GROUND WATER IN NORTH MONTEREY COUNTY, CALIFORNIA, 1980

By Michael J. Johnson

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[Plates are in pocket]

Plates 1-3. Maps of North Monterey County, California, showing--
1. Geology and sections, and generalized stratigraphic relations of geologic units in the North County area to those in the Salinas Valley.
2. Structure contours at the base of the Quaternary deposits, and potentiometric contours and direction of ground-water movement.
3. Saltwater intrusion, 1979, and ground-water subareas.

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CONVERSION FACTORS

The inch-pound system of units is used in this report. For those readers who prefer to use International System (SI) of Units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply	by	To obtain
acres	0.4047	hm^2 (square hectometers)
acre-ft (acre-feet)	0.001233	hm^3 (cubic hectometers)
ft (feet)	0.3048	m (meters)
gal (gallons)	3.785	dm^3 (cubic decimeters)
gal/d (gallons per day)	3.785	dm^3/d (cubic decimeters per day)
gal/min (gallons per minute)	0.06309	dm^3/s (cubic decimeters per second)
(gal/min)/ft (gallons per minute per foot)	0.2070	(L/s)/m (liters per second per meter)
in (inches)	25.4	mm (millimeters)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)
µmho/cm (micromhos per centimeter)	1.000	µS/cm (microsiemens per centimeter)

ALTITUDE DATUM

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

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ABSTRACT

Present ground-water demands exceed long-term recharge throughout much of North Monterey County in shallow Quaternary deposits--principally the upper part of the Aromas Sand--and the overlying alluvium. Recharge is largely from local precipitation, although small quantities of recharge are derived from outside areas. Water levels in the Pajaro and Salinas River valleys north and south of the study area are lower than in most of the intervening area, and recharge from the east is blocked by faults and impervious rock. Ocean water moves in from the west to replace depleted freshwater storage in the upper part of the Aromas Sand, alluvium, and terrace deposits.

The North County area is divided into subareas to estimate pumpage demands and to evaluate ground-water yields. Pumpage near the granitic ridge, an area of limited storage, nearly equals local recharge. West of the granitic ridge, pumpage exceeds available recharge but draws upon a large storage potential, which is in part maintained by the intrusion of seawater.

Deeper units than those now tapped by wells in the Aromas Sand and the underlying Purisima Formation may have substantial water-bearing potential for additional ground-water development. Development of water from these formations might be limited, however, by the remoteness of the recharge source and by the proximity to the ocean.

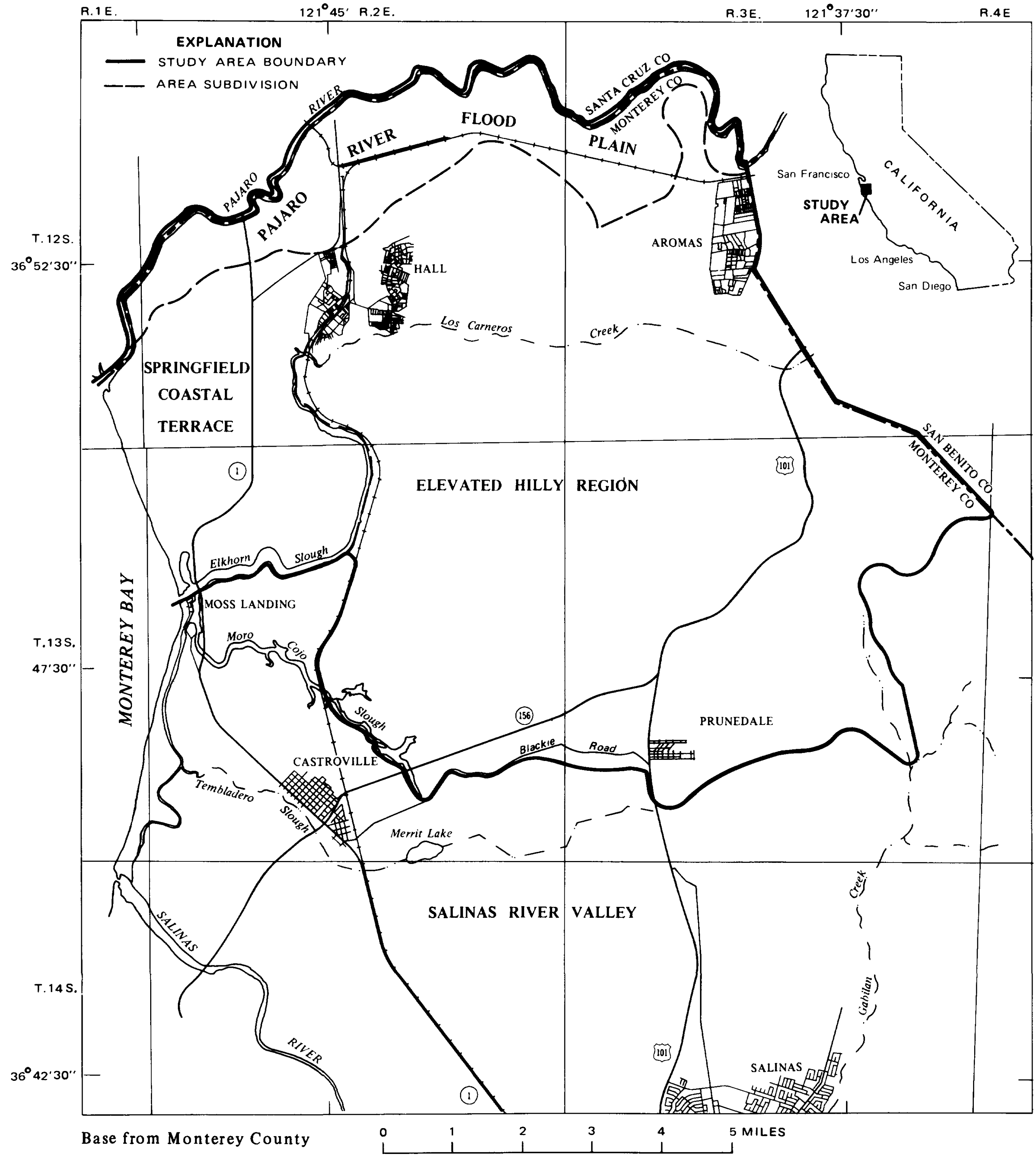


FIGURE 1.–North Monterey County.

INTRODUCTION

The North Monterey County study area extends from the Pajaro River on the north to the lower Salinas Valley on the south and includes part of the Pajaro River flood plain and the Springfield coastal terrace. This study primarily concerns the elevated, hilly region around the cities of Prunedale and Aromas (fig. 1).

The North County area is primarily rural, though suburban development has been increasing since the early 1970's, particularly in the hilly region. Strawberry farming is expanding along the flatter foothill slopes, and intensive vegetable farming continues in the Pajaro River flood plain and on the Springfield coastal terrace.

Water demands are met exclusively by ground water pumped from privately owned irrigation and small domestic wells. Typically, a well or wells in a community water system supply several homes. Excess irrigation water returns to the ground-water system by percolation through the surface soils, and sewage effluent returns by percolation through drain fields.

