

Cover photo: A section of the firing range on Camp Edwards,
Massachusetts Military Reservation, Cape Cod, Massachusetts

Simulation of Advective Flow under Steady-State and Transient Recharge Conditions, Camp Edwards, Massachusetts Military Reservation, Cape Cod, Massachusetts

By DONALD A. WALTER and JOHN P. MASTERSON

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CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS AND ABBREVIATIONS

CONVERSION FACTORS

	Multiply	By	To obtain
	acre	0.4047	hectare
	cubic foot per day (ft ³ /d)	0.02832	cubic meter per day
	foot (ft)	0.3048	meter
	foot per day (ft/d)	0.3048	meter per day
	foot per day per foot (ft/d/ft)	1	meter per day per meter
	foot squared per day (ft ² /d)	0.09290	meter squared per day
	inch (in.)	2.54	centimeter
	inches per year (in/yr)	25.4	millimeter per year
	mile (mi)	1.609	kilometer

VERTICAL DATUM

Sea level: Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).

ACRONYMS AND ABBREVIATIONS

AFCEE	Air Force Center for Environmental Excellence
ARNG	Army National Guard
CIA	Central Impact Area
DNT	dinitrotoluene
DRN	Drain Package
FHB	Flow and Head Boundary Package
GHB	General Head Boundary Package
HFH	Horizontal Flow Barrier
HMX	Her Majesty's Explosive
IAGWSP	Impact Area Groundwater Study Program
mg/L	milligrams per liter
MMR	Massachusetts Military Reservation
RDX	Royal Dutch Explosive
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UXO	Unexploded ordnance

Simulation of Advective Transport under Steady-State and Transient Recharge Conditions, Camp Edwards, Massachusetts Military Reservation, Cape Cod, Massachusetts

By Donald A. Walter *and* John P. Masterson

ABSTRACT

The U.S. Geological Survey has developed several ground-water models in support of an investigation of ground-water contamination being conducted by the Army National Guard Bureau at Camp Edwards, Massachusetts Military Reservation on western Cape Cod, Massachusetts. Regional and subregional steady-state models and regional transient models were used to (1) improve understanding of the hydrologic system, (2) simulate advective transport of contaminants, (3) delineate recharge areas to municipal wells, and (4) evaluate how model discretization and time-varying recharge affect simulation results.

A water-table mound dominates ground-water-flow patterns. Near the top of the mound, which is within Camp Edwards, hydraulic gradients are nearly vertically downward and horizontal gradients are small. In downgradient areas that are further from the top of the water-table mound, the ratio of horizontal to vertical gradients is larger and horizontal flow predominates. The steady-state regional model adequately simulates advective transport in some areas of the aquifer; however, simulation of

ground-water flow in areas with local hydrologic boundaries, such as ponds, requires more finely discretized subregional models. Subregional models also are needed to delineate recharge areas to municipal wells that are inadequately represented in the regional model or are near other pumped wells.

Long-term changes in recharge rates affect hydraulic heads in the aquifer and shift the position of the top of the water-table mound. Hydraulic-gradient directions do not change over time in downgradient areas, whereas they do change substantially with temporal changes in recharge near the top of the water-table mound. The assumption of steady-state hydraulic conditions is valid in downgradient area, where advective transport paths change little over time. In areas closer to the top of the water-table mound, advective transport paths change as a function of time, transient and steady-state paths do not coincide, and the assumption of steady-state conditions is not valid. The simulation results indicate that several modeling tools are needed to adequately simulate ground-water flow at the site and that the utility of a model varies according to hydrologic conditions in the specific areas of interest.

