Effects of Historical Withdrawals on Advective Transport of Contaminated Ground Waters in a Glacial-Drift Aquifer, Milford, New Hampshire

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Abstract

The long-term persistence of some contaminants in the subsurface causes contaminant plumes in ground water to incorporate the effects of previous long-term trends in ground-water recharge and withdrawals. If changes in these aquifer stresses are significant during the period of contamination, the size of the contaminant plume will increase. Therefore, it is important to understand the relation between the current distribution of contaminants and previous aquifer stresses.

A study on the effects of long-term withdrawals on movement of contaminated ground waters was done by the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), Region 1. The results show that increases in pumping rates, from negligible amounts in the early 1960's to average withdrawals exceeding 4 cubic feet per second (2.6 millions of gallons per day) in the late 1980's, have had a profound effect on a volatile organic contaminant (VOC) plume in a highly permeable, glacial-drift, river-valley aquifer, in Milford, N.H. Simulations of advective transport show that changes in withdrawals from 1960 to 1988 have more than doubled the lateral extent of contaminated ground waters perpendicular to the primary direction of flow. Withdrawals also have increased the longitudinal extent of contaminated ground waters by 1.5 times the original extent in the early 1960's.

Introduction

The long-term persistence (greater than 10 years) of some contaminants in the subsurface, including VOC's such as chlorinated alkanes and alkenes [trichloroethylene (TCE) and tetrachloroethylene (PCE)], may complicate the analysis of contaminant plumes in ground water because the distribution of the plume will be affected by changes in long-term or historical stresses over the period of contamination. Changes in historical stresses that are important to consider include differences in rates of recharge to the aquifer from precipitation and changes in rates and location of ground-water withdrawals. In some cases, historical stresses differ enough from current stresses and cause large changes in the distribution of contaminants. Understanding the historical factors that affect the evolution of a contaminant plume will help improve the prediction of future changes in the plume.

This report describes a case study of the influence of historical ground-water withdrawals on advective transport of ground waters in a VOC plume, consisting primarily of PCE, in the Milford-Souhegan glacial-drift aquifer (MSGD), Milford, N.H. Other factors, such as dispersion, retardation, and biodegradation that affect plume evolution are not addressed.

Description of Study Area

The study area is in the Souhegan River Valley in Milford, N.H. (fig. 1). The aquifer consists primarily of stratified sand and gravel with some basal till and is overlain in places by recent alluvium. Hydraulic conductivities in the aquifer range from 5 to 500 feet per day (ft/d), but throughout most of its extent range from 50 to 250 ft/d. The zones of highest hydraulic conductivity coincide with sediments deposited by glacial meltwaters originating from drainage channels to the northwest and west of the Souhegan River Valley. The maximum saturated thickness of the aquifer exceeds 100 feet near its eastern extent but generally ranges from 0 to 60 feet. Laterally, the aquifer is bounded by till-covered bedrock uplands.

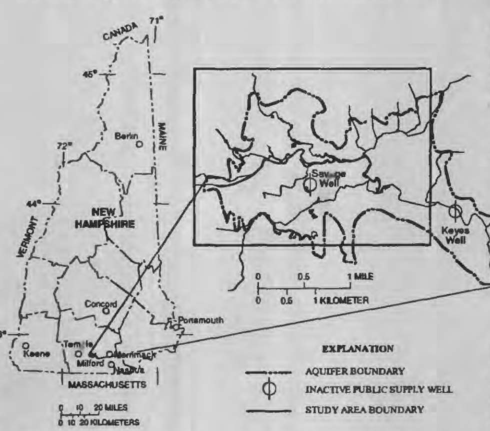

Figure 1. Location of study area in New Hampshire.

The Souhegan River Valley is gently sloping. Land-surface altitudes range from 230 to 280 feet. The MSGD aquifer is drained by the Souhegan River and its tributaries. A discharge ditch drains processed waters from several manufacturing companies in the southwestern part of the study area.