The California Department of Water Resources (1977) stated that a general ground-water overdraft existed in the North County area during the late 1960's and early 1970's. With continued and expanded use of ground water over the past decade, local concern about meeting future water needs has increased. Citizens have recognized the need to determine the availability of ground-water supplies in various parts of the North County area, particularly the Prunedale and Aromas areas. Knowledge of how the source, movement, and occurrence of ground water within the existing geologic framework relates to existing pumping stress will aid in management of the resource.

The purpose of this investigation is to provide the additional geohydrologic information needed for Monterey County to develop plans for the optimum utilization of its water resources--particularly in the Prunedale and Aromas areas.

The report includes definition of ground-water occurrence within the geologic framework, and the source and movement of water within the water-bearing strata, computation of present ground-water demand, and estimates of the ground-water yield within given subareas of the study area.

Acknowledgments.--The cooperation and assistance of the California Department of Water Resources and the Monterey County Flood Control and Water Conservation District in supplying well data, water levels, and chemical analyses of ground water are gratefully acknowledged. Special thanks are extended to Bob Binder and Gene Taylor of Monterey County Flood Control and Water Conservation District, Richard Thorup, consulting geologist, Monterey, Calif., and John C. Tinsley III, geologist, U.S. Geological Survey, for their cooperation and assistance.

GEOLOGY AND OCCURRENCE OF GROUND WATER

Ground water in North Monterey County occurs in a series of westward-dipping sedimentary strata formed in the late Tertiary and Quaternary periods. Older rocks in the area, except for the weathered part of the granitic basement, do not contribute substantially to the water supply. The surface distribution of the geologic units and the stratigraphic relation of these units to those in the lower Salinas Valley are shown on plate 1 and figure 3. The thickness of the unconsolidated deposits is inferred by comparing the land-surface altitude to the base of the Quaternary deposits mapped on plate 2.

Water-bearing strata in the study area include alluvium and terrace deposits of Holocene and Pleistocene age, the Aromas Sand of Pleistocene age, and the Purisima Formation of Pliocene and Miocene age. Pumpage is principally from the upper part of the Aromas Sand and from the alluvium and terrace deposits; however, the granitic basement rock west of the Vergeles fault yields small quantities of water to some wells. The Purisima Formation generally is not tapped in this area but may have substantial water-bearing potential. A brief discussion of the distribution, lithology, and water-bearing characteristics of the aquifers follows.

Granitic Basement

Crystalline rocks ranging in composition from gabbro to granite, but predominantly composed of quartz diorite and adamellite, underlie, on the surface or at depth, the entire North Monterey County area. These consolidated rocks are fractured and, in the upper 100 to 200 feet, are commonly weathered to the extent that coarse fragments have undergone some lateral transport and deposition with clay and sandy silt interspersed. Small yields to domestic wells, about 2-20 gal/min, are drawn from the weathered zone and from individual fractures. The granitic rocks are exposed in a ridge along the western side of the Vergeles fault but are buried at depths progressively deeper toward the west. The buried surface at the top of the granitic rocks dips approximately 7° west. The upper part of the Aromas Sand overlaps part of the buried granite ridge, but older strata pinch out against this basement high. Water-well logs suggest that the upper surface of this buried ridge is composed of a series of knolls and valleys. Gravity data (Clark and Rietman, 1973) indicate that these local buried-surface features have less than 200 feet of relief.

Older Tertiary Formations

The older Tertiary formations are consolidated marine sediments, which consist of sandstone, siltstone, and mudstone overlying or pinching out against the granitic basement (see sections, pl. 1). They include, in ascending order, the San Juan Bautista Formation and Pinecate Formation of Kerr and Schenck (1925), Miocene volcanics, and Monterey Formation. The Monterey Formation occurs only in the subsurface west of the Vergeles fault where it underlies the younger Purisima Formation and thickens westward out under Monterey Bay. The Purisima and the other units occur east of the Vergeles fault where, in places, they crop out to the southeast. East of the Vergeles fault, the older Tertiary formations are as much as 8,000 feet thick.

Water wells in the study area do not tap these marine formations, which are deeply buried, of low specific yield, and usually yield saltwater. Even at higher altitudes and at shallow depths where some flushing of connate water has occurred in north central Santa Cruz County, the older Tertiary formations have chloride concentrations ranging from less than 10 mg/L (milligrams per liter) to more than 1,540 mg/L (Johnson, 1980). Sandstone units in these formations in the Salinas Valley are known to yield small quantities of freshwater--sufficient for limited domestic use; the mudstone units yield virtually no water except where fractured to create secondary storage (Durbin and others, 1978).

Purisima Formation

The poorly consolidated rocks of the Purisima Formation consist of marine beds that conformably overlie the older Tertiary formations or, where the older Tertiary formations are locally absent, unconformably overlie or pinch out against the buried granitic ridge. The Purisima Formation has a maximum thickness of 800 feet near the coast (California Department of Water Resources, 1977). It consists chiefly of poorly indurated sand, silt, and clay and, in the Monterey Bay area, was divided into three hydrologic members of slightly different lithologic characteristics by Hickey (1968). The lower member consists of poorly indurated sand beds interbedded with clay and shale. The middle member consists of intercalated beds of poorly indurated sand, silt, and clay with some gravel. The sand is admixed with silt. The upper member consists largely of poorly indurated, thin sand beds interbedded with silt and clay.

The water-bearing properties of the Purisima Formation are largely unknown within the area shown in figure 1. It is believed that the upper part of the Purisima Formation may contain confined freshwater regionally throughout the Monterey Bay area, provided substantial displacement of connate water has occurred during Pleistocene and Holocene time (J. C. Tinsley III, U.S. Geological Survey, written commun., 1980). The Purisima is a major aquifer in coastal Santa Cruz County, north of the study area, where it extends southeastward, increasing in grain size and possible aquifer potential, under the Aromas Sand in the Pajaro Valley and into the western part of the study area. In the Salinas Valley the upper part of the Purisima Formation (see "Generalized stratigraphic relations," pl. 1) probably intertongues with the lower part of the younger Paso Robles Formation, an unconsolidated, fluvial, nonmarine deposit of indurated sand, silt, and clay (Greene, 1970). Water in the locally called "900-foot" aquifer in the Salinas Valley probably occurs in the Paso Robles and Purisima Formations.

Aromas Sand

The Aromas Sand is the major aquifer in the North Monterey County study area and is as much as 800 feet thick near the coast. The Aromas Sand consists of aeolian and fluvial beds of unconsolidated, well-sorted, quartzose--brown-to-red sand containing lenses of silt and clay. The aeolian sand beds become finer grained landward from Monterey Bay. Fluvial beds of silt and clay were deposited to the west in near-coastal and marine environments, reducing the vertical permeability of the Aromas in this area. This mix of fluvial marine clays has been interpreted by the California Department of Water Resources (1977) to extend continuously along the coast from the Springfield terrace area through Castroville. Beds of silt and clay that occur commonly at the unconformable base of the Aromas Sand reduce the rate at which water percolates vertically downward into the underlying Purisima Formation and granitic rock. The Aromas Sand thins to the south, where its lower part interfingers with the upper part of the Paso Robles Formation. These two units together compose the "400-foot" aquifer in this part of the Salinas Valley (pl. 1). The upper part of the Aromas Sand abuts areas of Holocene alluvium, which forms the "180-foot" aquifer in the Salinas Valley (California Department of Water Resources, 1970; Tinsley, 1975; Thorup, 1976).