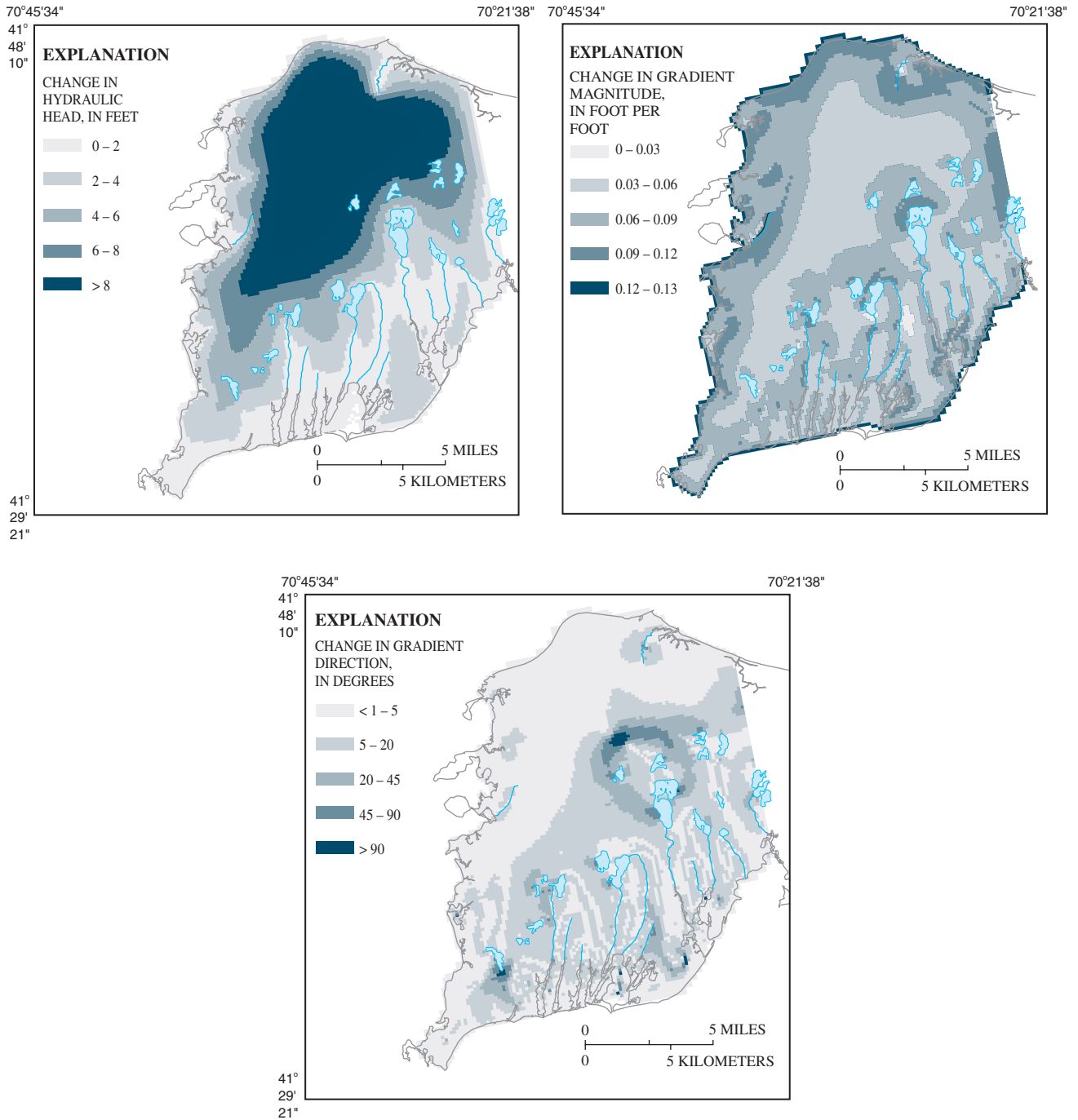


Figure 23. Simulated differences in hydraulic heads and in magnitude and direction of the hydraulic gradient between high-recharge (1955) and low-recharge (1965) conditions on western Cape Cod, Massachusetts.

As a result, the magnitudes of changes in hydraulic gradients upgradient of ponds, streams, and the coast are greater than in other areas. The change in hydraulic-gradient magnitude is smallest near the top of the water-table mound.

Hydraulic-gradient directions in the aquifer also change in response to changes in recharge rates. Between high-recharge (1955) and low-recharge (1965) conditions, changes in hydraulic-gradient direction ranged from 0 to 180° (fig. 23C). The greatest change in hydraulic-gradient direction occurs near the top of the water-table mound where simulated hydraulic gradients reverse direction. Large changes in hydraulic-gradient direction also occur near ponds, particularly near the boundaries between areas of pond inflow and pond outflow. Changes in hydraulic-gradient directions are small near discharge boundaries such as streams and coastal embayments. In general, there is an inverse relation between changes in hydraulic-gradient direction and magnitude (figs. 23C

and 24); areas that show large changes in hydraulic-gradient direction between high- and low-recharge conditions are areas where corresponding changes in hydraulic-gradient magnitude are small. This inverse relationship is shown in figure 24.

Changes in hydraulic-gradient directions between high-recharge (1955) and low-recharge (1965) conditions in the northern part of Camp Edwards, including the Impact Area, Demolition Area 1, and the J-Ranges, are shown in more detail in figure 25. The effects of changing recharge rates on the hydraulic gradients in the aquifer vary spatially. The changes in hydraulic-gradient direction in the Impact Area mostly are less than 5 degrees. Hydraulic gradients in Demolition Area 1 change direction by about 13 degrees. In the J-Ranges Area, changes in hydraulic-gradient directions range from 30 to 45 degrees in the southern J-Ranges Area and exceed 135 degrees in the northern J-Ranges Area.