History of Contaminant Plume

Volatile organic compounds, primarily tetrachloroethylene (PCE), have contaminated a large volume [473 million cubic feet (ft^3)] of the MSGD aquifer with an area of 0.34 square miles (mi^2). Widespread contamination, which was first detected in early 1983, forced the shutdown of a municipal supply well, called the Savage well. The well site was later placed on the National Priority List and became a "Superfund Site" (Wayne Ives, New Hampshire Department of Environmental Services, written commun., 1996). The mapping of contaminants in the aquifer, which forms a plume, began in 1983 (New Hampshire Department of Environmental Services, 1985) and was done in detail in 1989 (fig. 2). Figure 2 shows the highest dissolved VOC concentration found in the aquifer in 1989. The principal source area of contaminants is a former manufacturing company that operated from the late 1940's to the early 1980's (HMM Associates, Inc., 1991). Although the disposal of VOC's was discontinued at the source area in 1983, ground water flowing through the area continues to be contaminated from contact with contaminated soils, sediments, and undissolved contaminants.

The absence of information regarding the evolution of the contaminant plume, particularly before its discovery in 1983, complicated initial predictions of rate of transport and formulation of remedial strategies because the plume was very extensive and source areas were not easily identifiable. Furthermore, early comparisons of plume shape with ground-water heads, flowlines, and calibrated steady-state advective-transport models of the time did not adequately describe the lateral extent of the plume perpendicular to the predominant easterly direction of ground-water flow.

Ground-Water Withdrawals

Ground-water withdrawals from the western half of the MSGD aquifer have increased dramatically over the last 38 years. Before pumping began at the Savage well in 1960, withdrawals from the aquifer were less than 0.1 ft^3/s, or approximately 6,500 gallons per day. In 1988, withdrawals were 4.4 ft^3/s (table 1). Just as important as the increase in the amount of ground-water withdrawals is the historical distribution of the withdrawals, which have shifted from south of the Souhegan River to north of the river. The percent of historical withdrawals, north or south of the Souhegan River, is listed in table 1.

Withdrawals north of the Souhegan River include those at a State of New Hampshire Fish Hatchery that continuously uses ground water because of its ideal temperature for breeding trout and salmon. Withdrawals south of the Souhegan River include the Savage well (until 1983) and various industrial and commercial companies.

Evidence of Long-Term Withdrawal Effects on the Aquifer

Long-term trends in water levels are available from observation well networks operated as part of the USGS Federal-State Cooperative Program (Hammond and others, 1995). In the Milford area, data from two wells provide information on the possible effect of withdrawals on long-term water levels (fig. 3). Observation well NAW-218 in Nashua, N.H. (fig.1) is unaffected by large changes in ground-water withdrawals during the last 30 years, whereas observation well MOW-36 is affected by nearby withdrawal wells in Milford (fig. 2). Furthermore, patterns of precipitation over the last 30 years are similar between Milford and Nashua (data collected by the National Oceanic and Atmospheric Administration climatological stations in Milford and Nashua), therefore, differences between the two sites should be primarily attributed to anthropogenic effects of withdrawals on water levels.

Water levels from observation well MOW-36 (fig. 3), which is about 1,000 feet southwest of the Savage well (fig. 2), show a decrease in the amplitude of fluctuations from the 1960's to the late 1980's and 1990's corresponding to decreases in withdrawals in the southern part of the aquifer (table 1). In contrast, water levels from observation well NAW-218 (fig. 3) show a more consistent pattern of fluctuations over the same period and thus reflect ambient trends in the climatological conditions of the region.

