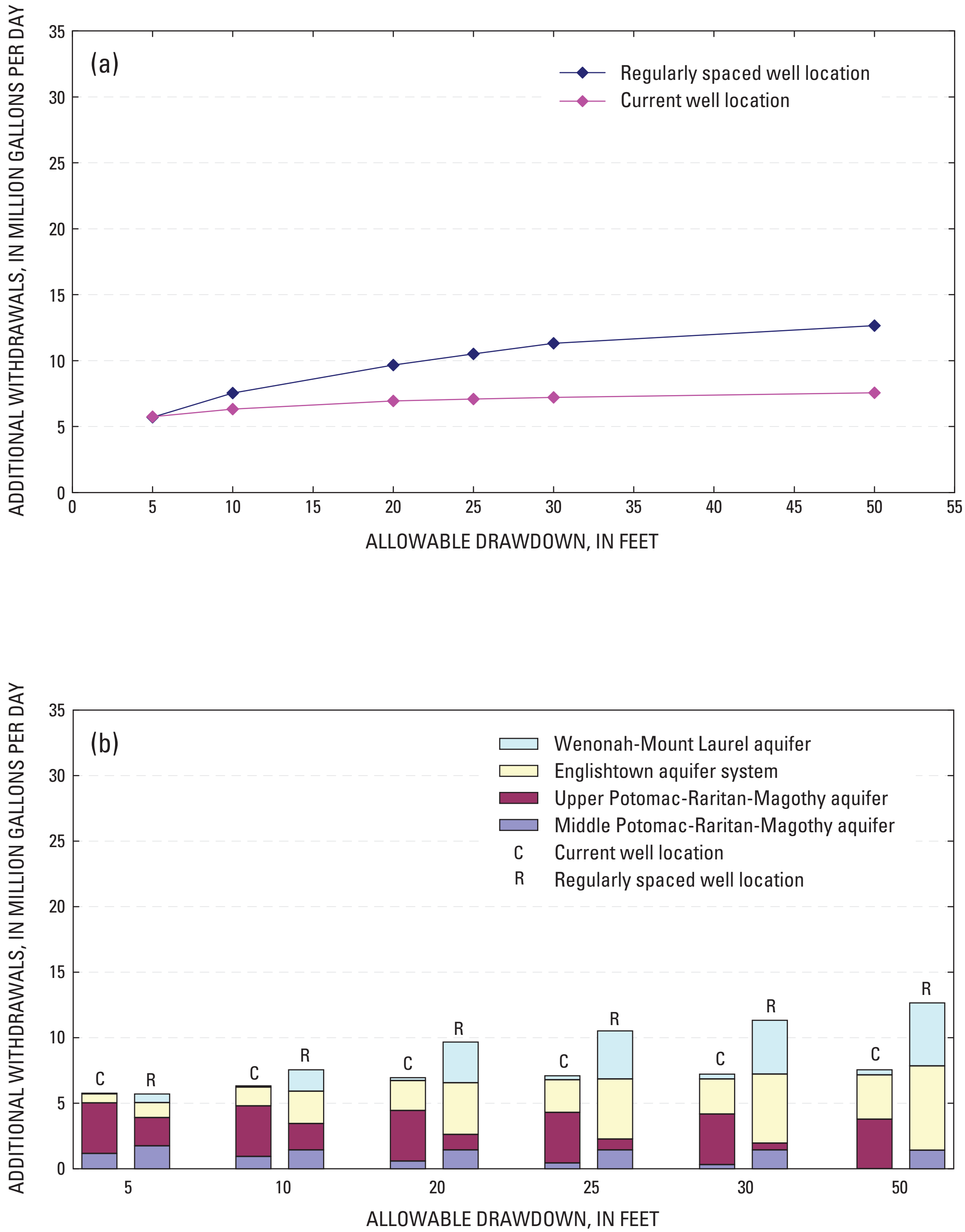

Figure 14. (a) Trade-off curves and (b) source of water to wells for management models MM06 and MM07 with various maximum allowable drawdowns in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system for current (2003) and regularly spaced well locations in Critical Area 1, east-central New Jersey.

Minimum Allowable Head in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system (Management Model MM08)

For this trade-off analysis, all initial constraints described on page 16 were held constant except for constraint 2, the minimum allowable head (comparable to maximum allowable drawdown) in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system, which was varied from -10 to -110 ft. Only withdrawals at regularly spaced well locations (MM08) were simulated because results for the previous trade-off curve were relatively flat for the current well locations.

Design of this management model is complicated by (1) wells located in areas with water levels lower than the particular head constraint and (2) the difference (residual) between the observed water levels and simulated 2003 heads. To address the first issue, only wells in areas with water levels greater than the constraint value were included in the simulation, similar to MM05a. To address the second issue, equation 6 was applied as before.

The resulting trade-off curve and source of water to wells are shown in figures 15a and 15b. The trade-off curve is not smooth for several reasons: the removal of a well from the model depends on its position relative to an observed contour line and the accuracy of that line. Some simulations were infeasible, resulting in the removal of some wells in order to obtain an optimal solution. These complexities affect the results obtained using this management model. A maximum additional withdrawal of up to 12.3 Mgal/d was derived with the minimum allowable head constraint ranging from -10 to -110 ft below NGVD 29. The greatest change in benefit was associated with minimum allowable heads between -30 and -60 ft below NGVD 29. The largest source of water was the Englishtown aquifer system in most cases. The distribution of withdrawals was concentrated in updip areas.

Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints for MM08 are listed in table 2. Results are listed only for the simulation represented by the endpoints on the curve. For the minimum allowable head constraint of -110 ft, the combined simulated area of heads below -30 ft in the four aquifers more than doubled compared to 2003 conditions. For the maximum allowable head constraint of -10 ft, the total number of binding constraints decreased by 90 percent compared to that for MM03.

Maximum Allowable Drawdown at the 250-mg/L Isochlor in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy Aquifers (Management Models MM09 and MM10)

For this trade-off analysis, all initial constraints described on page 16 were held constant except for constraint 4, the maximum allowable drawdown of 5 ft along the 250-mg/L isochlor in Ocean County in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers, which was varied from 1 to 20 ft. Simulations were run for current (MM09) and regularly spaced well locations (MM10).

The resulting trade-off curves and source of water to wells are shown in figures 16a and 16b. A maximum additional withdrawal of up to 17.4 Mgal/d was derived over this range for both well configurations. The higher additional withdrawals simulated using regularly spaced well locations diminishes with increasing drawdown (fig. 16a). Most of the source water was from the Upper Potomac-Raritan-Magothy aquifer with current (2003) well locations and the Englishtown aquifer system and Upper Potomac-Raritan-Magothy aquifer with regularly spaced well locations. The distribution of managed withdrawals was concentrated in updip areas for regularly spaced and current well configurations.

Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints for MM09 and MM10 are listed in table 2. Results are listed only for the simulations represented by the endpoints on each curve. For the largest drawdown constraint of 20 ft for both well configurations, the combined simulated area of heads below -30 ft in the four aquifers increased by more than 4 times compared to 2003 conditions. For regularly spaced well locations and the largest drawdown constraint, the combined maximum saltwater intrusion velocity increased by more than 50 percent in the Potomac-Raritan-Magothy aquifers. For both well configurations and the smallest drawdown constraint of 1 ft, the total number of binding constraints decreased by 50 percent compared to their respective baseline management model. For both well configurations and the largest drawdown constraint, the total number of binding constraints increased by 50 percent compared to their respective baseline management model.

Maximum Allowable Velocity at the 250-mg/L Isochlor in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy Aquifers (Management Models MM11 and MM12)

For this trade-off analysis, all initial constraints described on page 16 were held constant except for constraint 4, the maximum allowable velocity (comparable to maximum allowable drawdown) along the 250-mg/L isochlor in Ocean County in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers, which was varied from approximately 9 to 20 ft/yr. Simulations were run for current (MM11) and regularly spaced well locations (MM12).

The maximum velocity constraint was implemented in GWM by defining an equivalent gradient-type constraint. A total of 37 node pairs along the 250-mg/L isochlor in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy were used for computing the equivalent gradient constraints. Gradients across the 250-mg/L isochlor between