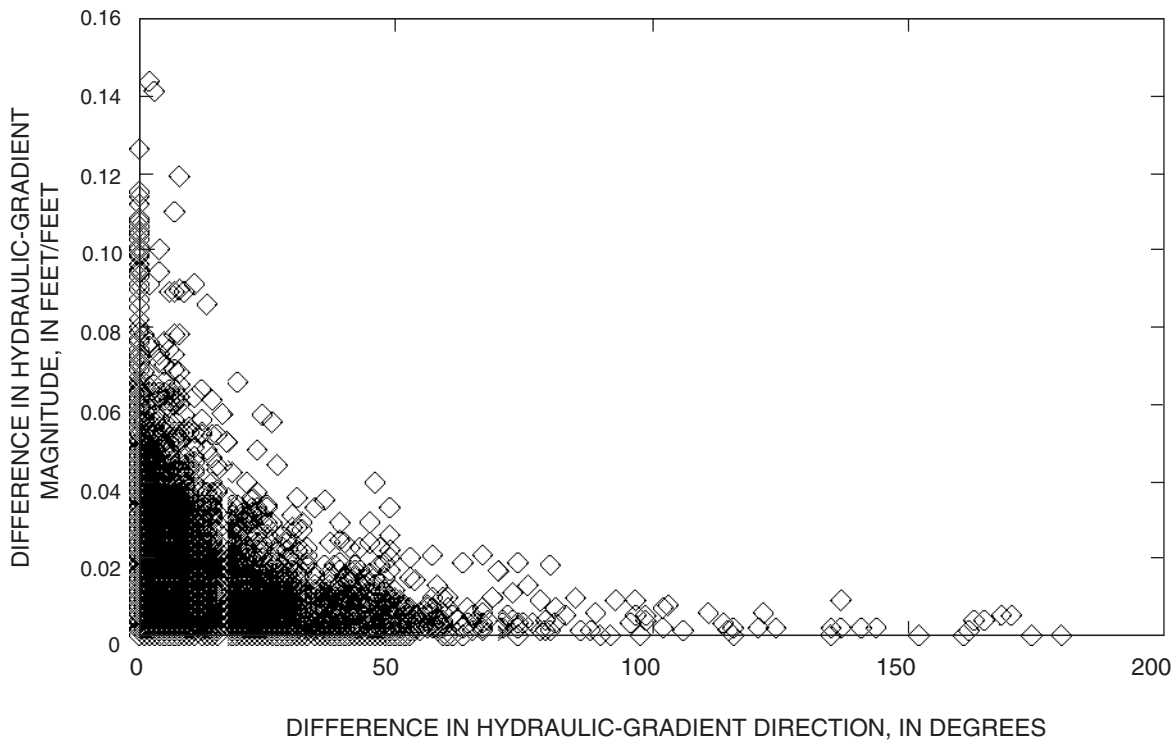
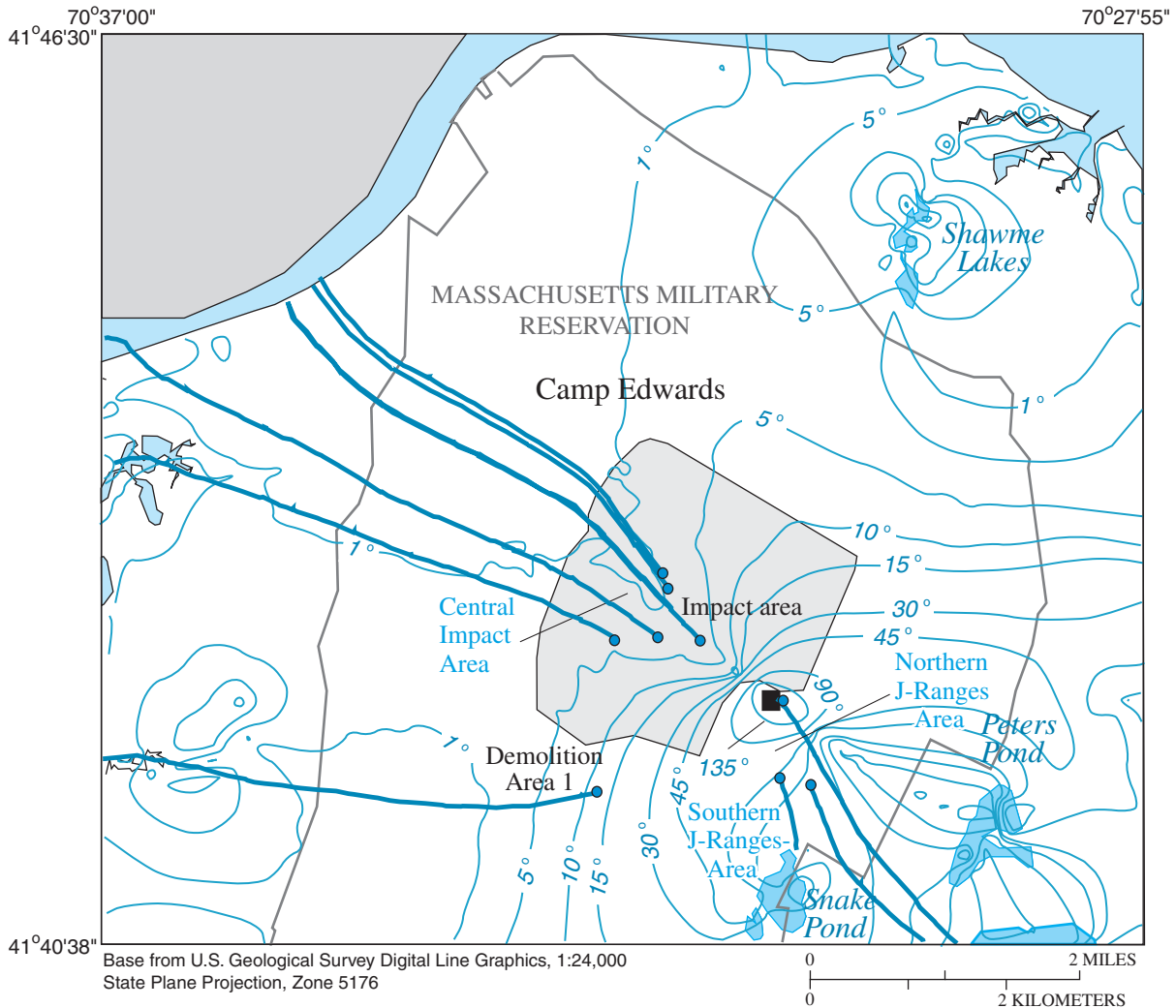


Figure 24. Relation between simulated differences in hydraulic-gradient directions and magnitudes for all active model cells for high-recharge (1955) and low-recharge (1965) conditions on western Cape Cod, Massachusetts.



EXPLANATION

- 15°— LINE OF EQUAL GRADIENT-DIRECTION CHANGE, IN DEGREES—Contour interval is variable
- MODEL-DERIVED ADVECTIVE FLOW PATHS CALCULATED BY STEADY-STATE REGIONAL MODEL WITH POINT OF ORIGIN
- TOP OF STEADY-STATE WATER-TABLE MOUND

Figure 25. Changes in gradient direction between high-recharge (1955) and low-recharge (1965) conditions for the northern part of the western Cape Cod, Massachusetts, flow cell and steady-state advective flow paths from selected locations.