Table 1. Type of ground-water simulation, withdrawals, and percent of withdrawals north and south of the Souhegan River from pre-1960 to December 1988 in Milford, New Hampshire

[Pre-1960 time period is not included in this fact sheet; fig., figure; <, less than; --, unknown; to convert withdrawals to millions of gallons per day, multiply by 0.646]

Time period	Simulation		Total withdrawals, in cubic feet per second	Percent of withdrawals	
	Steady state (fig. 4)	Transient stress period (fig. 5a)		north of the Souhegan River	south of the Souhegan River
Pre-1960	yes	no	<0.1	--	--
1960-1964	yes	yes	.32	0	100
1965-1970	yes	yes	.88	0	100
1971-1973	yes	yes	2.21	60	40
September 1974-January 1976	yes	yes	2.30	50	50
October 1976-January 1983	yes	yes	2.82	60	40
February 1983-September 1986	(1)	yes	2.16	62	38
October 1986-December 1987	(1)	yes	3.16	74	26
January 1988-December 1988	(1)	yes	4.38	81	19

[1]February 1983 to December 1988 was combined for steady-state simulation described in this fact sheet.

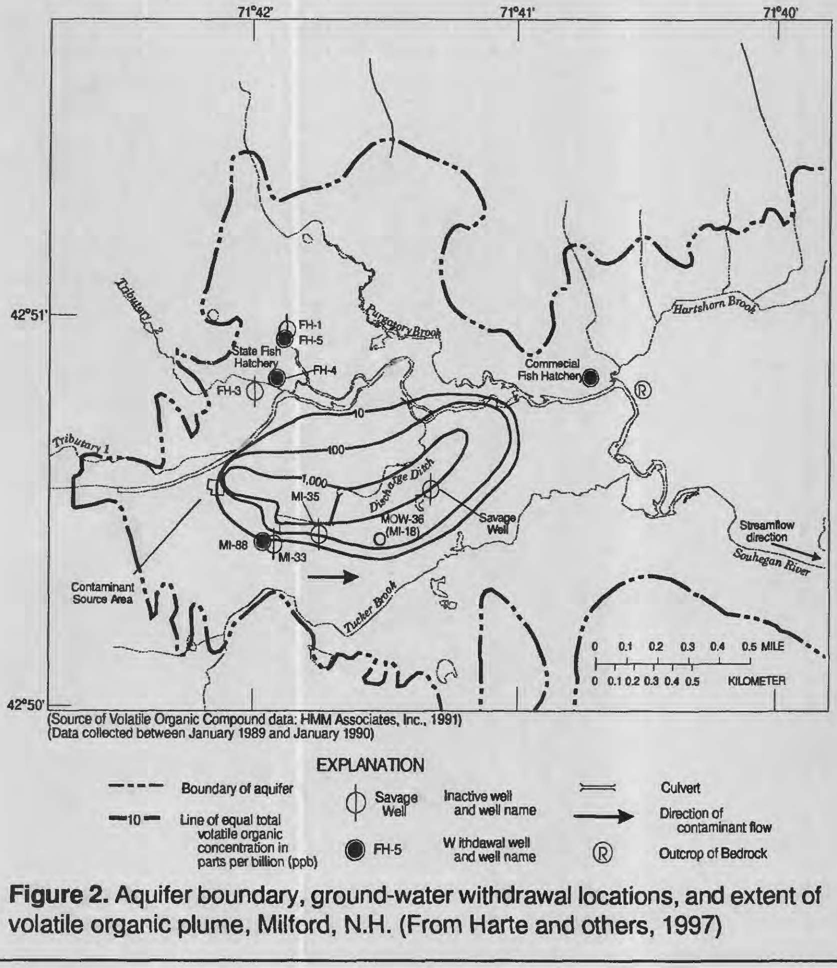

Figure 2. Aquifer boundary, ground-water withdrawal locations, and extent of volatile organic plume, Milford, N.H. (From Harte and others, 1997)

Simulation of Ground-Water Flow

A calibrated numerical ground-water-flow model was constructed for the western-half of the MSGD (Model documentation on file at the USGS office in Pembroke, N.H.) and based on work from a pre-existing model of the MSGD (Harte and Mack, 1992) by use of the computer code MODFLOW (McDonald and Harbaugh, 1988). Steady-state and transient ground-water flow was simulated for the period before withdrawals began at the Savage well in 1960 to 1995. In this report, results are presented from 1960, when withdrawals began at the Savage well, to 1988, when the first detailed mapping of the contaminant plume was completed (HMM, Associates, Inc., 1991). Periods of simulation correspond to those listed in table 1.

