PROBABLE HIGH GROUND-WATER LEVELS IN MASSACHUSETTS

By Michael H. Frimpter

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JAMES G. WATT, Secretary

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Doyle G. Frederick, Acting Director

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For additional information, write to:

U.S. Geological Survey
150 Causeway Street, Suite 1001
Boston, MA 02114

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ABSTRACT

Water-level records from an observation well network are analyzed for utility in estimating probable high ground-water levels in three different geohydrologic environments in Massachusetts. Analyses were made of 83 observation wells with between 8 and 37 years of record. Maximum annual water levels occur most frequently in March and April. The maximum range of water levels equaled or exceeded at 10 percent of randomly selected sites is estimated to be 16 feet in till, 9.2 feet in sand and gravel on terraces, and 4.0 feet in sand and gravel in valleys.

An approach to estimating probable high ground-water levels at construction sites is suggested. An estimate of the high water level at a site may be derived by solving the proportion in which the ratio of the potential water-level rise at a test site to the potential water-level rise at an observation well is equal to the ratio of the water-level range at the site to the historic water-level range at an observation well in a similar geohydrologic environment.

Precise description of the probabilities of exceedence of estimates made by this approach with the data available has not been made. Assuming that the data are representative of the future, estimates would not be expected to be exceeded at more than 1 in 10 sites over a period of 10 years or longer.

INTRODUCTION

Estimates of probable high ground-water levels are needed by the Massachusetts Department of Environmental Quality Engineering for regulating the construction of septic systems. Regulations contained in "Commonwealth of Massachusetts, Department of Environmental Quality Engineering, the State Environmental Code, Minimum Requirements for the Subsurface Disposal of Sanitary Sewage, 1977, Title 5" require that "Leaching fields shall not be constructed in areas where the maximum ground-water elevation is less than 4 feet below the bottom of the field." Environmental Code, Title 5, defines the maximum ground-water elevation as the "...height of the ground-water table when it is at its maximum level...". In this report, "maximum ground-water level" is taken to be the minimum depth below land surface to the water table.

Ground-water levels in Massachusetts fluctuate several feet through a seasonal cycle each year, and over the long term highest and lowest water levels at any site vary several feet from year to year; therefore, a single random measurement of water level at a site is unlikely to represent the maximum level that would occur at that site. The State Code suggests that allowances should be made for measurements made when the water level is not at its highest level, but no guidelines for such allowances have been provided.

The annual cyclic rise and fall of the water table under natural conditions in Massachusetts is due to seasonal differences in the rate of ground-water recharge and relatively constant discharge. Precipitation is fairly evenly distributed from month to month throughout each year, but there is little or no ground-water recharge from precipitation during the late spring to early fall growing season when evapotranspiration rates are high. Therefore, the water table generally declines steadily during the growing season except during periods of heavy precipitation such as during hurricanes. Most ground-water recharge occurs during late winter or early spring both from precipitation and melting of snow and ice, and annual ground-water levels (figs. 1 and 2) generally reach their maximum altitude during this period.