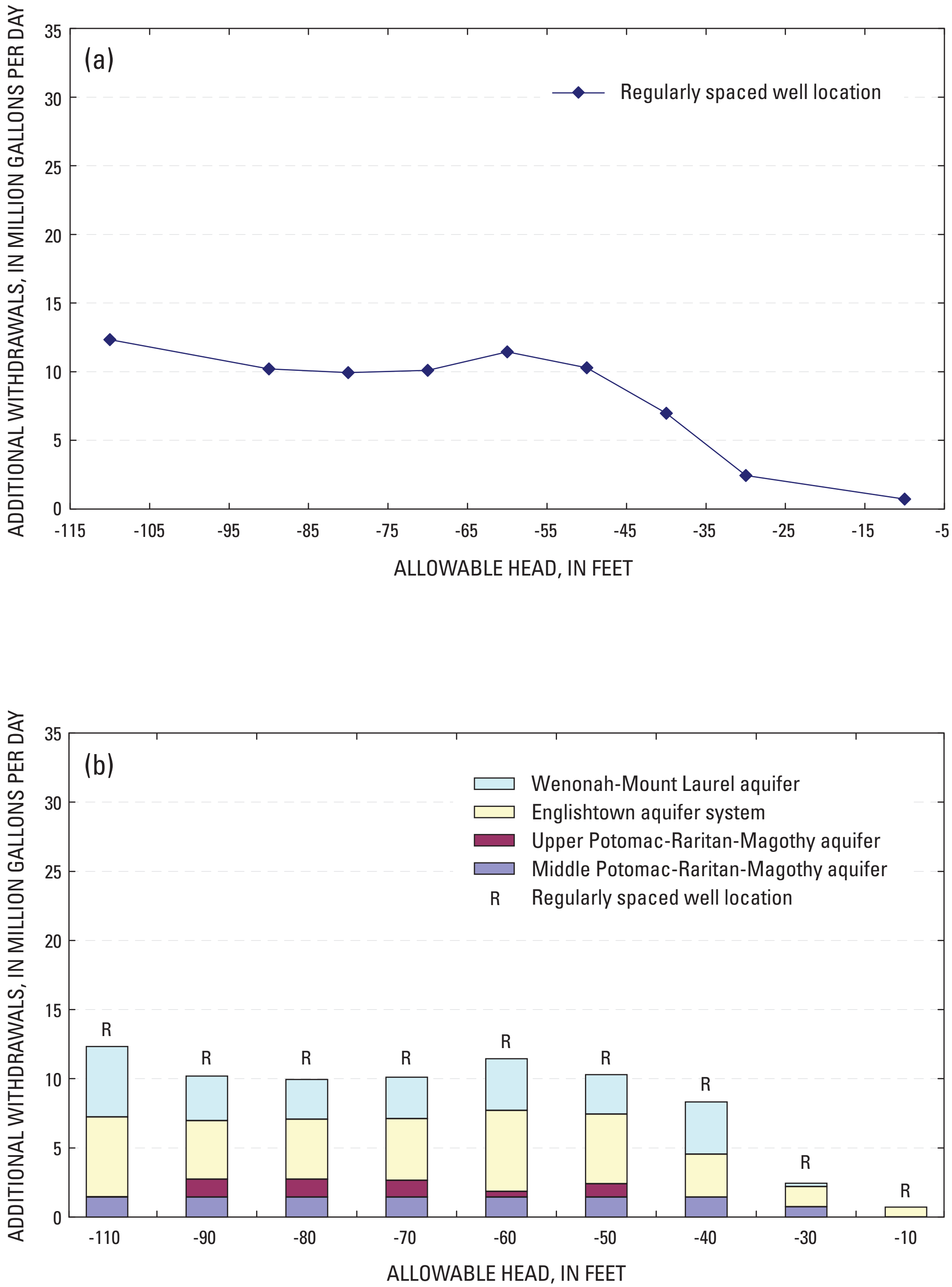

Figure 15. (a) Trade-off curve and (b) source of water to wells for management model MM08 with various minimum allowable head in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system for regularly spaced well locations in Critical Area 1, east-central New Jersey.

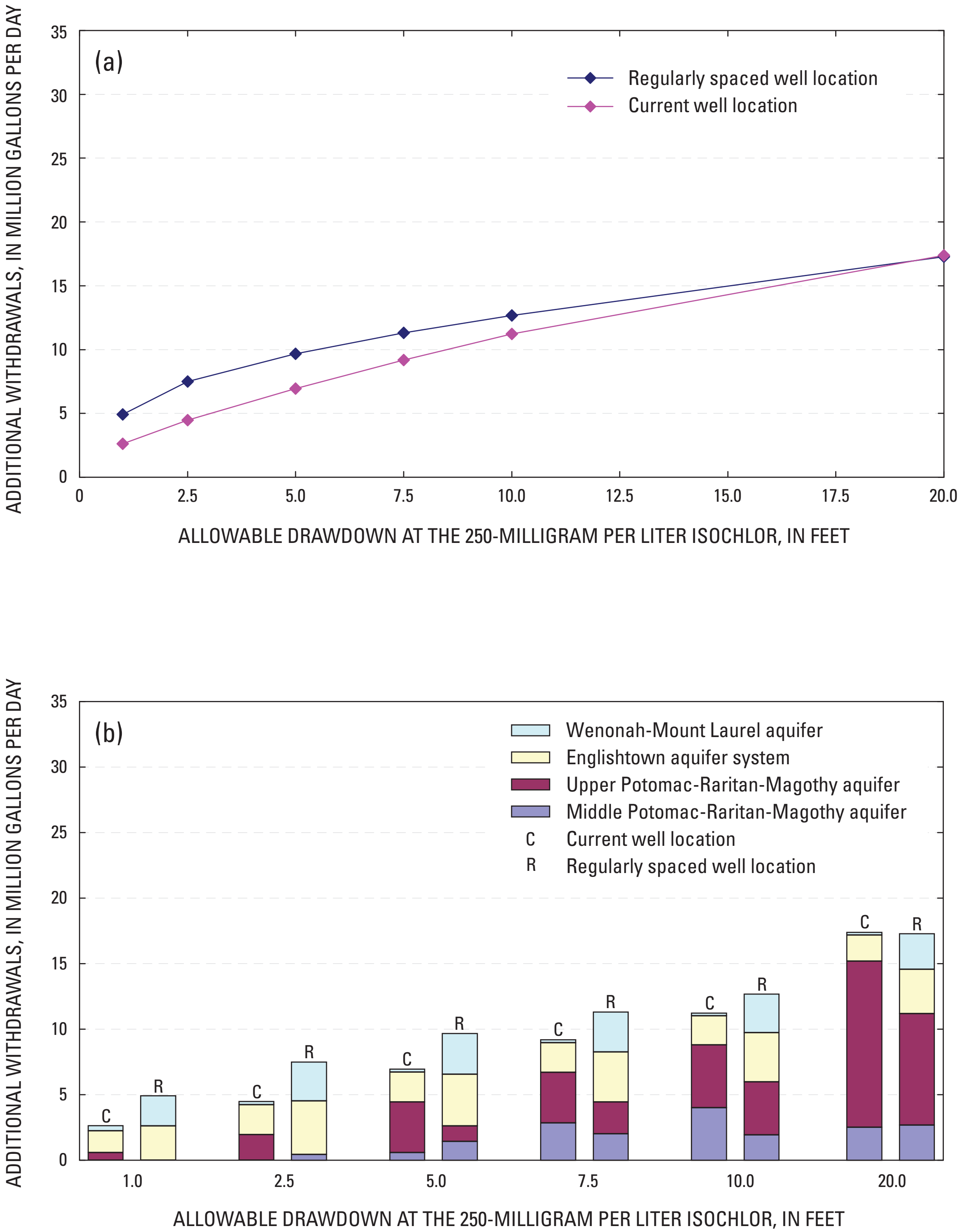

Figure 16. (a) Trade-off curves and (b) source of water to wells for management models MM09 and MM10 with various maximum allowable drawdowns at the 250-milligram per liter isochlor in the Upper and Middle Potomac-Raritan-Magothy aquifers for current (2003) and regularly spaced well locations in Critical Area 1, east-central New Jersey.

two model locations can be related to velocity using the following equation:

$$(grad_{i,j,k,t})_{1,2} \leq \frac{n_e * v_{max}}{K} \,, \qquad (7)$$

where

$(grad_{i,j,k,t})_{1,2}$ is the specified lower bound on gradient between model locations 1 and 2 (discussed above),

v_{max} is the maximum velocity,

n_e is the effective porosity (assumed to be 0.15), and

K is the hydraulic conductivity.