The steady-state and transient models of flow were used to examine different processes that occur in the aquifer as a consequence of ground-water withdrawals, by keeping all model parameters the same except withdrawals. The steady-state models of flow assume constant withdrawals with no changes in storage (aquifer heads remain fixed with time). Therefore, steady-state simulations represent a "snapshot" in time for periods with a fairly constant pattern of withdrawal. By not allowing changes in storage during each period, the steady-state simulations assume the aquifer reaches an instantaneous equilibrium with the imposed withdrawal. In contrast, the transient simulation represents a time-discretized continuum during which aquifer withdrawals, storage, and heads are allowed to vary. By comparing the results of the steady-state and transient simulations, the effect of storage changes and the rate at which the aquifer equilibrates to imposed withdrawals can be assessed.

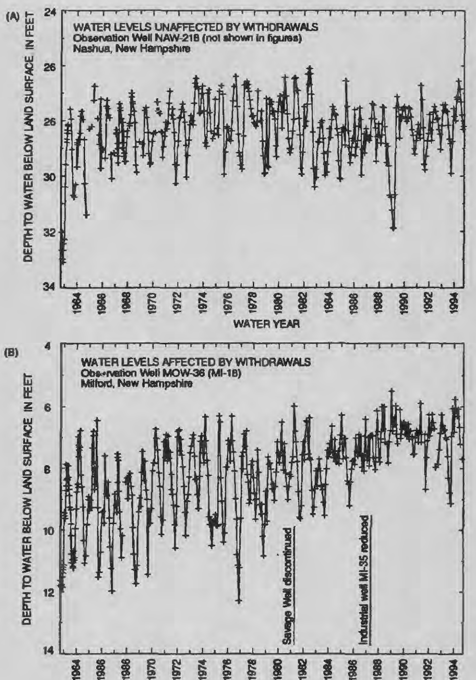

Figure 3. Comparison of water levels from observation wells in southern New Hampshire.

The computer code MODPATH (Pollock, 1994) was used to forward track the advective transport of water particles from three areas of known high concentrations of contaminants in the aquifer (greater than 10,000 parts per billion (ppb) of PCE) that represent possible contaminant disposal location areas (CDM Federal Programs Corporation, 1995). For the steady-state simulations, forward tracking of particles was started from the source area, as one instantaneous "release", at the beginning of each simulation, and terminated at the end of each simulation. The 1-year travel times of particles are delineated along each steady-state pathline. For the transient simulations, the advective transport of particles was forward tracked from the same starting locations, but were released by two different methods. In the first method, particles were released in the same manner as in the steady-state simulations, with a single instantaneous release at the start of each new stress period. In the second method, particles were released periodically every 2.5 months from 1960 to December 1988. The yearly travel of particles is also delineated along each transient pathline.

Advective transport is simulated in three-dimensions and particle distributions are projected onto a two-dimensional plane that represents the uppermost model layer. Initially, particles were tracked from source areas in all five model layers; however, because patterns of each particle trajectory or pathline were similar for each layer, the number of particles tracked was reduced to create a legible illustration. This report shows particles originating in layer 2 of the model.

Results of Flow-Model Simulations

The distribution of ground-water fluxes and the water budget are important factors in the computation of advective transport of contaminated ground waters. Water fluxes include the rate of discharge or recharge at aquifer boundaries and the internal distribution of water throughout the aquifer. The water budget includes the summation of water fluxes to aquifer boundaries. The major water-budget parameters include ground-water recharge, river leakage, ground-water withdrawals, and changes in aquifer storage.