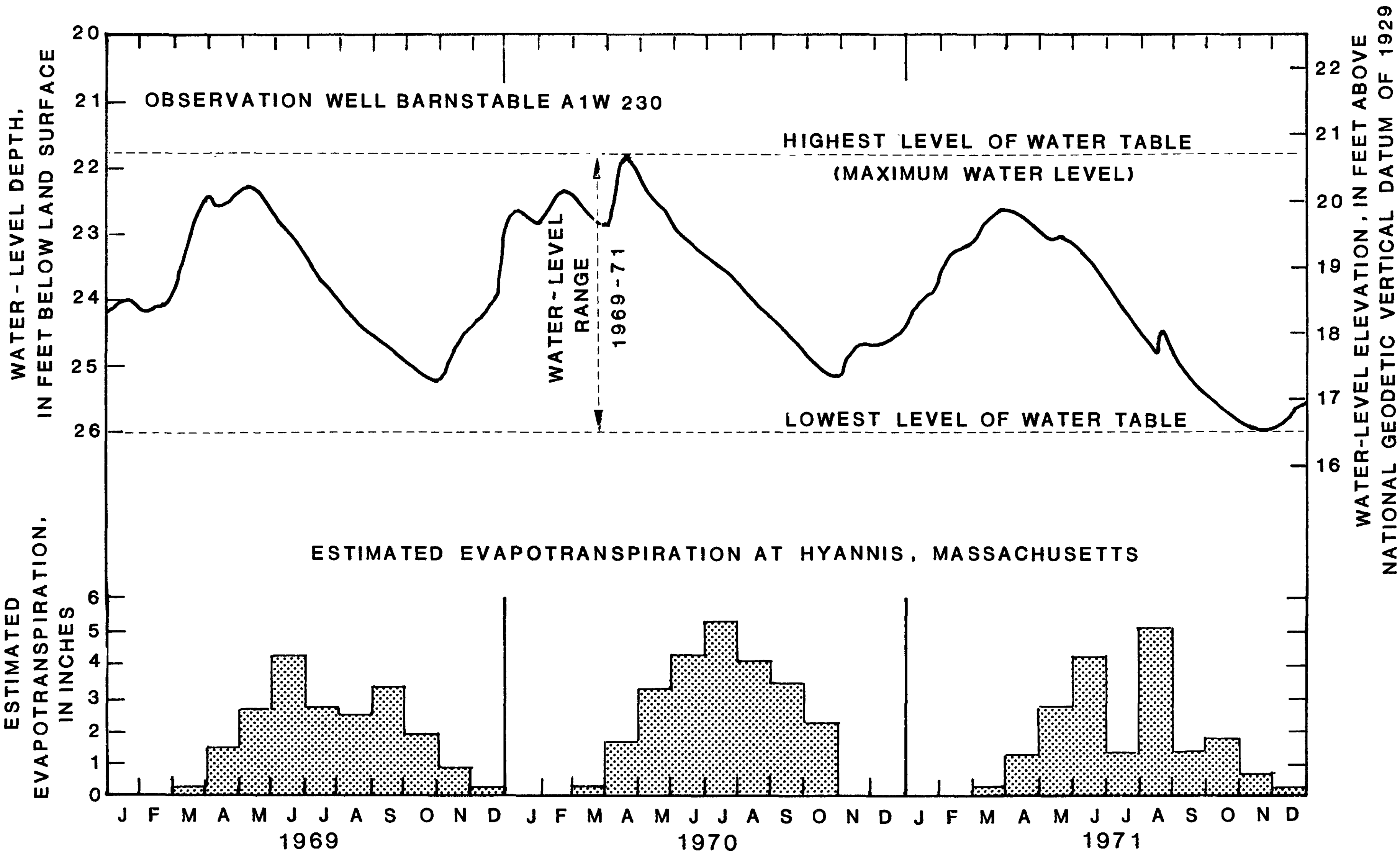

Figure 1.--Seasonal water-level fluctuations

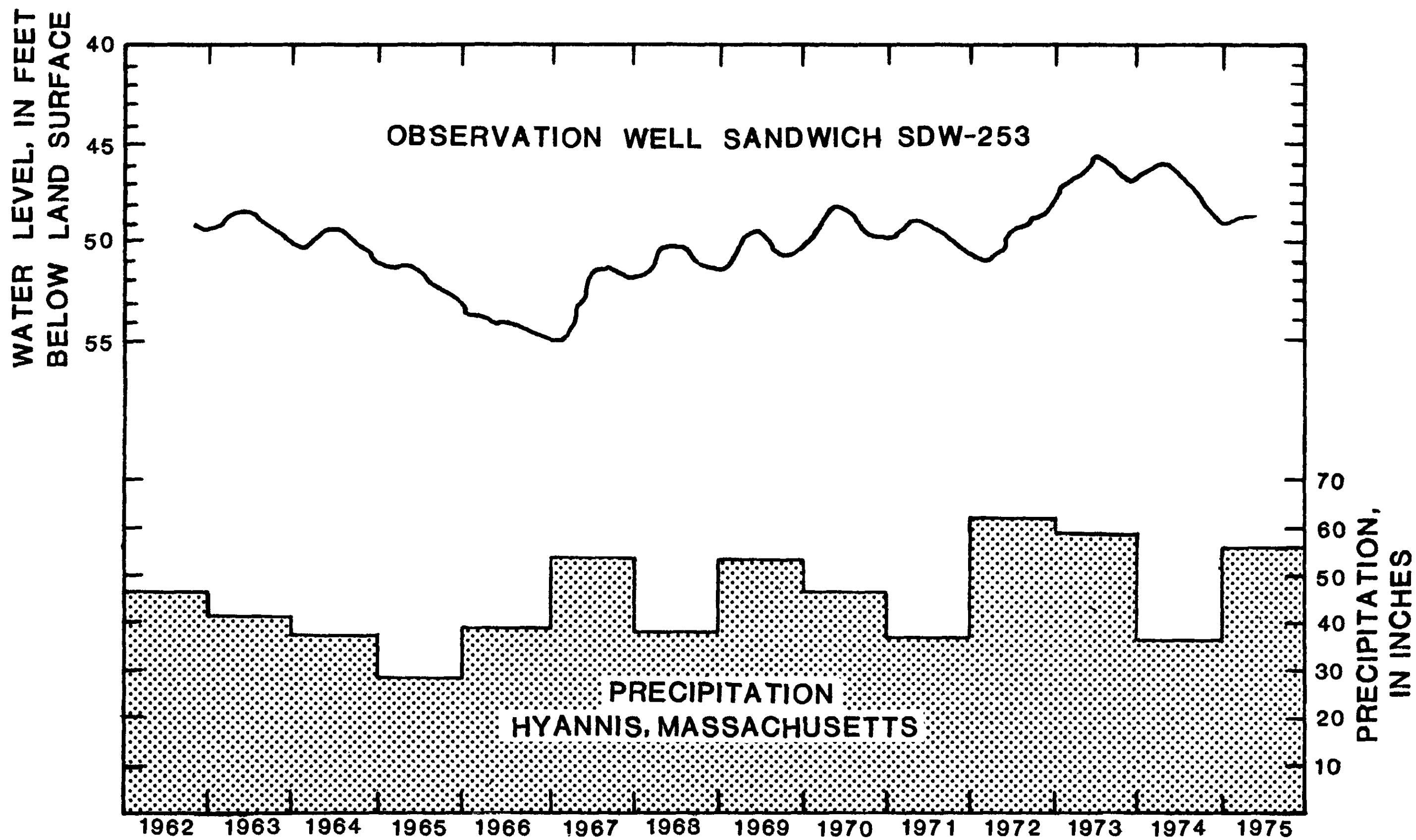

Figure 2.--Long-term water-level fluctuations

Differences in maximum and minimum ground-water levels from year to year are largely due to the amount and distribution of annual precipitation (fig. 2). Four successive years (1963-66) of below-average precipitation, commonly known as the midsixties drought, resulted in record low ground-water levels as shown by well SDW-253 in figure 2. This report, prepared by the U.S. Geological Survey in cooperation with the Massachusetts Department of Environmental Quality Engineering, reviews the records of ground-water levels from an observation well network in Massachusetts and suggests an approach to estimating the maximum ground-water level at any site from a random water-level measurement at any time at that site. Graphs for use in making estimates of maximum ground-water level are given for sites in three hydrogeologic situations: Sand and gravel on terraces, sand and gravel in valleys, and in till.

Maps, tables, and a step-by-step process for estimating probable high ground-water levels on Cape Cod were prepared from analysis of water-level records and the hydrologic description of Cape Cod and described in "Probable High Ground-Water Levels on Cape Cod, Massachusetts" (Frimpter, 1980).

Data Available from the Observation-Well Network

A network of observation wells in Massachusetts is maintained by the U.S. Geological Survey, in cooperation with the Massachusetts Department of Public Works. The network consists of 87 observation wells located within the 8,266 mi^2 (21,400 km^2) area of the State.

Water-level measurements are made at the end of each month in 79 wells and continuously in eight wells equipped with recording gages. For these eight wells, water levels are reported every fifth day and the end of each month.

Water-level measurements are given in feet, with reference to lsd (land-surface datum); land-surface datum is a datum plane that is approximately at land surface at each well.

The purposes of the ground-water-level-monitoring network are to provide the ground-water data needed for the planning, operation, management, administration, and research aspects of water resources and to provide the data for explanation and solution of water problems. The ground-water-monitoring program in Massachusetts has the following objectives relating to local, regional, and state, as well as national hydrologic-data needs.

1. Monitor ground-water levels in different physiographic regions, drainage basins, and geohydrologic environments in the State to provide a record of seasonal and long-term responses to variations in climate as indices of long term trends and assess, separate, and estimate water-level changes caused by water management, construction, land use, and natural conditions.

2. Monitor ground-water levels to provide long-term records for basin or watershed studies and hydrologic models and to provide pilot long-term records by means of which records from short-term investigations can be correlated, extended, and evaluated.

3. Monitor ground-water levels in major aquifers to describe status of ground-water storage and to provide a measure of depletion rates and stresses on recharge rates essential for water-supply planning and management. This information has a value analogous to stage measurements of water-supply reservoirs.

4. Monitor ground-water levels and salinity near shore in major coastal aquifers threatened by seawater intrusion to provide an early warning system and to determine freshwater storage for resources management and conservation in the coastal zone. The water-level gradient toward the shore is an index of fresh ground-water flow and, therefore, a variable index of hydrodynamic conditions controlling the position of the saltwater/freshwater interface.

5. Monitor ground-water levels to determine gradients for the purpose of detecting changes of ground-water-flow patterns in water-quality-sensitive areas in the vicinity of pollutant sources such as infiltration lagoons or disposal wells for sewage or industrial wastes.

6. Monitoring of water levels for specific research and resource appraisal projects of a short duration can have highly varied and multiple objectives tailored to study needs.

The goal of estimating high ground-water levels for septic-system regulation is consistent with the broad goals of ground-water-level monitoring to provide historical records of water levels that can be used to estimate water levels with respect to time and place. It is also consistent with the goals of the Massachusetts network to monitor water levels in different physiographic regions, drainage basins, and geohydrologic environments to provide a record of seasonal and long-term trends for designing construction and for evaluating the impacts of construction on water levels and water supply. However, the goal of estimating high ground-water level at any site at any time through analysis of long-term records was not specifically anticipated in the design of the observation-well network in 1963, and the network was, therefore, not tailored to meet that goal.

Because the approach to estimating is dependent on current water-level data from the observation-well network, collection of water-level data from the network must be maintained if the approach is to be used. Owing to changing uses and ownership of land, observation wells occasionally become unavailable and must be replaced. A network of observation wells on Cape Cod, maintained by Barnstable County and the National Park Service in cooperation with the Geological Survey, has only a few years of record, but is a source of replacement wells for the Massachusetts network. Several towns in the State have observation wells for various purposes, and integration of some of these with a network designed for estimating high water levels may be possible. Maintenance of an observation-well network includes acquisition of landowners' permission, construction of wells, description of wells and well sites, short- and long-term monitoring, periodic testing, and rehabilitation or replacement, if necessary.

Study Approach

The study consisted of an analysis of records of monthly water levels collected from the network of observation wells. The data were retrieved from a computer file of ground-water levels maintained by the Survey in Boston and analyzed by summarizing the data and use of statistical computer programs.

Data were analyzed for 15 wells in till (fig. 3), 13 wells on Cape Cod, 26 wells in sand and gravel on terraces, 17 wells in sand and gravel in valleys, 6 wells in sand and gravel on hillsides or hilltops (fig. 4), 4 wells in bedrock, and 2 wells in sand and gravel in undulating or poorly defined topographic situations.

Summaries of end-of-month water-level data for the periods of record ending April 1977 were used to determine the month in which maximum annual ground-water level occurred most frequently for different geohydrologic situations listed in the well descriptions. Most of this information is published in a report by Maevsky (1976). Monthly water-level measurements for pairs of wells were correlated by linear regression to illustrate the reliability of predictions of water level in one well made from measurements of water level in another well.

The maximum range of water levels for wells in similar geographic or geohydrologic situations were arranged in ascending order of magnitude and plotted against their percentage of the total number of wells in that situation. This approach is useful because it provides the opportunity to determine the probability of not exceeding a certain magnitude of water-level range. Because the values so arranged and plotted on graphs form a straight line when they represent a normal distribution, the approach is useful in differentiating groups of water-level data and evaluating the representativeness of the groups.