The value for effective porosity is based on Spayd and Johnson (2003, p. 16). The implementation of the constraint requires replacing equation 5 with an equation that defines an upper bound of the gradient. GWM only defines a lower bound of the gradient. Accordingly, equation 5 is modified as

$$\frac{(h_{i,j,k,t})_2 - (h_{i,j,k,t})_1}{\Delta x} \geq -\frac{n_e * v_{max}}{K} \,. \qquad (8)$$

The resulting trade-off curves and bar graphs of source of water to wells are shown in figures 17a and 17b. The left side of figure 17a contains a region in which solutions to the management model are infeasible; that is, one or more constraints cannot be met by any combination of withdrawals. This infeasibility occurs because there is already a background velocity that is greater than the value selected for the upper bound of the velocity constraint, which is related by the value chosen for n_e. To obtain an optimal solution requires simulating a greater maximum velocity for the constraint value.

The greatest change in additional withdrawals was derived over a narrow range of velocities between 9 and 12 ft/yr. In this range, a large change in withdrawals results from a small change in saltwater velocity. A maximum additional withdrawal of up to 20 Mgal/d was derived for both well configurations. Withdrawals level off on the right side of figure 17a because other constraints restrict the optimal solution. Regularly spaced locations may yield lower values for additional withdrawals at lower velocities because more wells are located close to 250-mg/L isochlor. Most of the source water was from the Upper Potomac-Raritan-Magothy aquifer for current (2003) well locations and from the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers for regularly spaced well locations. The distribution of withdrawals was somewhat random for both well configurations.

Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints for MM11 and MM12 are listed in table 2. Results are listed only for the simulations represented by the endpoints on each curve. For both well configurations and endpoints, the combined simulated area of heads below -30 ft in the four aquifers increased 3 to 4 times compared to 2003 conditions, potentially worsening initial constraint 3. For both well configurations and the largest velocities, the combined maximum saltwater intrusion velocity doubled in the Potomac-Raritan-Magothy aquifers.

Maximum Allowable Withdrawal Rates at Wells (Management Models MM13 and MM14)

For this trade-off analysis, all initial constraints described on page 16 were held constant except for constraint 1, the maximum withdrawal rate at each well, which was varied from 250 to 2,500 gal/min (0.36 to 3.6 Mgal/d). This constraint was varied for regularly spaced well locations (MM13) and for the clean-slate option described above (MM14).

The resulting trade-off curves and source of water to wells are shown in figures 18a and 18b. A maximum additional withdrawal of up to 32 Mgal/d was obtained over this range with the clean-slate option; about 11 Mgal/d was obtained with regularly spaced locations. Negative additional withdrawals, or less than the unmanaged withdrawals, were derived using the minimum withdrawal rates. The variation in additional withdrawals was less than 3 Mgal/d over the range for regularly spaced well locations, which indicates that one of the constraints may be restricting the optimal solution substantially. Most of the source water was from the Upper Potomac-Raritan-Magothy aquifer for the clean-slate option and the Englishtown aquifer system for regularly spaced well locations. The distribution of withdrawals was concentrated in the north and west for the clean-slate option and in updip areas for regularly spaced well locations.

Data on the simulated area of heads below -30 ft, maximum saltwater intrusion velocity, and number of binding constraints for MM13 and MM14 are listed in table 2. Results are listed only for the simulations represented by the endpoints on each curve. For the maximum withdrawal rate constraint and the regularly spaced well locations (MM13), the combined simulated area of heads below -30 ft in the four aquifers less than doubled compared to 2003 conditions. For the 2,500 gal/min withdrawal rate constraint and the clean-slate option (MM14), the simulated area of heads below -30 ft tripled in the four aquifers compared to 2003 conditions. For the 250 gal/min maximum withdrawal rate constraint and the clean-slate option, the maximum saltwater intrusion velocity was reduced substantially in the PRM aquifers compared to 2003 conditions. For the 2,500 gal/min maximum withdrawal rate constraint and the clean-slate option, the total number of binding constraints decreased by 50 percent compared to that for MM04.

Comparison of Water-Supply Management Models

General conclusions reached by comparing the water-supply management models are (1) the largest volume of additional withdrawals were obtained for the clean slate option (MM14), and the smallest volume were obtained by