The effect of increased ground-water withdrawals from pre-1960 to late 1988 results in a 2.3 ft^3/s decrease in ground-water discharge to rivers in the valley, from 5 to 3.7 ft^3/s. At the same time, withdrawals induce 3.1 ft^3/s of river leakage into the aquifer from 1.2 to 4.3 ft^3/s.

Changes in ground-water storage are a small component of the water budget for the simulated periods tested. Comparison of major components of the water budget, such as river leakage, are similar for the steady-state and transient simulations. Changes in storage in the transient simulation do not exceed 0.1ft^3/s in any stress period.

Results of Advective Transport Simulations

Particle paths from six steady-state models of flow representing six unique historical withdrawal patterns show a progressive southward shifting of particle pathlines from 1960 to January 1983 (fig. 4), when withdrawals at the Savage well were discontinued because of the detection of VOC's. The northernmost pathline shifts approximately 1,200 feet southward during this time. After 1983, when withdrawals were terminated at the Savage well, particle pathlines have moved northward. The northernmost pathline has moved about 200 feet north from February 1983 to January 1989. Although not shown, the configuration of pre-1960 pathlines is similar to that for the January 1960 to December 1964 simulation period because withdrawals were relatively low during both periods.

For several steady-state simulations, particles do not discharge before the end of the simulated period. These prematurely terminated pathlines are visible in