GROUND-WATER LEVELS IN TILL

The periods of water-level records for 15 observation wells in till range from 13 to 37 years and total over 4,200 monthly measurements. Sixty-one percent of the annual maximum water levels occurred in March and April; and 32 percent occurred in December, January, February, and May (fig. 5). The maximum annual water level occurred most frequently in March in 12 wells and in April in 3 wells.

All but one of the 15 sites in till have historical ground-water levels of less than 6 feet below land surface; even though four sites are on hilltops, three are on hillsides, and four are on terraces. The mean of maximum water-level range for the 15 wells is 11.95 feet, and the maximum range for any one site is 16.81 feet for 362 cumulative years of monthly water-level record.

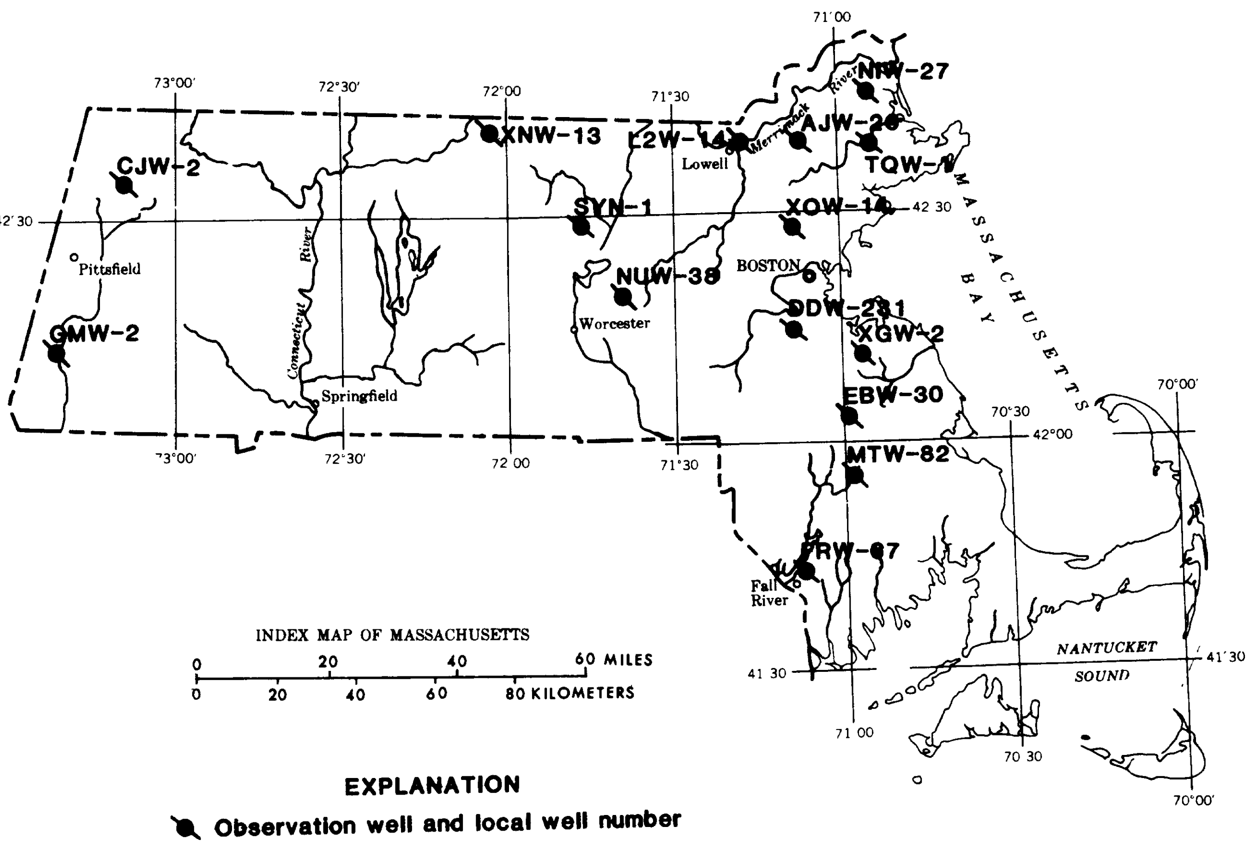

Figure 3.--Observation wells in till

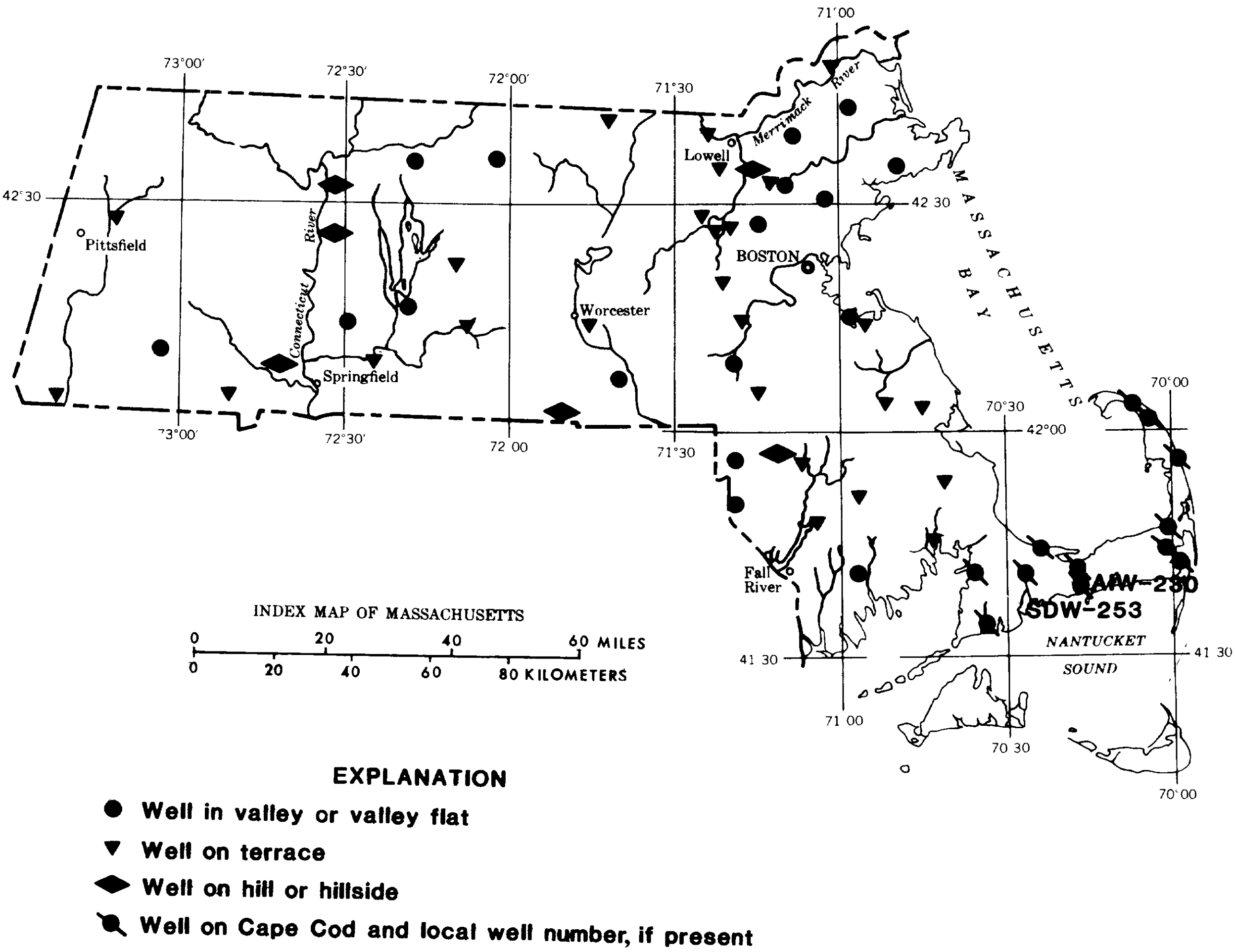

Figure 4.--Observation wells in sand and gravel

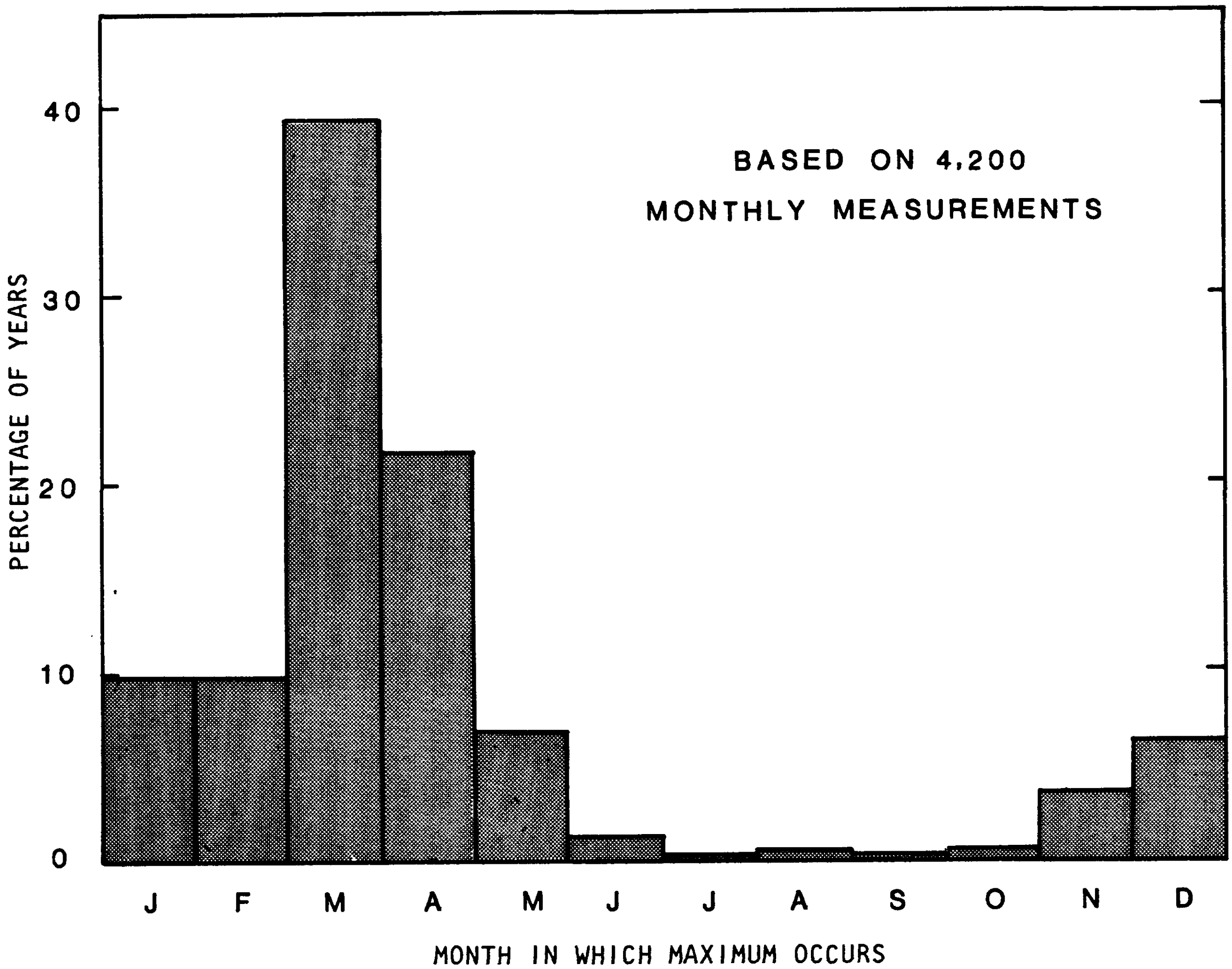

Figure 5.--Frequency of maximum annual ground-water levels in till

Water levels for all 15 wells were correlated by linear regression. The degree of correlation was fairly high, except for four wells: Cheshire CJW-2, Great Barrington GMW-2, Fall River FRW-67, and Lowell L2W-14, (table 1 and fig. 6). East Bridgewater EBW-30 (19 years of record) had correlation coefficients of greater than 0.8 and standard errors of estimate of 0.55 to 2.05 feet with all wells in till except Cheshire CJW-2 and Great Barrington GMW-2 (table 1). East Bridgewater EBW-30 might, therefore, be used as a key index well for water levels in till east of the Connecticut River valley. The observation-well network does