Effects of Long-Term Transient Recharge on Advective Transport

The transient regional models can be used to evaluate how changing stresses affect predicted advective flow paths in the aquifer. Seasonal changes in recharge stresses likely would not change predicted

advective transport paths. This assumption is based on the observation that although head elevations in the aquifer change, the position of the top of the water-table mound and general hydraulic gradients in the aquifer do not change seasonally. Seasonal stress changes likely would have no effect on advective transport because the time scale of the seasonal stress

changes, which is on the order of months, is small compared to the time scale of advective transport, which is on the order of decades.

The precipitation record from western Cape Cod yielded large, long-term variability in estimated recharge rates in the area (fig. 10). Long-term changes in recharge stresses likely would affect advective transport paths in some parts of the aquifer by changing hydraulic-gradient directions. The effect of long-term changes in recharge on advective flow paths likely is a function of proximity to hydrologic boundaries and to the top of the water-table mound. The long-term transient model estimates the degree to which changes in recharge affect advective flow paths in the aquifer and how predicted flow paths compare to those predicted by the steady-state model. Particles were started at the water table beneath the center of Demolition Area 1, three representative sites in the Impact Area, and three sites within the J-Ranges Area at four different times: 1955, 1965, 1975, and 1985. These times represent a general distribution of hydraulic conditions and span a period in which much of the observed ground-water contaminants were released into the environment at Camp Edwards. Particles also were tracked from the same locations under steady-state conditions. These particles were tracked forward through the modeled flow field until 1996.

Demolition Area 1 and Impact Area

The predicted advective transport paths of contaminants starting from the water table in the Impact Area and Demolition Area 1 1955, 1965, 1975, and 1985 and stopping in 1996 are shown in figures 26 and 27, respectively. The transport distances to current (1996) locations of particles vary with recharge locations within the Impact Area. As of 1996, maximum horizontal transport distances for particles started in 1955, 1965, 1975, and 1985 were 7,300, 6,400, 4,700, and 3,900 ft, respectively. As of 1996, particles started in 1955, 1965, 1975, and 1985 at the water table beneath Demolition Area 1 had traveled 7,800, 6,000, 3,300, and 2,700 ft downgradient of the source area, respectively.

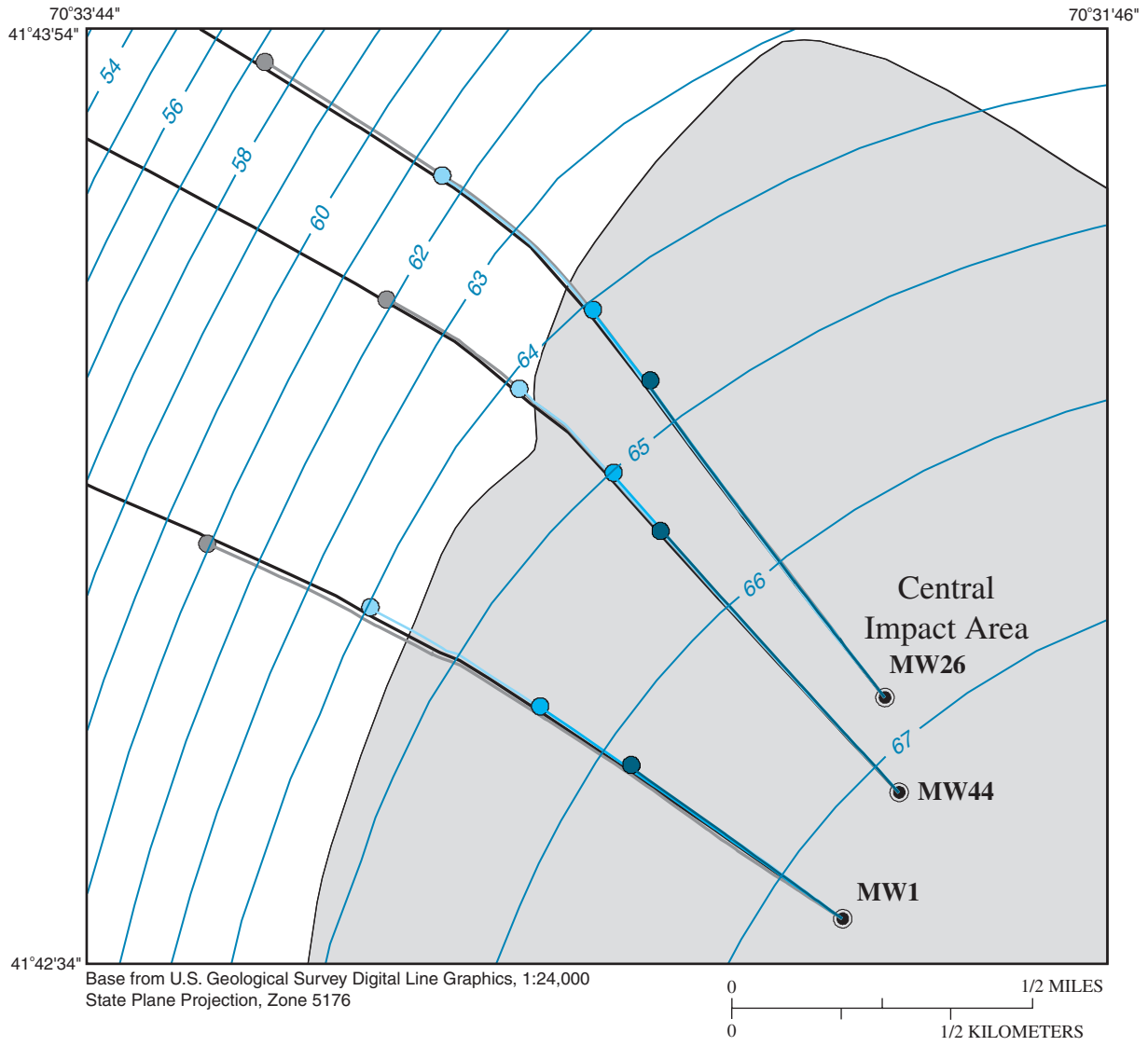
Particles started in 1955, 1965, 1975, and 1985 followed similar transport paths in the aquifer from the Impact Area and Demolition Area 1 (figs. 26 and 27). Over a transport distance of 2,000 ft, particle tracks started in 1955, 1965, 1975, and 1985 are separated by a total of about 180 ft in the Demolition Area 1 and by