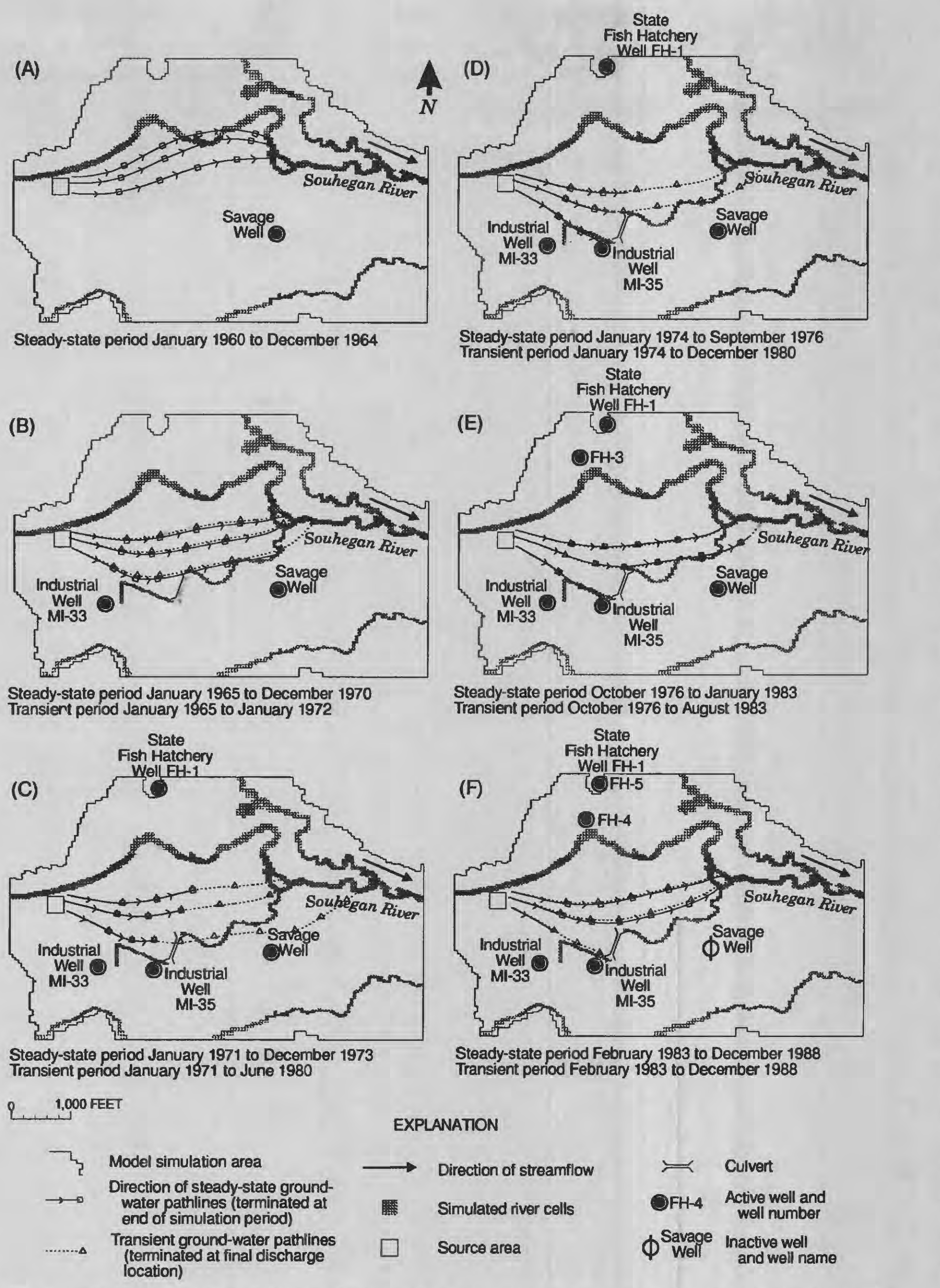

Figure 4. Historical pathlines of advective transport of contaminated waters from six steady-state simulations and one transient simulation.

figure 4 as a truncated pathline that ends in an area of the aquifer without external discharge sinks, such as rivers or wells. Pathlines are truncated in the shorter simulation periods, 1971-73 and 1974 to September 1976. The results of the steady-state advective transport simulation suggest that the average interstitial travel time or advection of ground water from the source area to discharge locations exceeds 3 years.

For the transient simulation, particles are not prematurely terminated because the period of transient simulation (29 years) exceeds the advective travel time of any one particle and transient pathlines are tracked to their final discharge locations from one stress period to the next. Therefore, for forward tracking in the transient simulation of the single, instantaneous release of particles at the beginning of each stress period (at the same time steady-state particles are released), all transient pathlines extend further than the steady-state pathline (fig. 4). Transient pathlines are shown in figure 4 for five of the six steady-state periods. There is little difference between the steady-state and transient pathlines during the same tracking time.

Computed transient travel times increase with increasing length of pathline as particles travel further downgradient because of increased withdrawals at wells south of the Souhegan River. The longest transient pathlines are for particles released in January 1971, which had a travel time of 9.5 years (fig. 4c). The shortest pathlines are for the simulation period January 1960 to December 1964, which had a travel time of 4.5 years (fig. 4a). Although particles tracked from the lowermost model layers (3, 4, and 5) follow a similar path as particles tracked from model layer 2, travel times are generally longer in the lowermost layers because of vertical differences in hydraulic conductivity. Travel times for particles tracked in the lower model layers can be 20 to 90 percent longer than those for particles in model layer 2.

Pathlines of particles tracked in transient simulations, from periodic, multiple particle releases every 2.5 months from January 1960 to December 1988, cover a larger area of the aquifer (fig. 5a) than do particle pathlines simulated with steady-state models of flow (fig. 4) and with single instantaneous releases of particles in transient tracking. The aquifer quickly equilibrates to a new pattern of withdrawal, as shown by the similarity in steady-state and transient pathlines for coincident tracking times. The larger area of particles, which is the result of the periodic release of particles rather than the single, instantaneous release of particles, indicates that the transition time between each change in withdrawal contributes to the spreading of contaminated ground waters.