not include any wells in till in the Connecticut River Valley. Cheshire CJW-2 and Great Barrington GMW-2 are located in the Berkshire section of western Massachusetts, geographically, physiographically, and climatologically different than the rest of the State.

Table 1.—Correlation of East Bridgewater EBW-30 with other wells in till

Location	Well number	Correlation coefficient (R)	Standard error of estimate* (SE) (feet)	Remarks
Andover	AJW-26	0.873	1.01	
Dedham	DDW-231	.875	1.30	
Fall River	FRW-67	.847	.55	City
Lowell	L2W-14	.805	1.53	City
Middleborough	MTW-82	.943	1.48	
Newbury	NIW-27	.909	1.00	
Northborough	NUW-38	.880	1.27	
Sterling	SYW-1	.802	2.05	Central Massachusetts
Topsfield	TQW-1	.890	1.23	
Weymouth	XGW-2	.968	1.08	
Winchendon	XNW-13	.816	1.58	Central Massachusetts
Winchester	XOW-14	.817	1.41	
Cheshire	CJW-2	.574	2.29	Berkshires
Great Barrington	GMW-2	.686	1.85	Berkshires

*Of all estimates, 68 percent would be in error by less than the value shown.

Although the water levels for the two observation wells in the Berkshire section seem reasonably well correlated with each other, they are poorly correlated with water levels for observation wells in eastern Massachusetts. This poor correlation coefficient of 0.574 is illustrated (fig. 7) by a plot of water levels for Cheshire CJW-2 versus water levels for East Bridgewater EBW-30, which is typical of eastern Massachusetts. This difference is interpreted as resulting from regional climatic variations rather than differences of ground-water hydrology.

Fall River FRW-67 and Lowell L2W-14 are located in urban environments and may be influenced by sewering, drains, pipelines, roofing, paving, and many other kinds of drainage rearrangement.