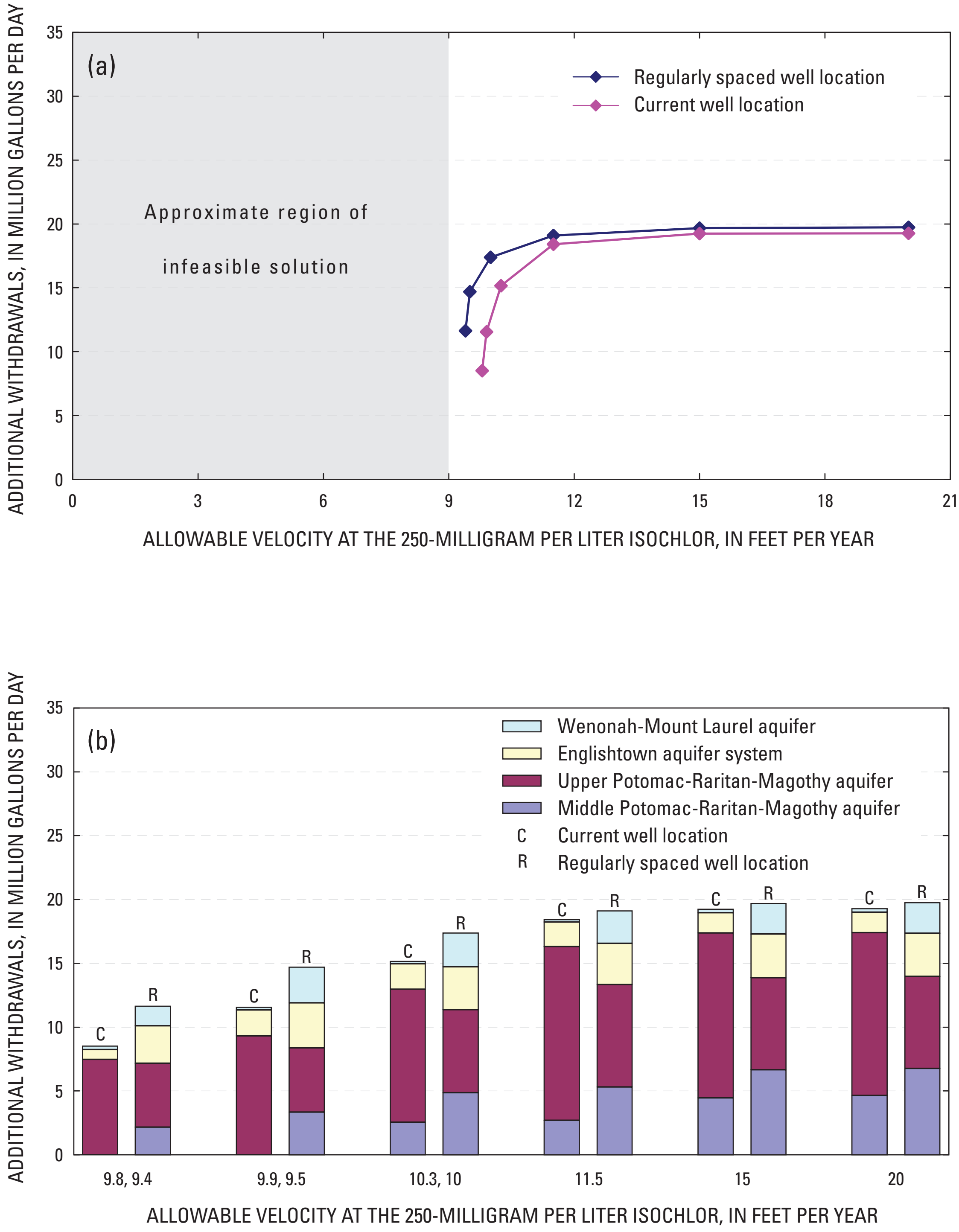

Figure 17. (a) Trade-off curves and (b) source of water to wells for management models MM09 and MM10 with various maximum allowable velocities at the 250-milligram per liter isochlor in the Upper and Middle Potomac-Raritan-Magothy aquifers for current (2003) and regularly spaced well locations in Critical Area 1, east-central New Jersey.