In the Pajaro Valley, wells perforated in the Aromas Sand have yields that average about 450 gal/min and specific capacities of about 20 (gal/min)/ft of drawdown (Muir, 1972). Wells in the Aromas Sand have yielded as much as 750 gal/min (California Department of Water Resources, 1977).

Analysis of water from wells indicates that water quality within the Aromas Sand is generally suitable for most purposes. An overabundance of magnesium and calcium cations, however, may make the ground water objectionably hard for domestic or industrial use. Locally, concentrations of iron and manganese may also be high enough to be objectionable. Troublesome anions include nitrate and chloride. High nitrate concentrations can be caused by malfunctioning septic systems, by a concentration of septic systems in densely populated areas of the elevated hilly region, or by leaching of fertilizers with wastewater return flow from irrigation. Chloride concentrations are high in coastal areas. Reversal of ground-water gradients due to ground-water pumping (see section on "Water-Level Gradients and Saltwater Intrusion") has caused a gradual degradation of ground-water quality in wells near the coast.

Terrace Deposits and Alluvium

The terrace deposits and alluvium are highly variable mixtures of unconsolidated gravel, sand, silt, and clay unconformably overlying the Aromas Sand. Some of the silt and clay units that were deposited in areas of low relief on the erosional surface of the Aromas Sand result in perched water conditions in the terrace and alluvial deposits.

The terrace deposits of both marine and continental origin accumulated in late Pleistocene time and are principally in the Springfield area, along Elkhorn and Moro Cojo Sloughs, and along Los Carneros Creek. Their thickness is highly variable, exceeding 100 feet in some places near the coast. The terrace deposits are permeable, but well yields vary considerably according to thickness, saturation, and composition of the deposits. Many wells drilled in the terrace deposits also penetrate the Aromas Sand; thus, these wells pump water from both units.

Most of the Holocene alluvium was deposited during intervals of relatively stable sea level from about 7,000 years ago until present (Dupré 1975). The alluvial deposits in the Pajaro and Salinas Valleys extend along the coastal estuaries and sloughs and up the major stream canyons that cut into the Aromas Sand. The alluvium in the Pajaro Valley is permeable and yields as much as 500 gal/min to wells. Specific capacities average 50 (gal/min)/ft of drawdown.

Fine-grained sediments, chiefly cohesive clays, predominate near the coastal estuaries and sloughs. One particularly thick section of alluvial clays extends 2 or 3 miles up Elkhorn Slough in a clay-filled gorge that is an extension of the offshore Monterey Submarine Canyon (California Department of Water Resources, 1977). This alluvial clay fill is thickest near the slough's mouth in section 18 (T. 13 S., R. 2 E.), where it is at least 600 feet thick (pl. 2). The alluvial clay fill restricts horizontal ground-water movement from the Salinas Valley into the Springfield coastal terrace. Alluvial clay beds that confine ground water are also deposited over fluvial deposits in the Castroville area of the Salinas Valley and they extend up the valley into the southwest part of the study area. Thin alluvial deposits with limited storage potential extend up the stream canyons. Water in these deposits and in the terrace deposits may be perched above the regional water table.

SOURCE AND MOVEMENT OF GROUND WATER

The direction of ground-water movement beneath the North County area is influenced near the surface mainly by topography and at depth mainly by lithology and structure. The source of ground water in elevated, near-surface formations is local rainfall, but at depth sedimentary units receive most of their ground water from rainfall over a much larger area via an underground flow system controlled by structural and lithologic boundaries. Generally, rainfall infiltrates and moves westward toward the ocean.

Following is a discussion of the source and movement of ground water within each of the major geologic units previously described. Estimates of the quantity of water recharged and of the quantity of water in storage within given subareas of the North County area are discussed in a later section.

Granitic Basement

East of the study area granitic basement rocks crop out along the San Andreas fault. An impermeable clay gouge created in the San Andreas fault zone prevents ground water east of the fault from entering North Monterey County through the pre-Quaternary units. Within the North County area the partly buried granitic ridge along the Vergeles fault is of local hydrologic importance.

Hydrologically, the granitic rock along the ridge consists of an upper weathered zone and a fractured zone underlain by impermeable rock. The weathered zone is 100 to 200 feet thick and generally has lower hydraulic conductivity than the overlying Aromas Sand, due to the weathered zone's finer grain structure of clay and sandy silt deposited between coarser granitic fragments. The fractured zone allows very limited recharge, storage, and movement of ground water. The source of water is local precipitation, either falling directly on the weathered granitic surface or moving downward through thin deposits of overlying Aromas Sand.

Beneath the weathered zone, fractures are more prevalent and open at shallower depths, and they decrease in number and size with depth. This decrease limits water storage in fractured rock to the uppermost few hundred feet (Arvey Swanson, California Department of Water Resources, written commun., 1972). Figure 2 diagrammatically explains how ground water moves through the upper 400 feet of the granitic rocks to replace ground water removed from voids in the rocks by a pumping well. With intermittent pumping, the dewatered voids may not be completely refilled, thereby preventing the water level in the well from recovering to its pre-pumping altitude.