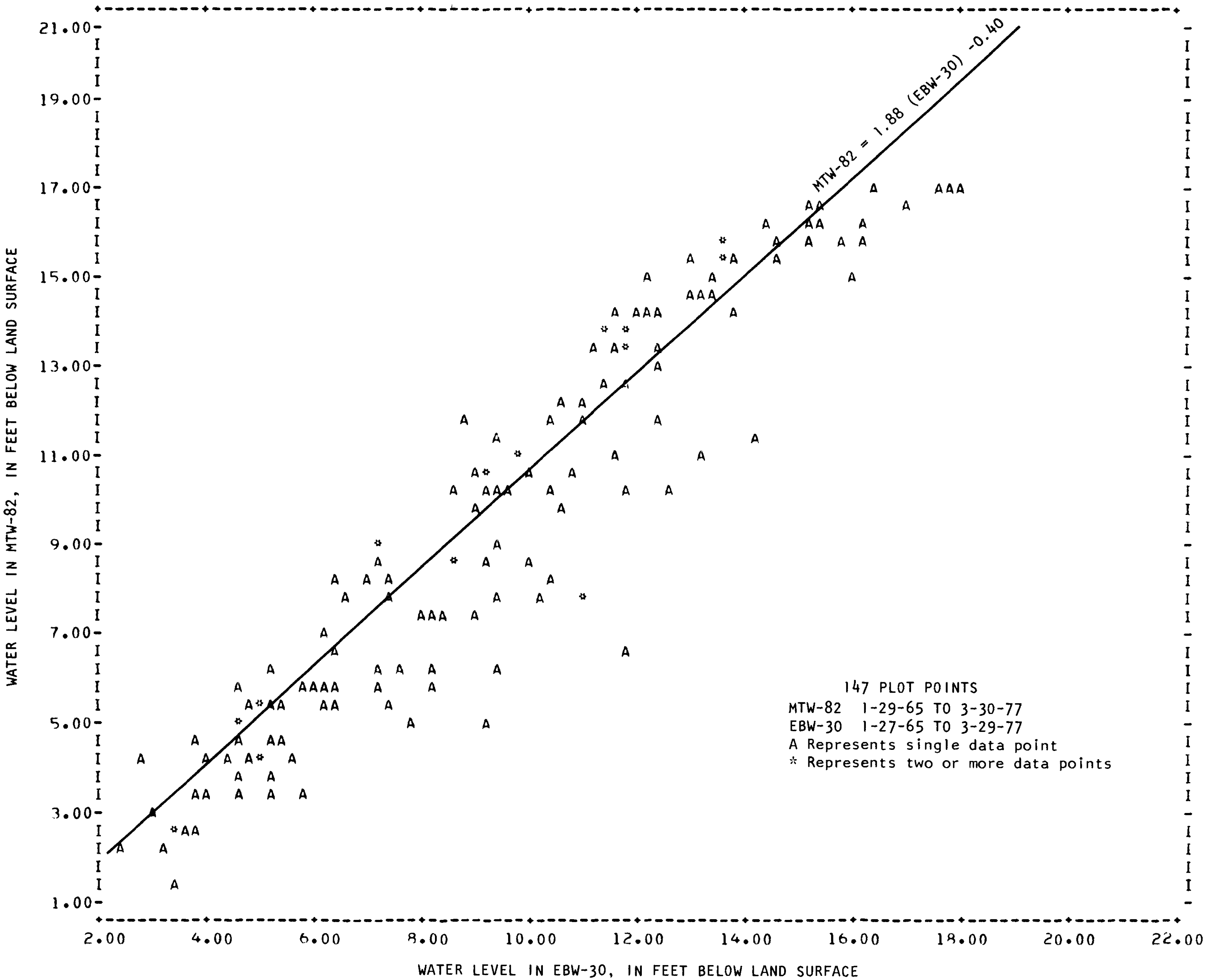

Figure 6.--Correlation of 147 monthly water levels in two wells in till in southeastern Massachusetts

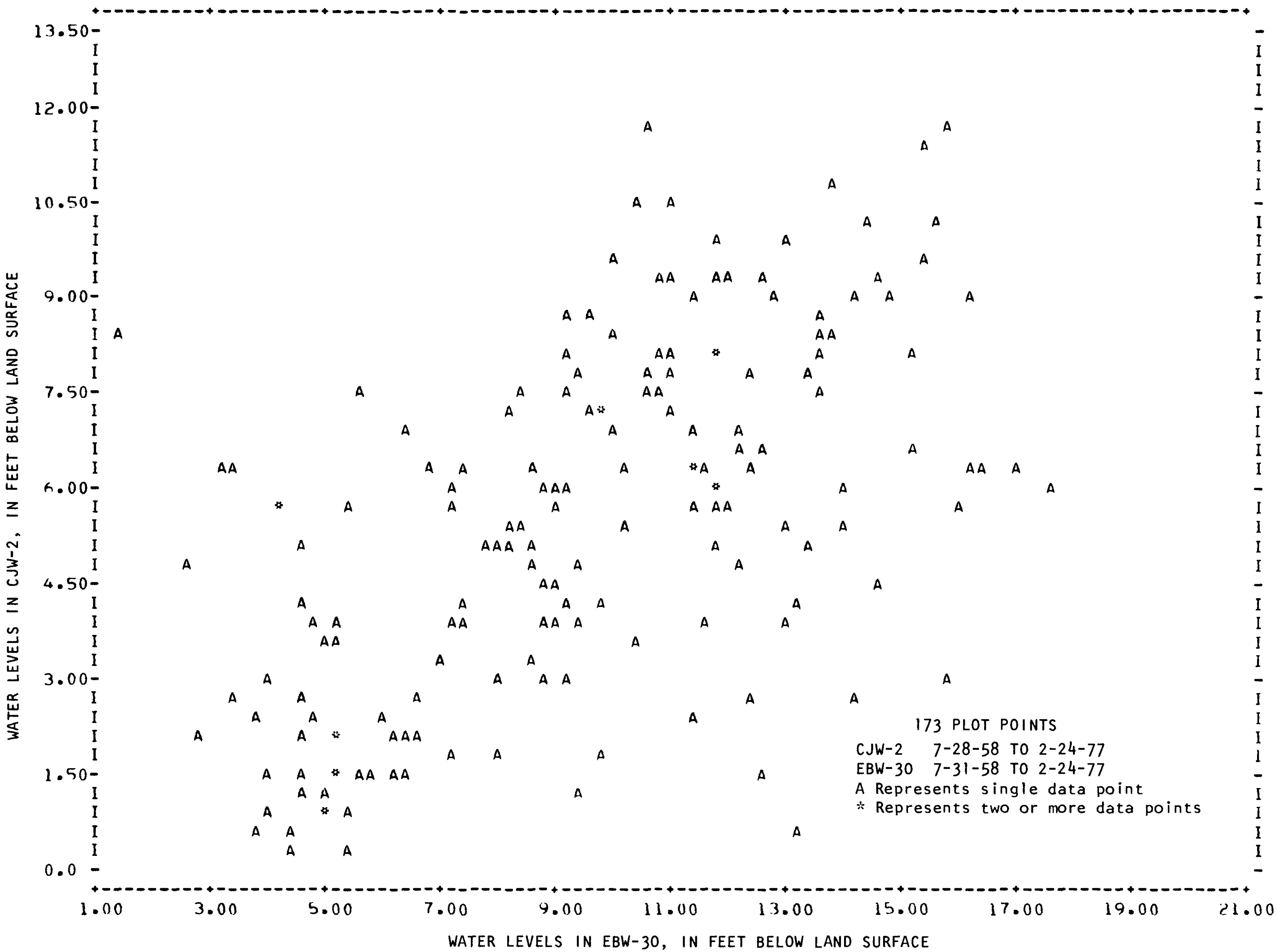

Figure 7.--Lack of correlation of monthly water levels in wells in till in eastern and western Massachusetts

Data from the 15 sites (fig. 8) seem to give a representative sample of maximum water-level range, because the ranges form an essentially normal distribution about a median of 11.80 feet; 47 percent of the maximum ranges are within 1 foot of the mean maximum range, and the remaining 53 percent are between 1 to 5 feet higher or 1 to 5 feet lower than the mean (fig. 8).

Topographic situation (fig. 8) or geographic location (fig. 3) show no apparent correlation with maximum water-level range for the 15-well sample. The lack of correlation between water-level range in till and topographic situation represents a lack of relationship between water-level range and apparent regional ground-water gradients to discharge boundaries. The significance of this observation is that till seems to act as a leaky aquifer in which water levels may be perched and hydraulic ground-water connections between till and other lithologies may be poor.