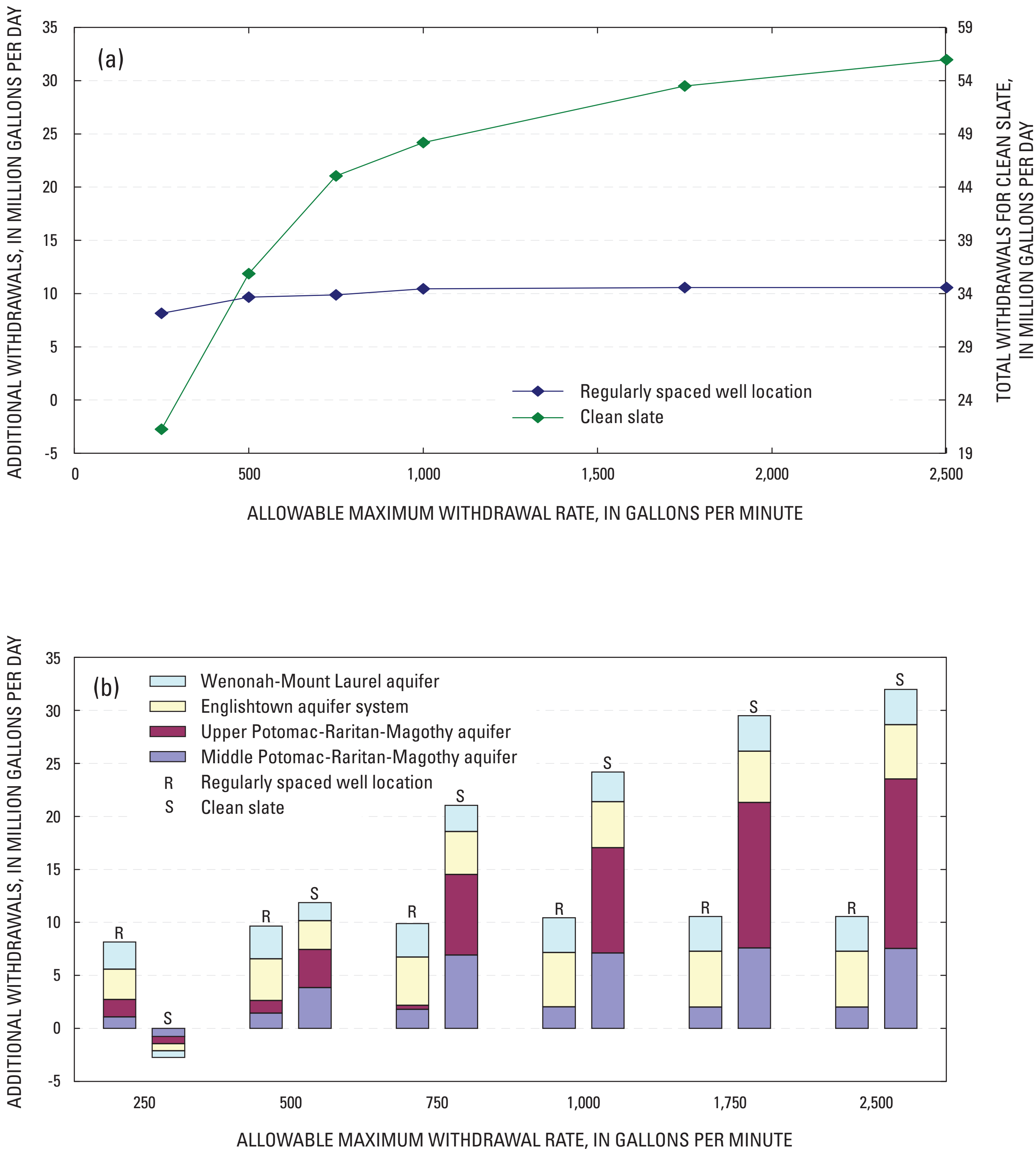

Figure 18. (a) Trade-off curves and (b) source of water to wells for management models MM13 and MM14 with various maximum withdrawal rates in the Wenonah-Mount Laurel, Englishtown, and Upper and Middle Potomac-Raritan-Magothy aquifers for regularly spaced well locations and clean slate in Critical Area 1, east-central New Jersey.

reallocation to small volume users (MM05); (2) additional withdrawals were greater when regularly spaced well locations were used than when current (2003) well locations were used; (3) managed withdrawals occurred in aquifer updip areas, except for MM11 and MM12, where managed withdrawals occurred throughout aquifer subareas; (4) the constraint to which the value of the objective function is most sensitive (based on **shadow prices**) appears to be the maximum allowable velocity at the southern 250-mg/L isochlor in the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers; (5) the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers provide more water to the wells than the Englishtown aquifer system and Wenonah-Mount Laurel aquifer; (6) the Upper Potomac-Raritan-Magothy and Middle Potomac-Raritan-Magothy aquifers show the most variability in the source water to wells; and (7) increasing the maximum allowable velocity constraint at the 250-mg/L isochlor or increasing the maximum withdrawal rate (clean-slate option) constraint yields the most withdrawals for the management models documented in this report.

Additional withdrawals that result when each management model is run are shown in figure 19. Simulations of the management models developed in this study resulted in available managed withdrawals that ranged from about 5 to 20 Mgal/d. This withdrawal range is dependent on the management model design. For example, additional withdrawals could be obtained if maximum allowable constraints were increased or minimum allowable constraints were decreased. In designing the various management models, the best choice or acceptable thresholds of constraints are not known. The management models developed in this study are estimates of an optimal design. Thus, the feasibility of additional withdrawals depends on the threshold for accepting adverse effects and the response of the aquifer system based on the trade-off curves and bar charts, as well as the time horizon. Greater additional withdrawals may be obtained by combining or changing selected constraints; however, adverse effects may result. The use of competing constraints also affects results. Accordingly, additional management models may need to be evaluated. In addition, measures such as field monitoring (for example, for saltwater intrusion) would provide data that would improve management model design.

Limitations of the Analysis

The validity of results of this study should be evaluated in terms of associated limitations and assumptions. Data error may include interpreted potentiometric surfaces, observed 250-mg/L isochlor locations, and withdrawal inaccuracies. The last example may be a source of error in the amount and location of managed withdrawals. Withdrawal data used in this study comes from values reported to the NJDEP by purvey-