about 50 ft in the Impact Area. This is consistent with model results showing that, although simulated head values (fig. 23A) and hydraulic-gradient magnitudes (fig. 23B) in these areas change, hydraulic-gradient directions in the Impact Area and Demolition Area 1 do not change substantially (fig. 23C) with changing recharge stresses. Between 1955 and 1965, simulated hydraulic-gradient directions changed by about 13 degrees and less than 5 degrees in Demolition Area 1 and the Impact Area, respectively (fig. 25). Demolition Area 1 and the Impact Area are located about 7,700 and 5,700 ft, respectively, from the steady-state position of the top of the water table mound and about 17,300 and 20,500 ft, respectively, from the coastal boundary.

J-Ranges Area

The predicted advective transport paths of contaminants from the J-Ranges Area for 1955, 1965, 1975, and 1985 are shown in figure 28. As of 1996, particles started in 1955, 1965, 1975, and 1985 from WT13 in the southern J-Ranges Area that had not discharged to Snake Pond had traveled 7,000, 3,000, 2,400, and 1,800 ft downgradient of the source area, respectively. These transient particle tracks generally follow similar paths for all four starting years. Over a transport distance of about 2,000 ft, particle tracks from WT13 are separated by a distance of about 190 ft.

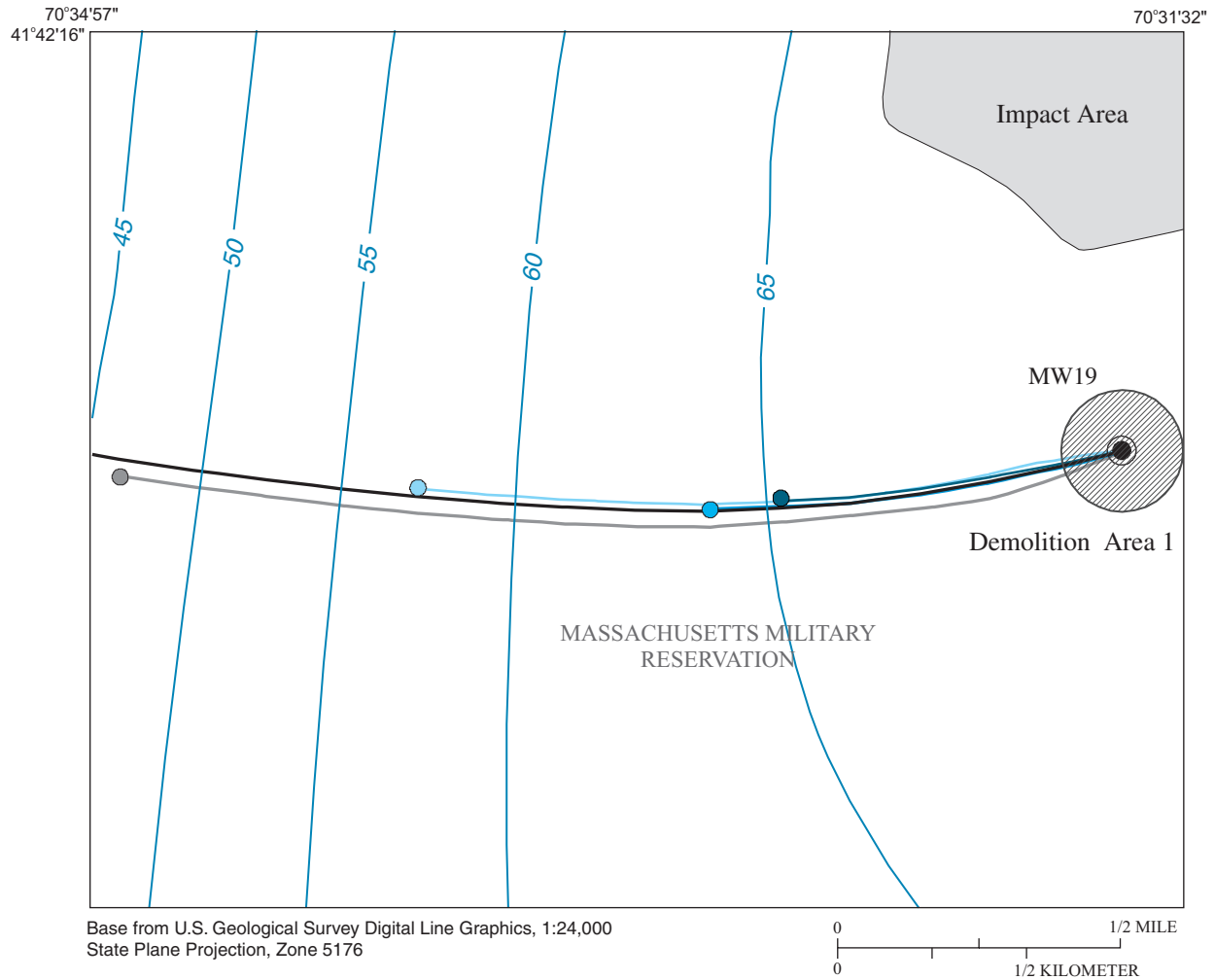
Particles started in 1955, 1965, 1975, and 1985 in the northern J-Ranges Area, which is located at or near the top of the water-table mound, had traveled only about 960, 190, 150, and 70 feet downgradient, respectively, as of 1996 (fig. 28). In this analysis, particles were started at the water table at a location coincident with the model-calculated top of the water-table mound under steady-state conditions. The simulated transport patterns are consistent with model results indicating a strong component of vertical flow and small horizontal gradients near the top of the water-table mound (figs. 12 and 13). The difference in predicted transport particle paths for the different starting dates is much greater in the northern J-Ranges Area. The predicted advective transport path is a function of the time when the particles were started at the water table; particles started at different times do not follow the same path in the aquifer. A parcel of water entering the aquifer in 1955 is transported to the southeast whereas a particle started in 1965 initially tracks to the northwest and then reverses direction and tracks to the southeast (fig. 28).