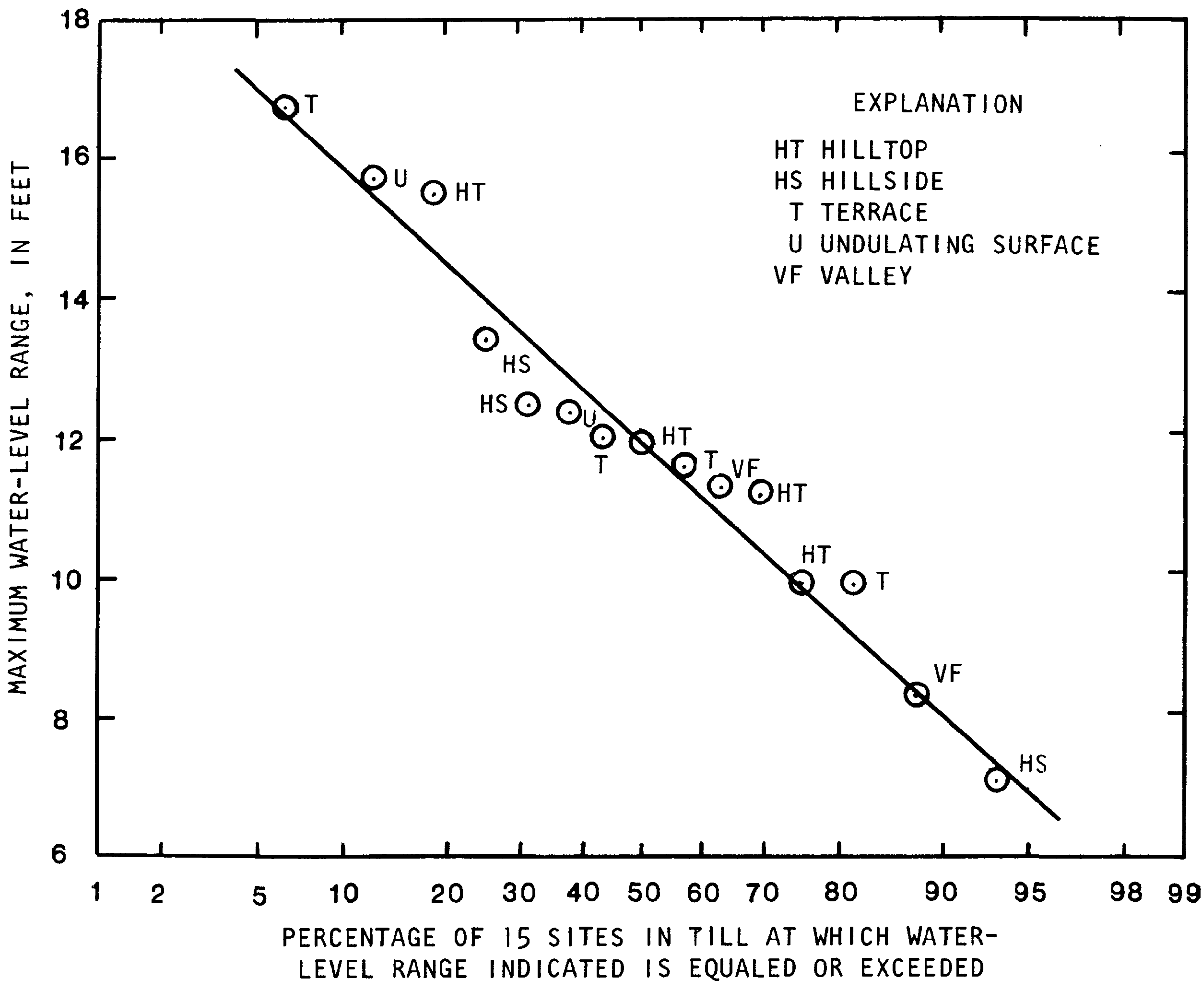

Figure 8.--Probability of water-level range in till

GROUND-WATER LEVELS IN SAND AND GRAVEL

Water-level records for 49 observation wells in sand and gravel throughout Massachusetts, excluding Cape Cod and the Islands, range from 8 to 36 years in length and total over 9,000 monthly measurements. Fifty percent of the annual maximum water levels measured occurred in March and April, 26 percent in March, and 24 percent in April (fig. 9).

The 49-well sample was divided into subgroups on bases of topographic situation and mean depth to water (fig. 9) to better differentiate between wells having maximum water levels in different months.

Annual maximum water levels occurred most frequently in March, 32 percent, in 18 wells on valley flats. Annual maximum water levels occurred 50 percent of the time evenly distributed between March and April in 31 wells on hills and terraces. Annual maximum water levels occurred in March, 35 percent, and in February and April, 15 percent each, in 28 wells with 10 feet or less mean depth to water. Annual maximum water levels occurred in April, 37.5 percent, and in March, only 12 percent, in 21 wells with more than 10 feet mean depth to water.

March is most frequently the month when melting of the winter snowpack occurs, and major infiltration of water from this source recharges the saturated zone. However, where the mean depth to water is greater than 10 feet, recharge to the saturated zone is usually delayed enough to cause the annual maximum water level to occur in April (fig. 9).

Further analysis of the water-level ranges (fig. 10) shows that at least two major groups occur among the 49 wells in sand and gravel. These two groups are apparently closely identified with the topographic situation of the observation wells: (1) valley and valley flat, or (2) terrace and hillside. This relationship indicates a good hydraulic connection between sand and gravel aquifers beneath hills, terraces, and valleys and discharge boundaries. One well on a terrace, but located near a lake regulated for recreation (constant elevation), plotted with the valley flat group, and one well located near a lake used for water supply (varying elevation) showed a greater range of fluctuation than the group in general. Two wells on terraces and one on a hillside, which also showed a greater range of water-level fluctuation than the group, were identified as located where tributary streams probably lose water as they cross highly permeable terrace deposits. After these wells, possibly influenced by surface-water regulation and influent streams, were removed from the terrace group, normal distribution of water-level ranges could be identified (fig. 11). Hillside situations were represented by only six wells, and although they plotted with the wells in terrace situations, they are not considered further because of their small number. These observations suggest that when attempting to measure maximum annual water levels which are likely to be less than 10 feet deep, March would be the preferred month of measurement.

TERRACES

The probability of exceedance for water-level ranges in the group of 20 wells in sand and gravel on terraces, exclusive of wells adjacent to regulated surface-water bodies and influent tributary streams, is shown in figure 11. These data are interpreted to mean that a maximum water-level fluctuation of 10 feet or more could be expected at about 5 percent (1 in 20) of randomly selected sites on terraces in Massachusetts.

VALLEYS

In the group of wells identified as located in valleys or valley flats but not plotting with the group (fig. 10), one well was near a pumping well, a second was near a regulated surface-water body, and the topographic location of a third well was not a clearly defined valley. Assuming that all sites near regulated surface-water bodies and ground-water pumpage can be identified and eliminated from the sample, randomly selected sites in clearly identifiable valley flat topographic situations can be expected to have water-level range probabilities as shown in figure 12. For example, a water-level range of 4.2 feet would be expected to be exceeded at less than 5 percent of randomly selected sites, and a range of 4.0 feet would be expected at less than 10 percent of randomly selected sites (fig. 12).