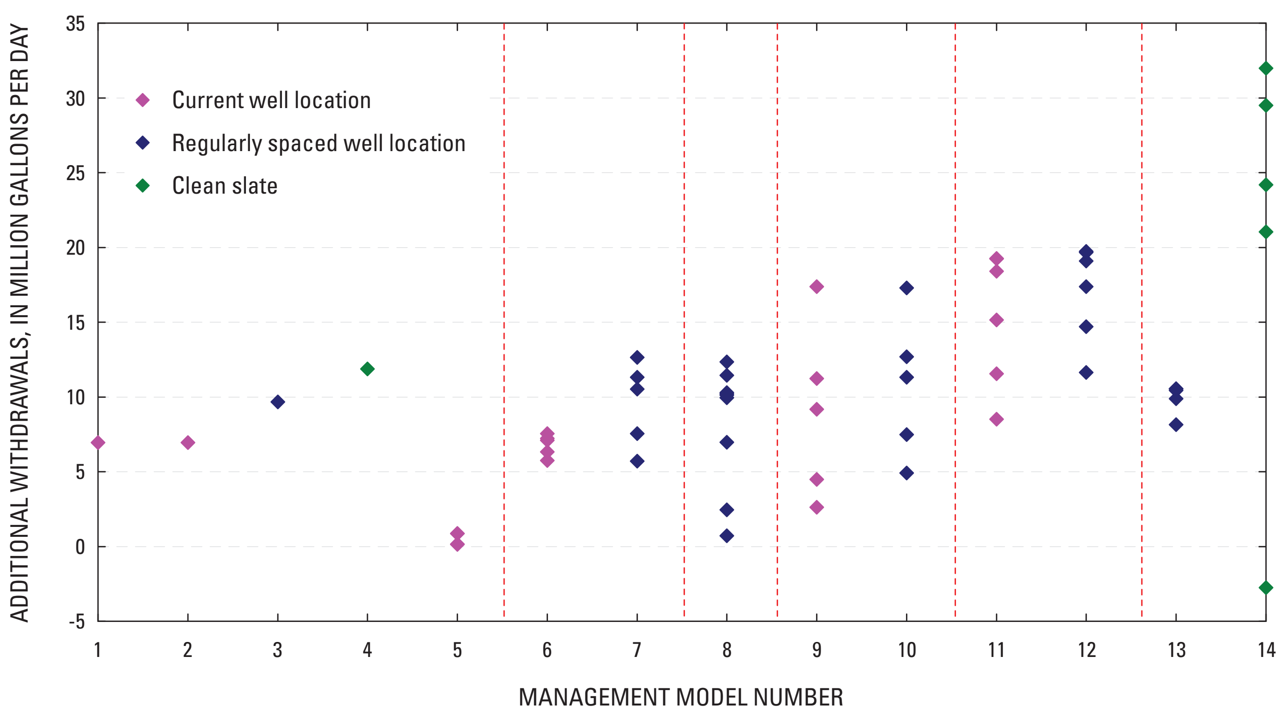

Figure 19. Summary of additional withdrawals computed by the management models for Critical Area 1, east-central New Jersey.

ors. (These data have been checked by USGS personnel and are maintained by the USGS West Trenton, N.J., office as an unpublished database.) These data represent the best information available, although the associated accuracy is not always known.

Limitations and assumptions of MODFLOW and GWM are relevant in the evaluation of management model results. This information is discussed in the reports that document the model codes. Limitations and assumptions of the RASA model and associated input data are discussed in the reports documenting that model by Martin (1998) and Voronin (2004). For example, there are differences between simulated heads and observed water levels due to model calibration. The model was not designed to detail changes in streamflow because of the large grid size, limited recharge input data, and type of stream boundary condition used. Despite these caveats, the RASA model has proven to be a good predictor when used in other hydrologic studies, particularly at a regional scale.

Limitations and assumptions of this study, in addition to those listed previously, include the use of different constraints or values of constraints that may lead to different results. Also, certain optimization designs may be too complex or impractical to simulate with the RASA model. Thus, optimization results are limited to the selected approach; effects on base flow, water quality, or other concerns cannot be evaluated. Steady-state conditions assume there is no further change in simulated heads with time as a result of withdrawal stresses for each of the model runs. These conditions represent the maximum effect of hydrologic stress; thus, estimates of optimized withdrawals are conservative. Ground-water velocity at the 250-mg/L isochlor is computed on the basis of a constant-density flow model, as opposed to a variable-density flow model, and uses an assumed value for effective porosity. However, density effects at the 250-mg/L isochlor location are minimal.

Summary and Conclusions

Ground-water levels in Water Supply Critical Area 1 in east-central New Jersey have recovered since the late 1980s as a result of reductions in ground-water withdrawals. Reductions in withdrawals were initiated by the New Jersey Department of Environmental Protection (NJDEP) in the depleted zones of the Wenonah-Mount Laurel aquifer, Englishtown aquifer system, Upper and Middle Potomac-Raritan-Magothy aquifers, and no additional withdrawals were allowed within the threatened margins. The intent of the reductions was to allow ground-water levels to recover to acceptable levels, but recent increased water demand as a result of development in Middlesex, Monmouth, and Ocean Counties has prompted the NJDEP to reevaluate the reductions for potential reallocations.

During 1988-2003, the most substantial changes in water levels were in the Wenonah-Mount Laurel aquifer and Englishtown aquifer system, where water levels recovered more than 80 ft along the coast in southern Monmouth and northern Ocean Counties. The recovery was greater than 40 ft over a large part of the Critical Area in these two aquifers. The amount of recovery in the Upper Potomac-Raritan-Magothy aquifer was the smallest—less than 40 ft. The largest withdrawals over the period were made from the Upper Potomac-Raritan-Magothy aquifer, but water levels were not as low in this aquifer in 1988 as in the other three aquifers. The recovery in the Upper Potomac-Raritan-Magothy aquifer was 10 to 20 ft over a large part of Monmouth County, but declines of 10 to 40 ft were observed in a 48 mi^2 area of northern Ocean County. Water levels in the Middle Potomac-Raritan-Magothy aquifer recovered 80 ft or more in areas along Raritan Bay, but most of the recovery was from 10 to 40 ft. A large area of 20- to 40-ft recovery occurred along the border of Monmouth and Ocean Counties.