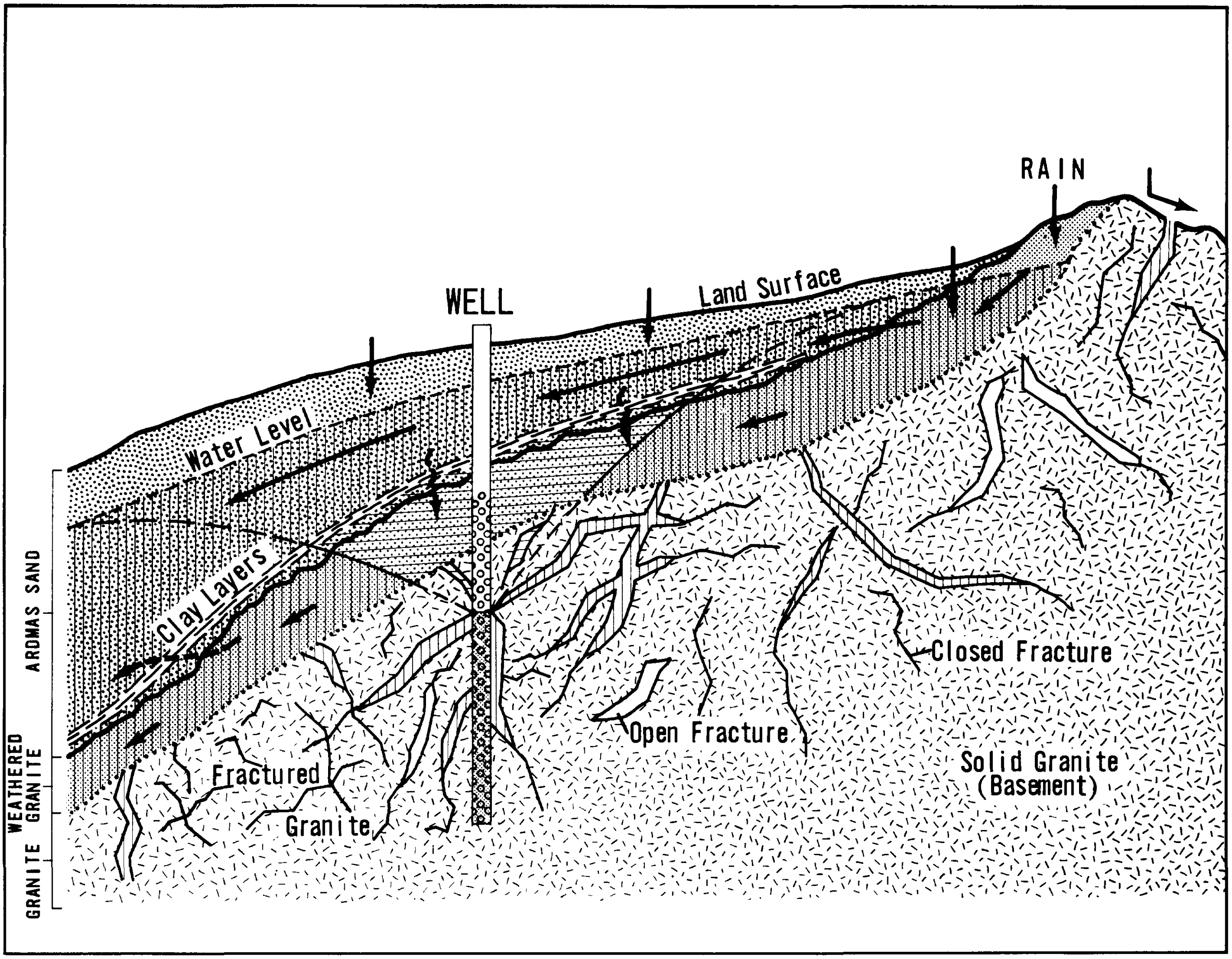
Wells perforated only in the fractured granitic rocks had water levels more than 100 feet below water levels in nearby wells perforated only in the overlying Aromas Sand. The water levels should be nearly the same under undisturbed conditions--that is, before any pumping began. The difference in water levels suggests that in some wells the rate of pumping from the fractured granite exceeds the rate at which the fractures can be recharged, and this accounts for the wells' sharply reduced yield with continued pumping. The fractures are recharged mostly by water moving downward from the overlying Aromas Sand and weathered granitic rock. This vertical movement is slowed by the silt and clay beds described earlier. Probably most ground water available to recharge the fractured rocks moves vertically into the fractures from a relatively small surface radius of influence near the well. Any horizontal movement of water in the granitic rock is probably limited mostly to the upper weathered zone, particularly near outcrop areas. In such areas adjacent wells perforated in the overlying Aromas Sand or perforated in the weathered granite maintain similar water levels.

Older Tertiary Formations

Sediments of older Tertiary formations are deeply buried west of the Vergeles fault and are of little hydrologic interest. Any movement of water within these sediments would be southwestward, following the trend of the regional dip. East of the Vergeles fault, gravity data by Clark and Rietman (1973) suggest that water movement would be northwestward, away from the exposed granitic ridge, and parallel to and between the San Andreas and Vergeles faults, as shown in figure 3. Recharge into and discharge from these consolidated formations are limited by low permeability due to compaction and the fine-grained texture of the sediments.

Purisima Formation

The direction of ground-water movement within the Purisima Formation is shown in figure 3. In the northern part of the study area, ground water moves southeastward from the Corralitos area into the northern part of the Pajaro Valley area, then southward toward Watsonville and southwestward toward and out under Monterey Bay. In the southern part of the study area ground water moving northwestward down the Salinas Valley supplies water to the Purisima Formation south of Elkhorn Slough. Within the central part of the study area, the Purisima Formation receives a small amount of recharge through silt and clay beds at the base of the overlying Aromas Sand, and from the weathered granite to the east where the Purisima Formation pinches out.



EXPLANATION

WATER SATURATED SEDIMENTS AND FRACTURES

ZONE OF LOWERED HYDROSTATIC WATER PRESSURE WITHIN RADIAL INFLUENCE OF WELL

UNCONFORMABLE CONTACT BETWEEN AROMAS SAND AND GRANITE

GRADATIONAL BOUNDARY BETWEEN WEATHERED AND CONSOLIDATED GRANITE

DIRECTION OF WATER FLOW – Length of arrow approximates relative amount of flow. Dashed arrow indicates restricted flow.

BOUNDARY OF PUMPING WELL'S CONE OF RADIAL INFLUENCE

WELL

CASING

PERFORATION

FIGURE 2.–Diagrammatic sketch of water movement near a pumping well in upper 400 feet of fractured crystalline rock.

Davis and Turk (1964, 1969) analyzed data from over 2,500 wells and from nearly 1,300 pressure tests in 340 drill holes in various crystalline rock types to find that all have about the same depth-yield relationship. This relationship is a function of two variables--the abundance of fracture openings and their size--both of which decrease with depth. It was observed that the logarithm of yield decreased linearly with the logarithm of depth. This relationship explains why well yields in fractured areas decline so sharply when the water table drops to the seasonal low. It also explains why wells having fairly high initial pumping rates (25 gal/min) tend to fail if pumped continuously. The apparent explanation is that high-yield wells do not necessarily have substantially more ground water stored in their area of influence than do low-yield wells. Hence, the ground-water reservoir is drained at a faster rate, and the well goes dry.

As stated by Arvey Swanson (1979), Senior Engineering Geologist for the California Department of Water Resources:

> "If hard-rock wells are to be the sole source of water for a small community, several factors must be carefully considered. The number of wells needed in a climate that is dry for several consecutive months each year is controlled by the amount of ground water in storage around the wells, not the pumping rate of the individual wells. This means that well locations should be chosen with care, giving ground-water storage and recharge primary considerations, and making well spacing adequate to minimize interference between the various wells' areas of influence.
>
> "It also means that the sum of the continuous pumping rates of the wells should exceed the anticipated water consumption rate by a large safety factor; three times the consumption rate is suggested. The excess capacity anticipates well failures, or greatly reduced pumping rates. Standby wells should be provided initially, since the abrupt decline in pumping rate will not allow replacement at time of failure without interruption of service. Wells with relatively low yields should be used, as a 20-litre-per-minute (5 gpm) well that produces until the end of the dry period will yield as much water as a 95-litre-per-minute (25 gpm) well that fails early in the dry period. This fact also suggests that wells with high yields would produce longer if pumped at a smaller percentage of their maximum yield. Municipal or industrial wells that are expected to be in more or less continuous use should be pump tested continuously at maximum rate for at least 100 hours to make a reasonable estimate of the long-term pumping rate. Finally, well stimulation, such as the use of dry ice, should be tried on wells of inadequate yield, especially if the well intercepted a number of fractures that appeared to yield only minor amounts of water."