EXPLANATION

- | | |
|--|--|
| <p>MODEL-DERIVED ADVECTIVE FLOW PATHS</p> <ul style="list-style-type: none"> — Particles started in 1985 — Particles started in 1975 — Particles started in 1965 — Particles started in 1955 — Steady-state <p>— 65 — MODEL-DERIVED WATER-TABLE
CONTOUR—Altitude in feet. Vertical
datum is NGVD29</p> | <p>CURRENT (1996) LOCATIONS OF PARTICLES</p> <ul style="list-style-type: none"> ● Particles started in 1985 ● Particles started in 1975 ● Particles started in 1965 ● Particles started in 1955 <p>MW26 ● WELL WITH ROYAL DUTCH EXPLOSIVE
DETECTION AND IDENTIFIER</p> |
|--|--|

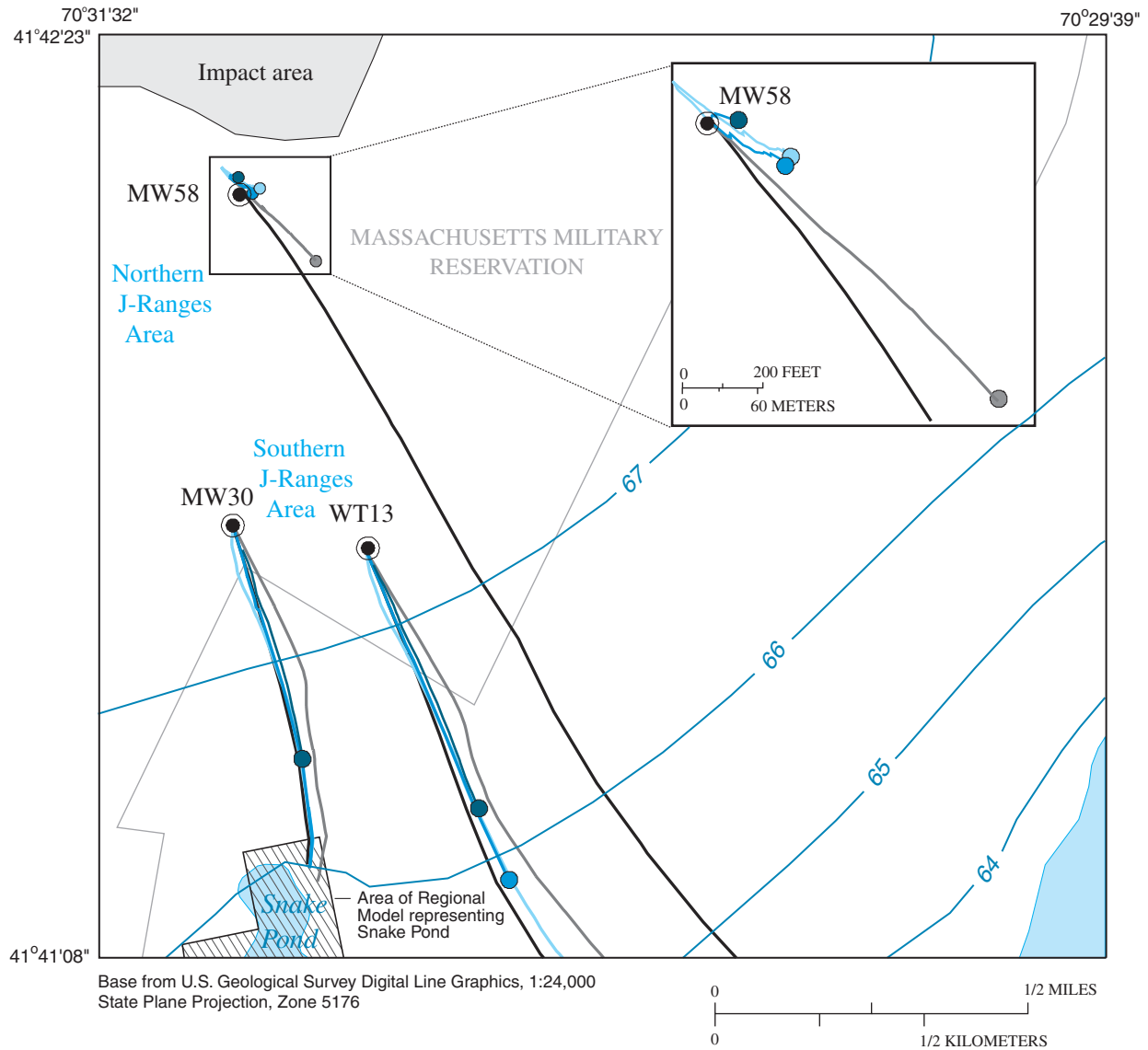
Figure 26. Steady-state and transient advective flow paths of particles started in 1955, 1965, 1975, and 1985 from three locations in the Central Impact Area, western Cape Cod, Massachusetts. Paths are projected to map view. Transient flow paths end at predicted 1996 locations.