To provide a technical basis to water-resource managers for the reallocations, the USGS used an existing regional ground-water-flow model along with optimization techniques to determine optimal withdrawals at selected locations within the Critical Area. Unlike previous simulation studies involving design of withdrawal scenarios and evaluation of effects, this study set the hydrologic constraints and then determined the optimal withdrawals. Such an approach is particularly beneficial for a regional-scale study of this kind because of the large number of wells to be simulated. A buffer analysis was done to define an area for no additional withdrawals to minimize changes in simulated streamflow in aquifer outcrop areas and simulated movement of ground water toward wells from areas of possible high chloride concentrations in the northern and southern parts of Critical Area 1. Five base water-supply management models were developed. Each management model has an objective function, decision variables, and constraints. Nine additional management models also were developed as part of a trade-off analysis between withdrawal amounts and constraint values. The 14 management models were used to simulate withdrawals at current (2003) and regularly spaced well locations with variations on ground-water head, drawdown, velocity at the 250-mg/L isochlor, and withdrawal rate constraints.

Results of each management model were analyzed in terms of withdrawals, heads, saltwater intrusion, and source water by aquifer. The results of approximately 60 management-model runs are documented in this report. The conclusions reached by comparing the results of the water-supply management models are (1) the largest volume of additional withdrawals was obtained using the clean-slate option (assumes withdrawals were optimized from the start of water-supply development); (2) greater withdrawals were derived using regularly spaced well locations than using current (2003) well locations; (3) managed withdrawals typically occurred in aquifer updip areas; (4) the most limiting constraint appears to be the maximum allowable velocity at the southern 250-mg/L isochlor; (5) the deeper aquifers provided more water to the wells than the shallower aquifers; (6) the deeper aquifers had the most variability in the source of water to wells; and (7) increasing the maximum allowable velocity at the 250-mg/L isochlor or increasing the maximum withdrawal rate (clean-slate option) constraints yielded the most withdrawals for the management models. On the basis of the management models designed in this study, and caveats provided, the amount of available withdrawals within Critical Area 1 generally ranges from 5 to 20 Mgal/d.

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Glossary

A

Aquifer Subarea the boundary of Critical Area 1 is a composite of the surface expression of each of four aquifers. Accordingly, the total area for managed withdrawals will differ for each aquifer. An aquifer subarea is the area relevant to a specific aquifer.

B

Base Allocation a purveyor's portion of the safe or dependable yield of the affected water resource within the Critical Area.

Binding Constraints constraints that restrict the value of the objective function, or bind the solution of the management problem, by preventing decision variables from taking on values that further improve the objective function.

Buffer Area protective area designed to minimize the effects of managed ground-water withdrawals on simulated streamflow in aquifer outcrop areas and simulated saltwater intrusion in areas with ground-water chloride concentrations greater than 250 mg/L.

C

Clean Slate if withdrawals could have been optimized from the start of water-supply development in the Critical Area.

Constraints impose restrictions on the values that can be taken by the decision variables.

Critical Area a region where excessive water use or diversion causes undue stress, or wherein conditions pose a significant threat to the long-term integrity of a water-supply source, including a diminution of surface water due to excess ground-water withdrawal.

D

Decision Variables the decisions that are to be determined by the management model, such as the managed withdrawal rates at a set of wells. The values determined by the Ground-Water Management (GWM) Process for these decisions define the solution of the problem.

Depleted Zone an area within the Critical Area where ground-water levels in selected aquifers have declined so substantially that the water resource is of concern.

Distance to Right-Hand Side the value of the right-hand side of the constraint, in ft. It indicates how far away the optimal solution is from the specified constraint value.

F

Fall Line topographic boundary between physiographic provinces; the western margin of the Coastal Plain and the eastern margin of the Piedmont.

I

Isochlor contour line of equal chloride concentration.

M

Management Options alternative approaches for addressing a particular water-supply issue.

Managed Withdrawals are those from wells where the withdrawal rate is unknown at the start of the MODFLOW run and is determined as part of the GWM process.

Maximum Saltwater Intrusion Velocity the maximum steady-state rate of landward ground-water movement at the 250-mg/L isochlor computed using simulated gradients and aquifer properties.

N

Near-Binding Constraints those constraints in the final output from the Ground-Water Flow (GWF) Process (Ahlfeld and others, 2005, p. 52) that were binding constraints in the linear program output. The difference can result from nonlinear responses in the GWF Process and precision limitations in the computation of heads.

O

Objective Function a measure of the performance of the management-decision process. The objective function is used to identify the best solution among many possible solutions and is stated in terms of one or more of the decision variables. The function may be maximized or minimized.

Optimization the methodology of making a decision as effective as possible; specifically, the mathematical procedures (for example, finding the maximum of a function) involved.

Optimal Solution one that satisfies all the constraints and gives the best possible value of the objective function.

R

Reallocation an increased apportionment of withdrawals, in this case, following reductions in Critical Area 1.

Regularly spaced well locations placement of equally spaced modeled wells that potentially maximizes (optimizes) withdrawals while keeping the number of wells manageable from a modeling standpoint.

S

Shadow price the resulting increase in benefit from relaxing each constraint. When the right-hand-side value of a binding constraint increases by a unit amount, the objective function will change by an amount determined by the shadow price. This implies that the optimal solution is quite sensitive to constraints that have large shadow prices.

Smart Growth Areas areas of well-planned, well-managed growth that adds new homes and creates new jobs, while preserving open space, farmland, and environmental resources.

T

Threatened Margin borders the depleted zone of a water supply Critical Area and located where the decline of ground-water levels in selected aquifers may accelerate saltwater intrusion.

Trade-Off Analysis an evaluation done to determine how various constraint values affect the optimal solution of the water-supply management problem.

U

Unmanaged Withdrawals specified "fixed" withdrawals that are simulated by the model and are not modified as part of the optimization solution (that is, managed withdrawals), but contribute to the total stress on the modeled ground-water-flow system.

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