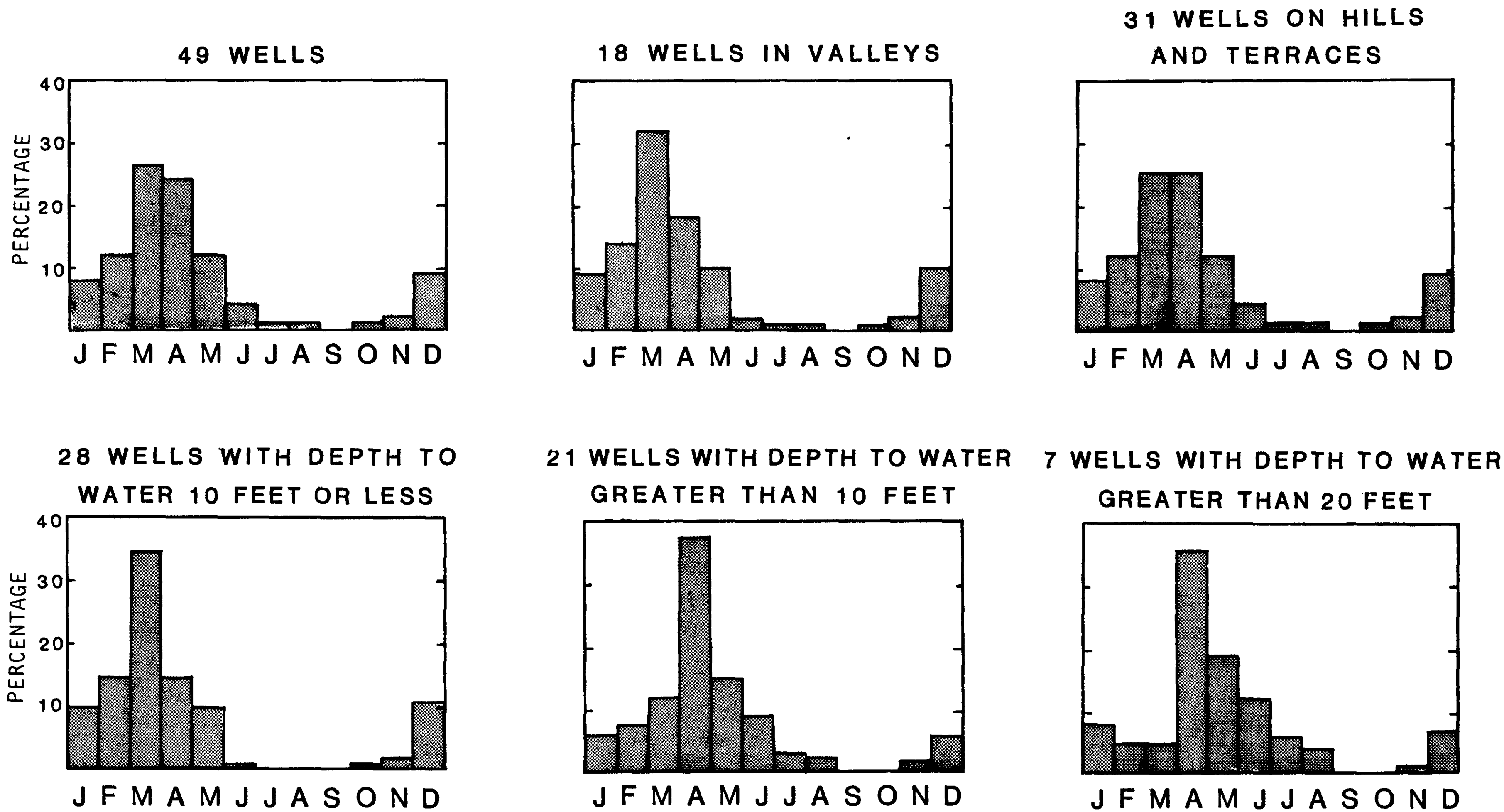

Figure 9.--Frequency of maximum annual water level in groups of wells in sand and gravel

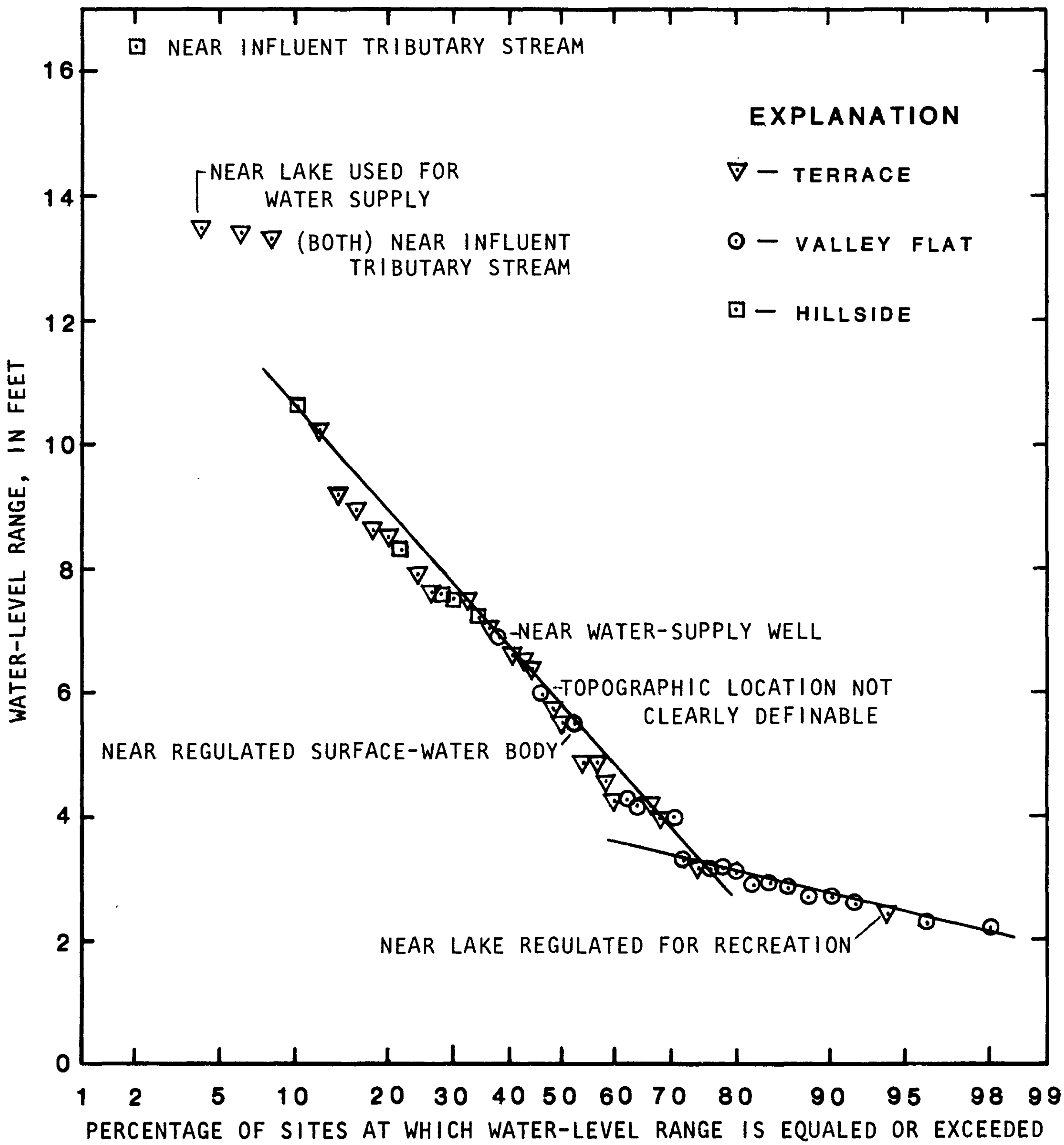

Figure 10.--Probability of water-level range in sand and gravel showing terrace and valley flat subgroups