The enlarged area of particles for the transient simulation with multiple releases (fig. 5) is particularly pronounced in the direction perpendicular to the primary longitudinal direction of flow. The northernmost to southernmost particle pathlines are approximately 2,000 feet apart, about twice as wide as

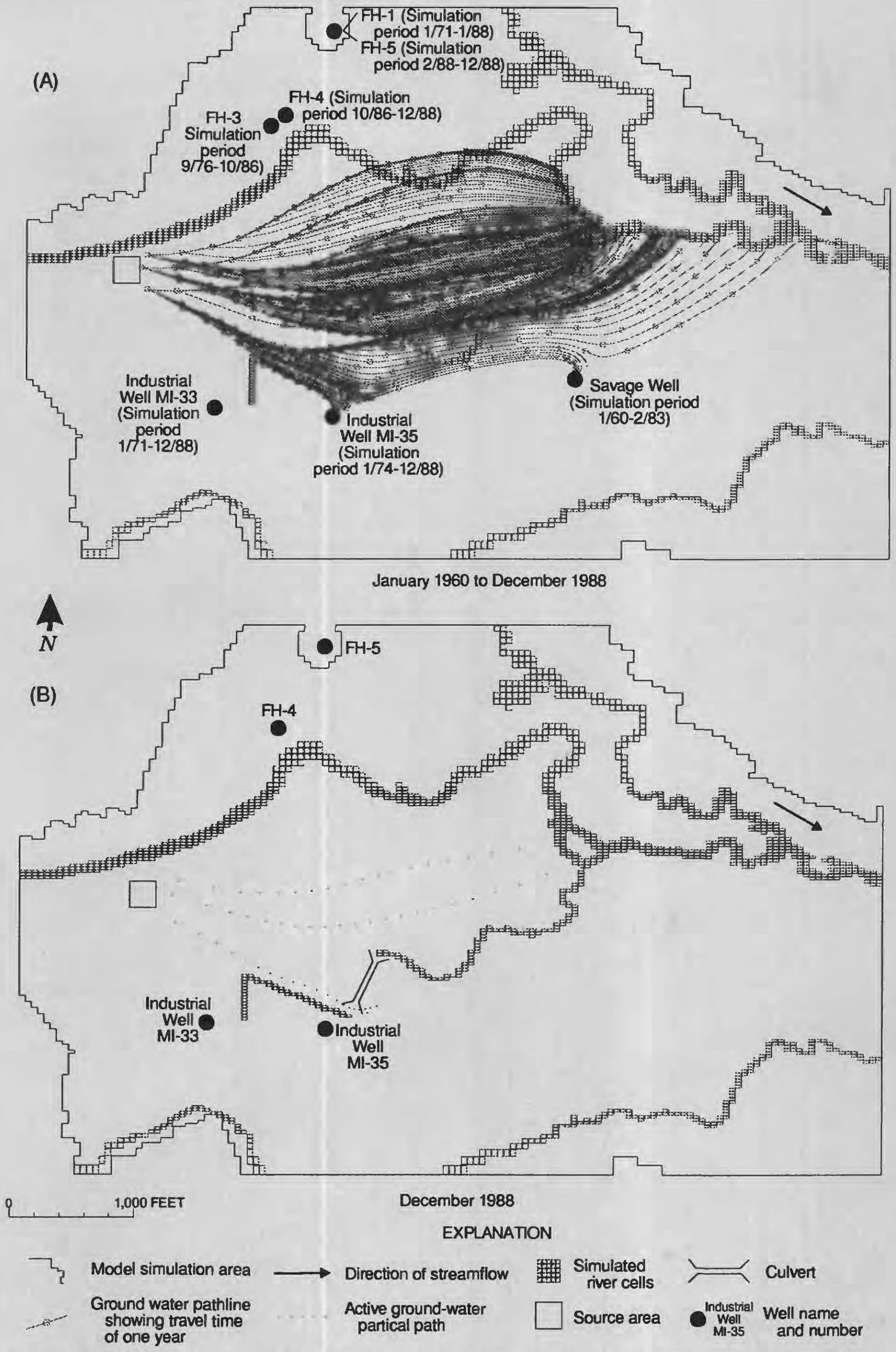

Figure 5. Transient pathlines of advective transport showing (A) composite of all pathlines and (B) active particles as of December 1988.

the distance between the northernmost and southernmost particle pathlines for any of the steady-state simulations or for the single release of particles in the transient simulation (fig. 4). Furthermore, along the longitudinal direction of ground-water flow, particle paths for transient models extend about 1,000 feet farther downgradient than the longest particle paths for the steady-state models of advective transport, and about 200 feet farther downgradient beyond the longest particle path for the single, instantaneous release transient model of advective transport.