EXPLANATION

- | | | | |
|---|--|--|--|
| MODEL-DERIVED ADVECTIVE FLOW PATHS | | CURRENT (1996) LOCATIONS OF PARTICLES | |
| — | Particles started in 1985 | ● | Particles started in 1985 |
| — | Particles started in 1975 | ● | Particles started in 1975 |
| — | Particles started in 1965 | ● | Particles started in 1965 |
| — | Particles started in 1955 | ● | Particles started in 1955 |
| — | Steady-state | | |
| —65— | MODEL-DERIVED WATER-TABLE CONTOUR—Altitude in feet. Vertical datum is NGVD29 | ● | WELL WITH ROYAL DUTCH EXPLOSIVE DETECTION AND IDENTIFIER |

Figure 27. Steady-state and transient advective flow paths of particles started in 1955, 1965, 1975, and 1985 from Demolition Area 1, western Cape Cod, Massachusetts. Paths are projected to map view. Transient flow paths end at predicted 1996 locations.



EXPLANATION

- | | | | |
|------------------------------------|--|---------------------------------------|--|
| MODEL-DERIVED ADVECTIVE FLOW PATHS | | CURRENT (1996) LOCATIONS OF PARTICLES | |
| | Particles started in 1985 | | Particles started in 1985 |
| | Particles started in 1975 | | Particles started in 1975 |
| | Particles started in 1965 | | Particles started in 1965 |
| | Particles started in 1955 | | Particles started in 1955 |
| | Steady-state | | |
| | MODEL-DERIVED WATER-TABLE CONTOUR—Altitude in feet. Vertical datum is NGVD29 | | WELL WITH ROYAL DUTCH EXPLOSIVE DETECTION AND IDENTIFIER |

Figure 28. Steady-state and transient advective flow paths of particles started in 1955, 1965, 1975, and 1985 from three locations in the J-Ranges Area, western Cape Cod, Massachusetts. Paths are projected to map view. Transient flow paths end at predicted 1996 locations.

These tracks are consistent with model results showing that the position of the top of the water-table mound and hydraulic-gradient directions in the northern J-Ranges Area change substantially in response to long-term changes in recharge rates (figs. 22 and 25). The temporal variability seen in particle tracks in the northern J-Ranges Area is a result of changes in hydraulic gradients near the top of the water-table mound. For example, the top of the water-table mound shifted from a position northwest to a position southeast of the northern J-Ranges Area in response to a period of low recharge in the mid-1960s; gradients and flow directions in the area were to the northwest during this time. After recharge rates increased, the top of the water-table mound shifted back to the northwest and flow directions were to the southeast, which is the general flow direction under average hydraulic conditions. As a result, the particle track which was started at the water table in 1965 reversed direction. The southern J-Ranges Area is farther from the top of the water-table mound and closer to the hydrologic boundary at Snake Pond; hydraulic gradients in that area are less variable with time than in the northern J-Ranges Area. Between 1955 and 1965, simulated changes in hydraulic-gradient directions ranged from about 30 to 45 degrees in the southern J-Ranges area and exceeded 135 degrees in the northern J-Ranges Area (fig. 25).

Implications for the Use of Transient and Steady-State Models

Transient particle tracks from the Impact Area and Demolition Area 1 are in close agreement with steady-state particle tracks from the same locations (figs. 26 and 27). The assumption of a steady-state recharge stress for the aquifer is valid for particle tracking in these areas, and the steady-state regional model can be used to simulate advective transport. Likewise, transient particle tracks in the southern J-Ranges area are in general agreement with steady-state particle tracks (fig. 28); this agreement

indicates that a steady-state regional model can predict general ground-water-flow directions in the aquifer with some degree of uncertainty arising from the assumption of steady-state conditions. Snake Pond locally affects ground-water-flow patterns in that area, and a coarsely discretized regional model may not be appropriate for predicting advective transport whether steady or transient conditions are assumed. This is consistent with model results showing that hydraulic-gradient directions in the southern J-Ranges Area do not change substantially with changing recharge stresses. Demolition Area 1, the Impact Area, and the southern J-Ranges area are located about 7,700, 5,700, and 3,100 ft, respectively, from the steady-state position of the top of the water-table mound. Although simulated head values and hydraulic-gradient magnitudes in these areas change, the general hydraulic-gradient directions do not change substantially in response to long-term changes in recharge.