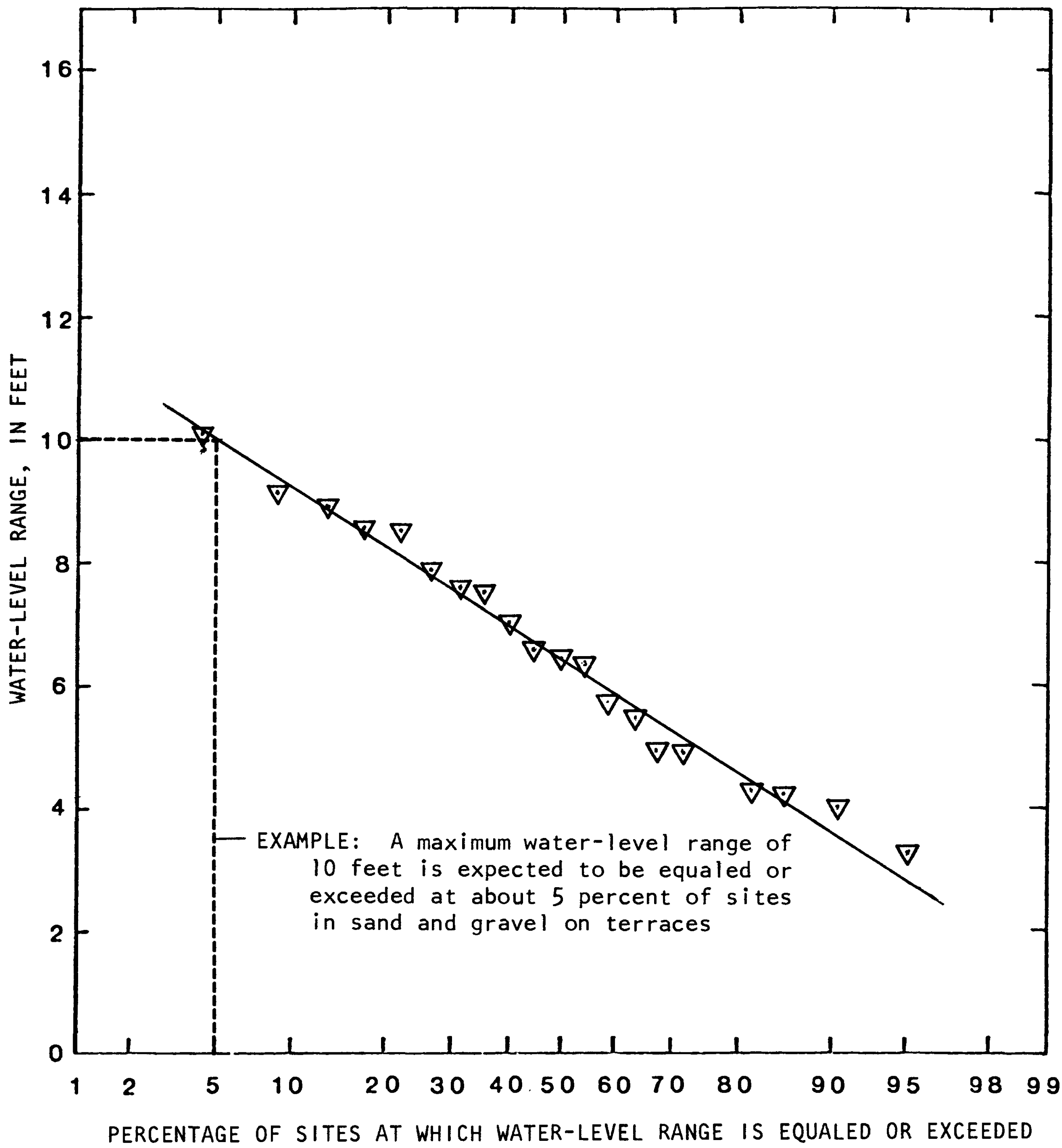

Figure 11.--Probability of water-level range in sand and gravel on terraces

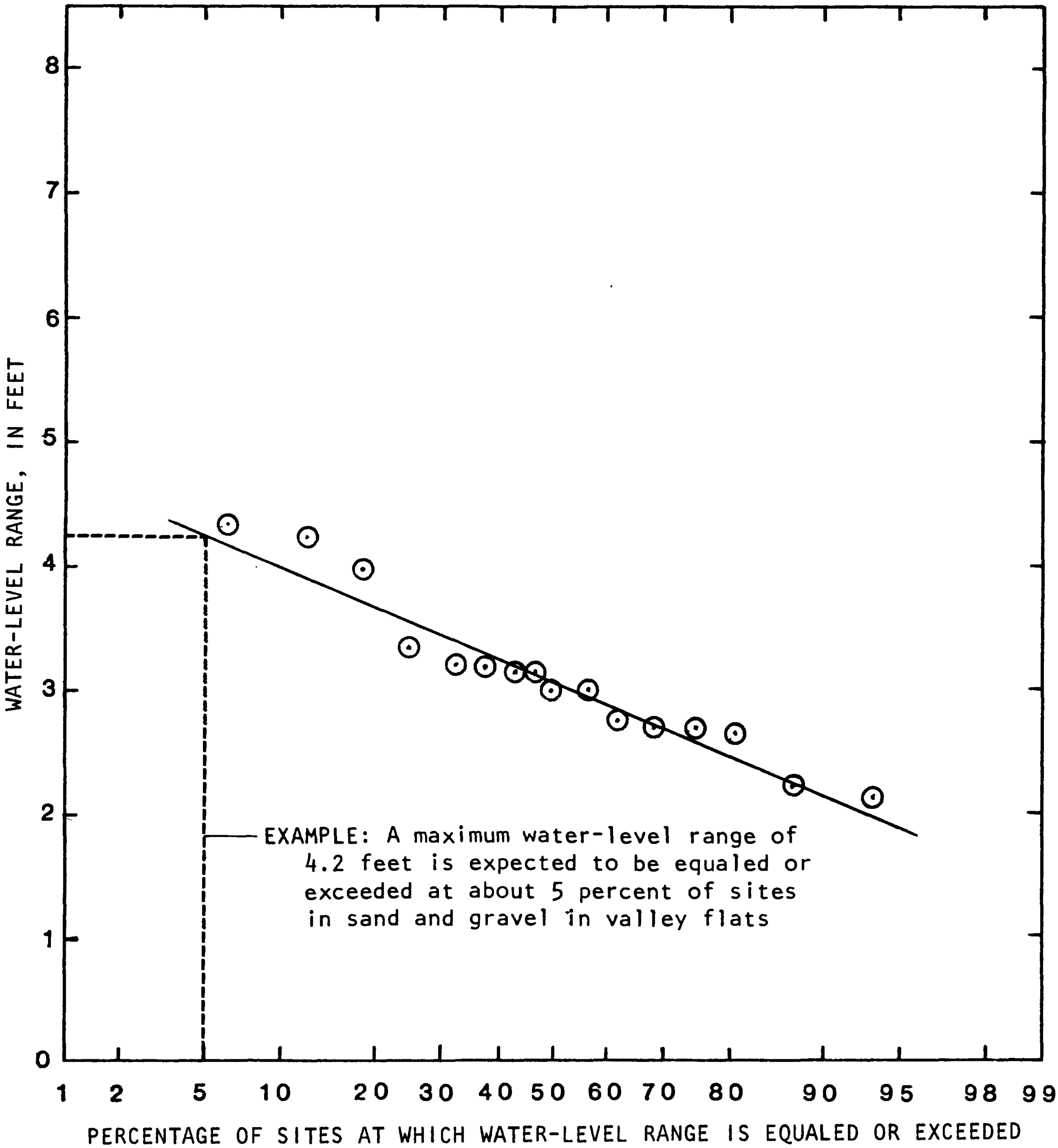

Figure 12.--Probability of water-level range in sand and gravel in valley flats

ESTIMATING APPROACH

Estimates of the potential water-level rise from a current level in an observation well can be made on a basis of historical water-level records from that observation well: Generally, the longer the historical record, the less likely the estimate is to be exceeded. At a construction or septic-system site, estimates of the potential ground-water-level rise might be made by correlation with the potential rise in an observation well if the climate and hydrogeologic conditions at the site and the well are similar. The likelihood of such an estimate being exceeded can be reduced by selecting an observation-well range for correlation which is exceeded at only a small percentage of observation-well sites in a single hydrogeologic environment, such as those shown in figures 8, 11, and 12. The foregoing analysis of the observation-well network identifies and graphs the probabilities of water-level ranges being exceeded at sites for the three hydrogeologic environments--till, sand and gravel on terraces, and sand and gravel in valleys.

An estimate of the probable high water level at a site might be made on the basis of the assumption that water-level fluctuations at the site are directly correlated with water-level fluctuations at a selected observation well. The mathematical expression of this assumption follows:

$$\frac{S_c - S_h}{OW_c - OW_{max}} = \frac{S_r}{OW_r}$$

where:

S_c	=	measured depth to water at the site;
S_h	=	estimated depth to probable high water level at the site;
OW_c	=	measured depth to water in the observation well which is used to correlate with the water levels at the site;
OW_{max}	=	depth to recorded maximum water level at the observation well which is used to correlate with the water levels at the site;
S_r	=	range of water level where the site is located. Values of range with varying exceedance probabilities may be selected from figures 8, 11, or 12. For example, a range of 10 feet would be expected to be exceeded at 5 percent of sites in sand and gravel on terraces; and
OW_r	=	recorded upper limit of annual range of water level at the observation well which is used to correlate with the water levels at the site.

Rearranging the equation, the estimated depth to probable high water level at the site (S_h) is given by:

$$S_h = S_c - \frac{S_r}{OW_r}(OW_c - OW_{max})$$

In the above equation, S_c and OW_c are measured at the time of interest, the values of OW_{max} and OW_r may be obtained from the observation-well record (Maevsky, 1976) and the value of S_r may be selected from the probability graph of water-level range in figures 8, 11, and 12.

Selection of the water-level range exceeded at only 10 percent of the observation wells for S_r should result in an estimate of high ground-water level which would be exceeded at only 10 percent of randomly selected test sites over a period about equal to the length of record for the observation wells. The average lengths of record for the observation wells used to prepare figures 8, 11, and 12 were 24, 16, and 14.5 years, respectively. No observation well records used to prepare figures 8, 11, and 12, which describe probability of water-level range, were less than 8 years in length. Use of the information and approach as described in this report would seem to be capable of providing estimates which would not be exceeded at more than 1 in 10 sites over a period of 10 years or longer. Attempts to describe the probabilities rigorously would be complicated by the irregular lengths of observation-well record available for Massachusetts. Additional research to determine the probabilities of exceedance of estimates with respect to time and with respect to location may be desirable.

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