FIGURE 2.– Continued.

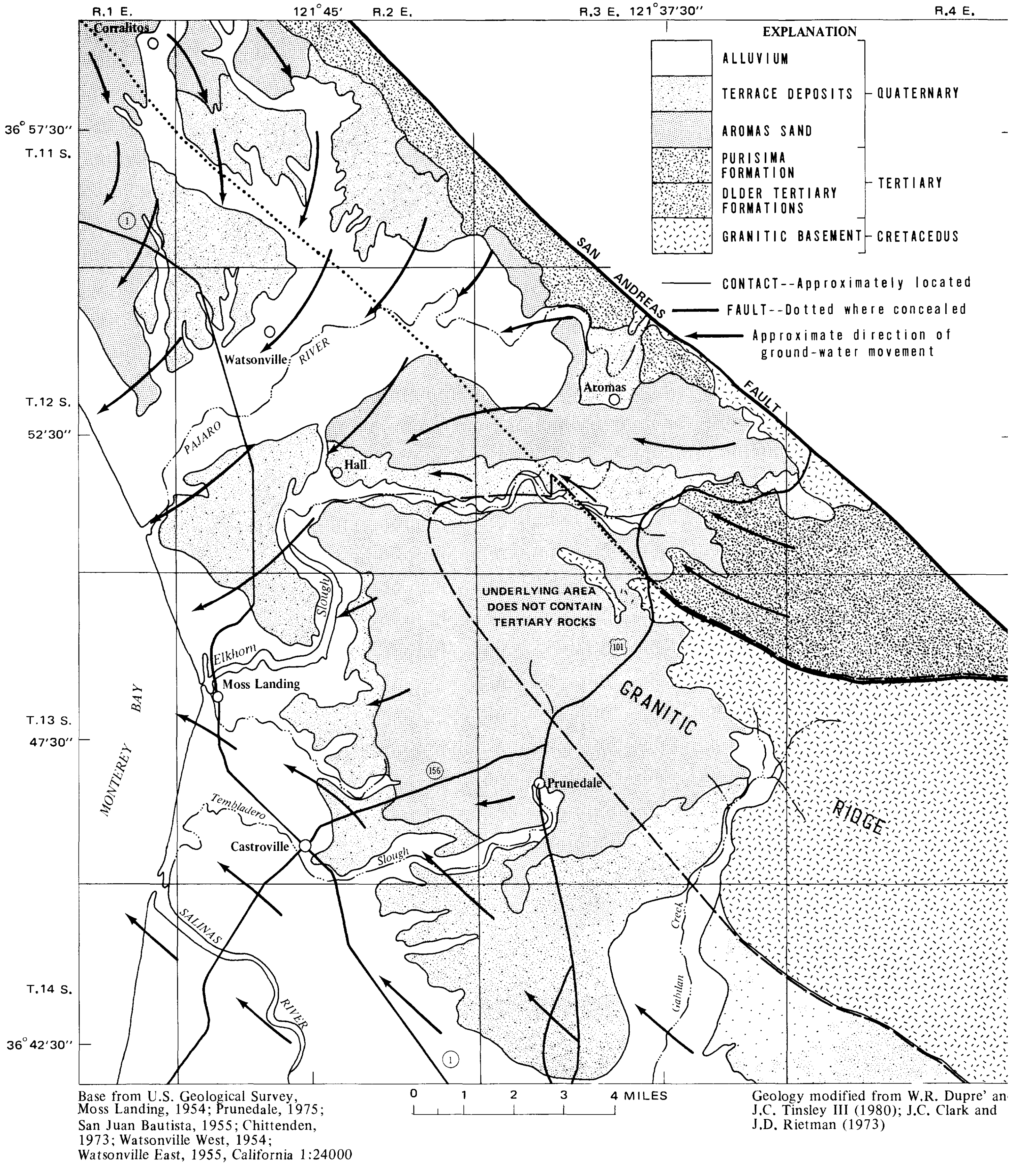


FIGURE 3. – Direction of ground–water movement in the deeper Tertiary rocks.

Aromas Sand

The direction of ground water movement in the upper part of the Aromas Sand is shown on plate 2. The source of this water is solely from rainfall within the drainage basins of the study area. Ground water drains from the granitic ridge and other elevated areas, moving northward into the Pajaro Valley alluvium, westward under the upper part of Elkhorn Slough, and southward into the Salinas Valley. The water moving into the Salinas Valley recharges the confined river-channel deposits, known as the 180-foot aquifer, and the upper part of the Paso Robles Formation. North of the granitic ridge, in the Los Carneros drainage, ground water moves westward within the Aromas Sand across the Vergeles fault. The thick clay fill at the mouth of Elkhorn Slough deflects the westward movement of ground water in the upper part of the Aromas Sand. Based on seismic projections, well logs, and water-level data, the author's belief is that the clay fill thins from 300 feet about 2.5 miles up the slough to less than 150 feet just east of the central part of the Springfield coastal terrace (about 5 miles up the slough). Deeper ground water probably moves westward under the clay fill into that part of the Aromas Sand underlying the Springfield terrace. At greater depths within the Aromas, ground-water movement, influenced more by regional structure, is southwestward under the Pajaro Valley into the study area west of the granitic ridge and out into Monterey Bay. Deeper flow patterns probably are similar to those of the underlying Purisima Formation.

Terrace Deposits and Alluvium

Water moves in response to gravity in the elevated terrace deposits of the Elkhorn Slough and the Springfield areas. Winter rains and runoff infiltrate these deposits, but subsequently drain out, and little ground water remains in storage during the summer months. Much of the ground water drains into streams or tidal sloughs; some, however, percolates downward and recharges the Aromas Sand. With the exception of the Pajaro Valley and Castroville areas, the alluvial deposits are confined to relatively narrow stream channels in the North County area. The most extensive deposits of stream-channel alluvium are along Los Carneros Creek. Recharge to and discharge from these alluvial deposits are determined by stream-channel geometry and streamflow characteristics.

Within the Pajaro Valley alluvium, ground water moves westward, parallel to the west-flowing Pajaro River. Recharge is from local precipitation, seepage from the upper Pajaro River and its tributaries, and underflow from the adjacent hills to the south that are underlain by Aromas Sand. In the Castroville area, the fluvial deposits (180-foot aquifer of the Salinas Valley) receive recharge from freshwater underflow moving southward and southwestward from the Aromas Sand in the elevated hilly region of the North County area.

Water-Level Gradients and Saltwater Intrusion

Undersea exposures of Holocene alluvium, the Aromas Sand, and the Purisima Formation occur in Monterey Bay and the Monterey Submarine Canyon (Greene, 1977). Landward movement of saltwater occurs where the ground-water-level gradients slope eastward. The alluvium and Aromas Sand contact saltwater near the coastline in tidal estuaries, whereas the Purisima Formation extends out under the bay and is exposed along the walls of the Monterey Submarine Canyon.