Transient particle tracks started at different times in the northern J-Ranges Area differ substantially from the steady-state particle track from the same location (fig. 28); this difference indicates that the assumption of a steady-state recharge condition is not valid for particle tracking in that area and that the use of a the steady-state regional model could yield inaccurate results. Also, the lack of agreement between particle tracks started at different times indicates that the use of a transient model to predict advective transport accurately would need an accurate estimate of recharge rates over time. This conclusion is consistent with model results indicating that hydraulic-gradient directions near the top of the water-table mound change in response to temporal changes in recharge rates. As a result, the use of a transient model likely would have uncertainties associated with simulated stresses.

The reason that the steady-state particle track started in the northern J-Range is not bracketed by transient particle tracks started at the same location is not known. One factor may be the large sensitivity of the direction of the steady-state particle to the starting

location. The particle was started in the center of the model cell representing the top of the water-table mound, which is the center of the radial flow system, and very small shifts in the starting location would cause the particle to move in very different directions. This could make steady-state particle tracks from this location suspect. Another possible factor could be that particle tracks started in the transient flow field are ultimately controlled by movement in the earliest years of simulated transport and that the years chosen for the start of the transient particle-tracking analysis were years characterized by extreme hydrologic conditions.

Particles started in the northern J-Ranges Area and at Demolition Area 1 and transported through the aquifer for 41 years travelled 960 and 7,800 ft away from their starting positions, respectively. The differences in transport distances arise from the locations of these two areas within the hydrologic system. The northern J-Ranges Area is located near the top of the water-table mound where there is a strong component of vertical flow and horizontal gradients are small. Contaminants released in this area at a specific time will not migrate as far horizontally downgradient as contaminants released at the same time in the Demolition Area 1 and the Impact Area, which are located farther downgradient in areas where the component of horizontal flow is greater.

SUMMARY AND CONCLUSIONS

Contaminated ground water emanates from a number of sources on Camp Edwards on western Cape Cod, and there is concern that contaminants could adversely affect regional water supply. The Army National Guard (ARNG) has been investigating possible ground-water contamination at the site since 1997. Three primary areas of ground-water contamination have been identified: downgradient of Demolition Area 1, in the Central Impact Area, and in the J-Ranges Area. The U.S. Geological Survey (USGS) has assisted in the investigation by developing

models to simulate ground-water flow in the aquifer. As part of this effort, USGS developed regional and subregional steady-state models and transient regional models that incorporate seasonal and long-term changes in recharge. The USGS used these models to characterize the hydrologic system, simulate advective transport at specific areas of interest, delineate the recharge areas to water-supply wells, and evaluate the effects of model discretization and the assumption of steady-state hydraulic conditions on model results.

Ground-water flow in the aquifer is radially outward from a water-table mound located to the south of the Impact Area near the northern section of the J-Ranges. Vertical flow is large and horizontal hydraulic gradients are small in areas near the top of the water-table mound. Contaminants in downgradient areas, where the ratio of vertical to horizontal gradients is small and horizontal flow predominates, migrate farther in a specified period of time than contaminants in areas closer to the top of the water-table mound. Forward particle tracking was particularly useful in determining the advective transport paths of contaminants in the direction of ground-water flow in areas with well-defined source areas and histories, such as Demolition Area 1. In areas where source areas are poorly defined, such as the Central Impact Area, reverse particle tracking was used to determine potential source areas of contaminants detected in the subsurface. Particle tracking also was used to determine spatial relationships between sporadic subsurface detections and to interpret water-quality results in a hydrologic context.

The regional model also was used to delineate recharge areas to existing and proposed municipal wells. This activity was done as part of a parallel USGS investigation into the source of water to wells and natural receptors on western Cape Cod. A subregional model was needed to delineate recharge areas to some municipal wells that are either weak sinks in the regional model or located in close proximity to other pumping wells.

A subregional model was used to simulate advective transport in the southern J-Ranges Area. Snake Pond and extraction and injection wells that are part of a remediation system control the local ground-water-flow paths in the area, and simulation results indicate that the regional model is too coarsely discretized to represent the pond and wells adequately and to simulate ground-water flow accurately.

A transient version of the regional model that incorporates seasonal changes in recharge and pumping showed that simulated heads in the aquifer change seasonally, but that the location of the top of the water-table mound and hydraulic-gradient directions in the aquifer do not change seasonally. Seasonal changes in recharge stresses do not change hydraulic gradient directions and likely do not affect advective transport paths because the time scale of the changes (months) is much smaller than the time scale of advective transport (decades).

A version of the regional model that incorporates long-term changes in recharge, as estimated from a 60-year precipitation record from western Cape Cod, showed that long-term changes in recharge cause heads in the aquifer to fluctuate and hydraulic gradients to change. Heads fluctuated by up to 12 ft and the top of the water-table mound migrated nearly 1,500 ft between periods representing high-recharge (1955) and low-recharge (1965) conditions.

Downgradient of the Impact Area, Demolition Area 1, and the southern J-Ranges Area, simulated paths of advective transport do not change in response to temporal changes in recharge rates. Predicted advective transport paths from the northern J-Ranges Area do depend on when particles are started in the long-term transient model. The northern J-Ranges Area is located near the top of the water-table mound where hydraulic-gradient directions change in response to changes in the position of the top of the water table. The Impact Area and Demolition Area 1 are located in downgradient areas where hydraulic-gradient

directions do not change substantially with time. In these downgradient areas, transient particle tracks agree with the corresponding steady-state particle track, whereas transient particle tracks started near the top of the water-table mound are not always consistent with the steady-state particle track. The assumption of steady-state conditions appears valid within and downgradient of the Impact Area and Demolition Area 1; however, the assumption is not valid and steady-state models cannot be used to simulate advective transport in areas near the top of the water-table mound.

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