Pathlines illustrated in figure 5a are a composite of all pathlines traveled from 1960 to 1988. The distribution of active particles in transport as of 1988 is narrower (fig, 5b) than the composite distribution of all current and previous pathlines (fig. 5a) but wider than any of the steady-state models (fig. 4).

Comparison of Transient Advective Transport to Contaminant Plume

Particle tracking from the multiple release, transient-advective transport covers a 0.23 square mile area of the aquifer, which is approximately 68 percent of the contaminant plume delineated to a concentration of 10 ppb. The 10 ppb line of VOC concentration (fig. 2) extends approximately 600 feet farther south than the most southern-tracked particles in the area near the Savage well. One possible explanation in the difference between the extent of advective-transport particles and the contaminant plume in this area is the potential for secondary source areas of contamination (Environmental Science and Engineering, Inc., 1995, 1997). The 10 ppb line of VOC concentrations (fig. 2) also extends farther northward of and beneath the Souhegan River than any tracked particle. Because no secondary sources of contamination are known in this area, the differences between the results of the advective-transport simulations and the extent of the contaminant plume could be attributed to (1) solute-transport processes not addressed in the simulated-advective models; and(or) (2) inadequacies in the approximation of field conditions in the advective-transport model, such as, oversimplification of aquifer hydraulic properties and(or) lumping of seasonal conditions into average annual conditions. Important solute-transport processes to consider in plume distribution include dispersion of solute and density differences between contaminated and uncontaminated ground water.

Perhaps a more accurate analogy of comparing advective transport to the 1989 contaminant plume (fig. 2) is the comparison of the plume to currently active particles at the end of December 1988 (fig. 5b), rather than to all historical pathlines (fig. 5a). Areas with currently active particles as of December 1988 would represent areas influenced by the active advective transport of solutes at the time of contaminant sampling. Areas without active particles, but which were formerly covered by pathlines, may represent areas where residual contamination exists from previous advection of contaminants. The distribution of active particles is coincident with the area delineated by the 100 ppb line of VOC concentrations, but not with the area delineated by the 10 ppb line, except that the 100 ppb line is about 500 feet farther downgradient than the active particle path (fig. 5b). The coincidence of the location of active particles with the area of highest concentration of VOC's suggest that advection is perhaps the most important component of solute transport in the MSGD aquifer.

Conclusions

The effect of historical changes in ground-water withdrawals on advective transport of contaminated ground waters is significant in the MSGD aquifer. Withdrawals have more than doubled the advective transport of contaminated ground waters perpendicular to the primary (longitudinal) direction of flow. Withdrawals also have increased longitudinal advective transport by 1.5 times the original longitudinal extent in the early 1960's.

The areal extent of advective transport of contaminated ground water indicated by transient simulations that incorporate changes in past and present patterns of ground-water withdrawals compares favorably with the observed distribution of the VOC plume. This suggests that advective transport is an important component of solute transport in the aquifer. Furthermore, transient simulation of advective transport of periodic (virtually continuous) releases of water particles into the aquifer during periods of changes in withdrawals showed a significantly larger area of advective transport of contaminated ground water than did simulations with less frequent releases into the aquifer.

The delineation of previous or historical pathlines provides insight into the fate and mechanisms of transport of contaminated waters. For example, the presence of contaminated waters in areas of historical pathlines may indicate areas of persistent residual contamination. By acknowledging the possibility that contaminants could be transported into different areas of the aquifer as aquifer stresses change, an explanation of the distribution of contaminants and the resulting estimation of aquifer and solute properties will be more accurate.

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