As indicated by water levels and direction of ground-water movement shown on plates 2 and 3, saltwater has intruded the upper aquifers due to pumping stress. The intrusion potential is less at greater depths because of less pumping stress, increased confinement, and greater distances from the shoreline to the point where the aquifers crop out along the ocean floor. A 1,600-foot well (Leonardi No. 3) was drilled by Pacific Gas and Electric Company in the southeast quarter of section 19 (T. 13 S., R. 2 E.) to intercept ground water moving down the Salinas Valley through deposits of Pliocene and Pleistocene age. Preliminary tests indicated yields of about 2,000 gal/min and water quality that meets or exceeds the California State "Class 2" irrigation-water requirements (the electrical conductance at 25°C declines from 1,067 μmho/cm at a depth of 640 feet to 316 μmho/cm at the bottom of the well). How long these deeper sediments will continue to yield large quantities of water without significant deterioration in water quality has yet to be determined.

Saltwater has been intruding the upper coastal aquifers in Monterey County for the past several decades (California Department of Water Resources, 1970). The degree of degradation of the aquifer waters and the areal extent of landward intrusion is determined by measuring the concentrations of chloride in well-water samples. Plate 3 is a map showing lines of equal chloride concentration of water derived from wells sampled along the coast. Aquifers in the areas between the 500 milligram-per-liter lines of equal concentration and the coast yield water with a chloride concentration of 500 mg/L or greater. In this report ground water near the coast containing chloride concentrations of less than 100 mg/L is generally considered unimpaired.

Salinas Drainage Area

Saltwater intrusion in the lower Salinas Valley near Castroville has been evident since the early 1940's. Saltwater intrusion initially began in the shallow 180-foot aquifer and later occurred in the 400-foot aquifer when deeper wells were drilled to avoid the 180-foot intrusion. Since the first occurrence, saltwater has intruded progressively farther inland in both aquifers.

The lines of highest chloride concentration on the map (pl. 3) represent 500 mg/L. At this concentration, injurious effects are noticeable when the water is used for irrigation, and crop production is severely affected. It is a common practice to mix poor-quality water from intruded wells with higher quality water from other wells during irrigation. Many high-chloride wells have been abandoned and can no longer be readily sampled. Improperly abandoned wells, or wells with casings that have corroded, increase chloride contamination by acting as conduits moving ground water between aquifers.

Because only four wells have been drilled into the 900-foot aquifer to date (1980), the extent of the aquifer and the character of its water is not completely known. A slight increase in chloride in one of these wells has been noted, but indisputable evidence of saltwater intrusion has not yet been identified.

Chloride in well-water samples has been increasing in the Moro Cojo area. An interpretation of ground-water quality is complicated by water wells that are perforated in multiple aquifers. There is a strong possibility that deeper aquifers have become degraded by saline water from shallower aquifers, and that well construction facilitates transfer of water from one aquifer to another. There were no provisions to regulate the construction or abandonment of wells prior to adoption of Monterey County Ordinance 1967 on May 29, 1973.

The water-quality data collected to date (1980) do not allow for precise mapping of chloride concentrations in the ground water. It appears, however, that most of the ground water to a depth of about 200 feet and extending 2 miles inland to Avila Road contains chloride concentrations of 250 mg/L or more. One 200-foot deep well, about 1 mile inland, yielded water with a chloride concentration of 5,220 mg/L in 1978. Deeper wells (one 950 feet deep) yield water with chloride concentrations over 250 mg/L as far inland as 1 mile. These observations and results of interpretation of all data that were compiled are presented on plate 3.

Pajaro Drainage Area

Little was known about the geology of the Pajaro drainage area until investigations were made during the mid-1960's and early 1970's. During this time the Monterey County Flood Control and Water Conservation District noted variations in water quality of well water pumped from different depths, indicating multiple aquifers in the area. In the early 1970's, the U.S. Geological Survey (Muir, 1972, 1980) provided cross sections delineating different aquifers separated by clay confining beds. The clay beds were described as fairly continuous and thick enough to act as barriers to vertical flow between aquifers.

Evidence of saltwater intrusion was first noted in the Pajaro Valley in the early 1940's. The intrusion was probably limited to the shallow aquifer, which reaches a depth of about 200 feet below sea level. Few wells at that time penetrated the deep aquifer, which extends from about 300 to 600 feet below sea level, because an adequate supply of good water was available from the terrace deposits and alluvium.

By the early 1950's, a moderate amount of water-quality data had been collected. The earliest reconstruction and mapping that could be done of saltwater intrusion in the shallow aquifer for the three areas shown on plate 3 was 1951. However, data available before and after that time were used to prepare plate 3. Plate 3 also shows the extent of the saltwater intrusion at the 500- and 100-milligram-per-liter levels in both aquifers in the summer of 1979.

Water-quality tests show a low concentration of chloride in most deep aquifer wells south of the Pajaro River. An exception is the area from north of Bennet Slough southward to Elkhorn Slough. In well 13S/2E-7R1, adjacent to Elkhorn Slough, concentrations of chloride have increased from 86 mg/L in 1956 to more than 700 mg/L in 1980. The area of 500-mg/L chloride concentration shown on plate 3 has been defined on the basis of samples taken from this well and from water-quality information supplied by Capurro Ranch. One well on the Capurro Ranch, drilled to a depth of 356 feet and perforated from 294 to 344 feet, was abandoned because of saltwater. The confining layer above the Aromas Sand is probably absent in parts of the Capurro Ranch.

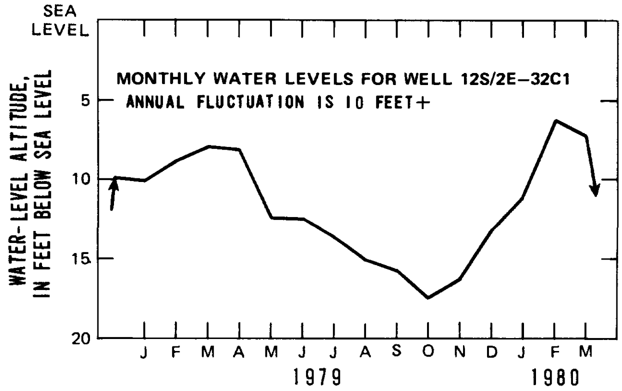
The chloride concentration is high in wells southeast of Elkhorn Slough along Dolan Road in sections 15 and 16 (T. 13 S., R. 2 E). Water levels in wells in this area have been below sea level for several years. At this time, it has not been proved whether the increase in chloride is caused by a saltwater front advancing eastward via shallow coastal aquifers or by intrusion of saline water from adjacent sloughs. The author believes that vertical seepage of tidal marsh water is the mechanism involved. The mud deposits above the Aromas Sand are known to thin and become less effective barriers to vertical percolation of water as they extend up small drainage tributaries adjacent to the slough. This, together with lowered ground-water levels, is probably allowing additional landward movement of tidal marsh water and subsequent downward percolation.

Water Levels

Water levels in the shallower aquifers of North Monterey County have adjusted to pumping stress, as shown in figures 4 and 5 and indicated on plate 2, and show a decline of from 0 to 20 feet during 19 years of record. Water levels in wells west of the granitic ridge typically have continued to decline since the early 1970's and averaged 10 feet of decline by 1980 (fig. 4). This decline has caused water levels to remain below sea level during most of the year in a large part of the North County area (pl. 2), and has permitted additional seawater intrusion.

In the granitic ridge area, water levels in many monitored wells have remained fairly stable over many years, particularly in wells perforated in the overlying Aromas (fig. 5). Although pumping in this area is generally assumed to be from ground water that would otherwise drain to lower levels to recharge the aquifer west of the granitic ridge, some wells may be tapping locally perched water. Wells perforated in deeper confined water within the granitic ridge area tend to show erratic but generally declining water levels. Declining water levels in these wells are attributed to limited ground-water storage in the fractured granitic rock that is being removed more quickly than it can be replaced. Additional monitoring, however, would be needed in the granitic ridge area before conclusions could be reached, because some of the monitored wells may have undergone clogging of perforations due to chemical reactions or silting. Observation wells in the granitic ridge area would need to be cleaned out by means of swabbing, bailing, acidizing, dry-icing, or a combination thereof and tested for production. Successfully restored wells will be useful for monitoring.

Plate 2 shows the potentiometric contours from wells obtaining ground water in the Quaternary Aromas Sand. West of the granitic ridge, contouring indicates a landward movement of the zero contour over the last decade. In the granitic ridge area is a zone of complex hydrology in which contours are drawn only from wells obtaining ground water in the upper Aromas Sand. Between the 0- and 200-foot contours within the zone of complex hydrology, at least two distinct potentiometric head levels are observed in the Aromas Sand depending on the altitude of the perforation interval. Generally, deep wells near the western edge of the zone had water levels near sea level and shallow wells or deep wells to the east had water levels from 150 to over 400 feet in altitude (and these were the wells used in contouring within the zone of complex hydrology). Not shown on plate 2 are many deep wells just west of the 200-foot contour that tap the granitic rock and have erratic but significantly lower heads than wells tapping the overlying Aromas Sand. These heads are generally -50 to 50 feet above sea level. Wells tapping the granitic rock east of the 200-foot contour to its outcrop generally have potentiometric heads comparable to the overlying Aromas Sand.



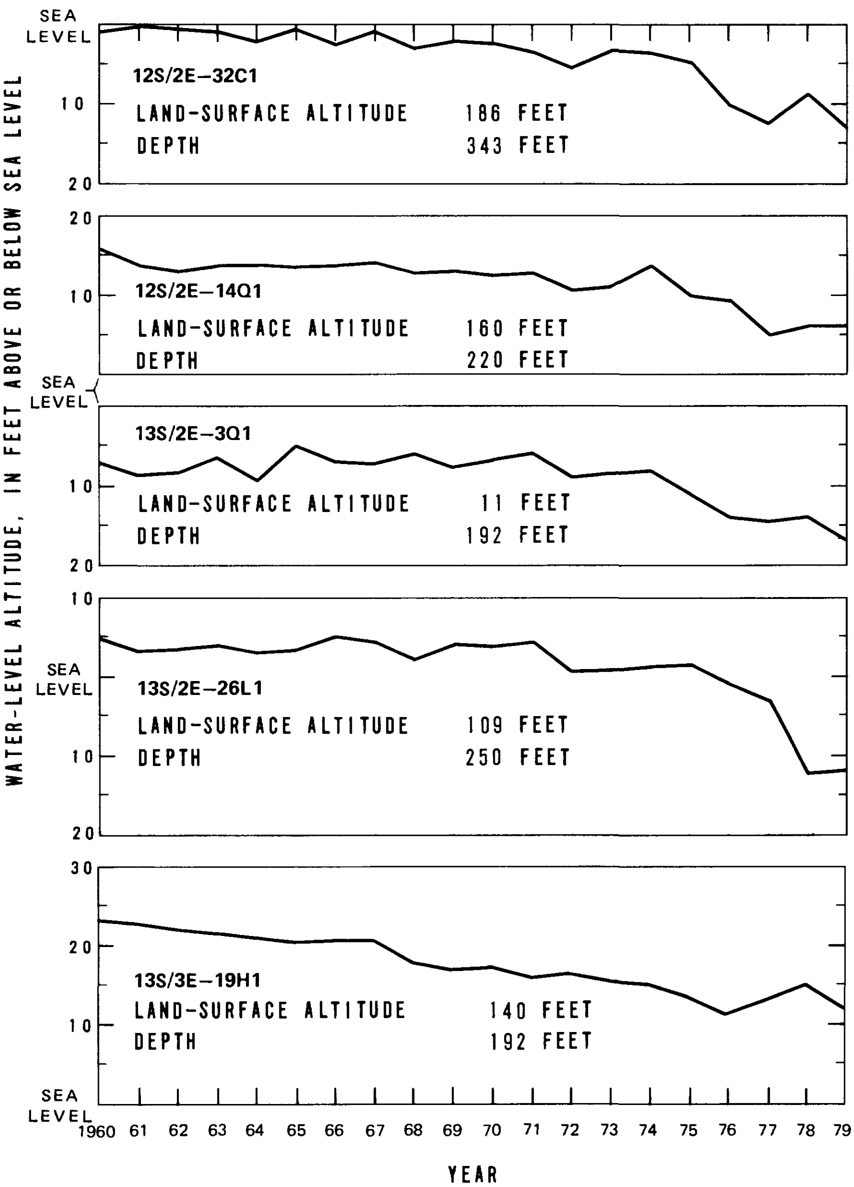


FIGURE 4.—Hydrographs of five wells in the area west of the granitic ridge. Water levels measured in December of indicated year. Land-surface altitude in feet above sea level. Depths are below land surface.

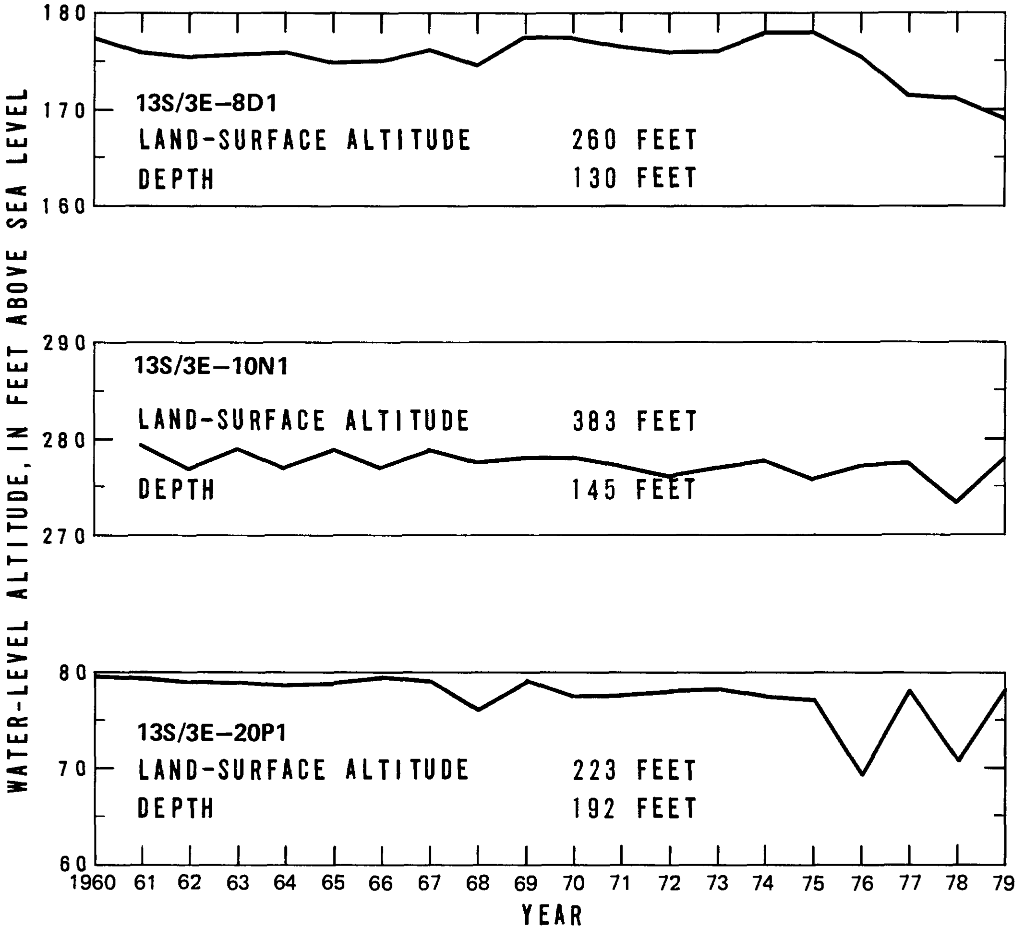


FIGURE 5.—Hydrographs of three wells in the granitic ridge area. Water levels measured in December of indicated year. Land–surface altitude in feet above sea level. Depths are below land surface.

GROUND-WATER DEMANDS

The 1979 ground-water demand for the North Monterey County area was 36,300 acre-ft/yr: this included 31,800 acre-ft/yr for irrigation, 2,700 acre-ft/yr for domestic use, and 1,800 acre-ft/yr for commercial-industrial use. The ground-water demand of 36,300 acre-ft/yr represents an estimate of the amount of water pumped from the ground to meet the water needs of North Monterey County in 1979. As discussed in the section "Ground-Water Yields," some of the water returns to the ground-water system, leaving a net removal (or consumptive use) of 28,000 acre-ft/yr in 1979.

Ground-Water Subareas

To clarify discussion of local ground-water demands and ground-water yields, the North Monterey County area was divided into 16 subareas plus one additional subarea in San Benito County (pl. 3). The area was first divided into six surface-water drainage areas: Pajaro River (hydrologically separated into Aromas highlands and alluvial lowlands), Springfield Coastal Terrace, Elkhorn Slough, Moro Cojo Slough (Castroville area), Tembladero Slough (Prunedale area), and Gabilan Creek (Crazy Horse Canyon area). The Vergeles fault further subdivides the area. Within the granitic ridge area, surface-water drainage areas were further subdivided, somewhat subjectively, on the basis of geology, drainage divides, and land development. Also delineated was the part of Los Carneros Creek in Elkhorn Slough drainage that extends beyond the county boundary.

Irrigated Lands

The Monterey County Planning Department's agricultural land-use map of 1979 was used to define irrigated acreage within each subarea (table 1). Strawberries are separated from other row crops because of their appreciably higher irrigation needs. The farm advisor in Watsonville (Norman Welch, oral commun., 1980) estimates that 70 percent of the area's strawberry growers use furrow irrigation, which requires 4 to 5 acre-ft/yr of water per acre; the remaining 30 percent use drip irrigation, which requires 35 percent less water. Therefore, the weighted mean seasonal unit use of applied irrigation water for strawberries is 4 acre-ft/yr, as compared with the average value of 2 acre-ft/yr for other row crops, as shown in table 2. The row crop composition for the North County area is also shown in table 2 (Monterey County Planning Department, 1978).

Table 1 shows that in the 53,300-acre North County area, 12,500 acres were irrigated with 31,800 acre-ft of ground water in 1979. The California Department of Water Resources (1977) estimated that 13,090 acres were irrigated with 26,800 acre-ft of applied water in 1971. Increased strawberry production accounts for most of the increased water demand.

TABLE 1. - Land-use types (in acres) and irrigation demand (in thousands of acre-feet per year), for 1979

Subarea (pl. 3)	Row crops	Demand	Straw-berries	Demand	Orchards/ nurseries	Demand	Grazing/ dry farming	Other	Total Area	Total Demand
P_1	2,900	5.8	80	0.3	180	0.3	--	620	3,800	6.4
P_2	1,600	3.2	260	1.0	540	1.0	--	120	2,500	5.2
P_3	--	--	80	.3	--	--	60	2,100	2,200	.3
P_4	170	.3	20	.1	100	.2	--	800	1,100	.6
S	3,000	6.1	330	1.3	20	.1	330	4,000	7,700	7.5
E_1	60	.1	980	3.9	160	.6	1,200	4,900	7,300	4.6
E_2	--	--	100	.4	60	.2	--	1,500	1,700	.6
E_3	--	--	--	--	--	--	--	830	830	.0
E_4	--	--	--	--	--	--	800	--	800	.0
E_5	--	--	520	2.1	--	--	300	4,800	5,600	2.1
E_6	--	--	15	.1	180	.3	1,800	1,900	3,900	.4
M	130	.3	910	3.6	--	--	620	4,700	6,400	3.9
G	--	--	--	--	--	--	840	180	1,000	.0
T_1	--	--	25	.1	--	--	60	4,900	5,000	.1
T_2	--	--	--	--	--	--	230	2,400	2,600	.0
T_3	--	--	35	.1	--	--	--	820	860	.1
Total[1]	7,900	15.8	3,400	13.3	1,200	2.7	6,200	34,600	53,300	31.8
Farm irrigation use (percent)		50		42		8	0	0		100
Land use (percent)		15		6		2	12	65		100

[1]Totals for land-use types rounded to hundreds.

TABLE 2. - Weighted mean seasonal unit values of applied irrigation water (in feet per acre per year)

Type	Percent composition	Value (range)
Row crops	100	2
Artichokes	38	2½ (>2)
Lettuce	29	1½ (1½ to 1-3/4)
Cauliflower	9	2 (1½ to 2½)
Brussel sprouts	8	2
Other	16	2
Strawberries	100	4
Furrow irrigation	70	4½ (4 to 5)
Drip irrigation	30	3¼ (3 to 3-3/4)
Orchards	100	1½
Established trees	80	1½ (1 to 1½)
Saplings	20	1½
Nurseries		4 (2 to 6)

Residential Use

The population within each subarea was estimated by dwelling count based on the Monterey County Planning Department land-use map of 1979, and assuming an average of 3.15 people per household (Monterey County Planning Department, 1978). Table 3 shows the population by subarea and domestic water demand based on a per capita water demand of 125 gal/d per person. The California Department of Water Resources (1977) estimated a 1970 population of 13,000 with a water demand of 1,800 acre-ft/yr. The population estimates for both 1970 and 1979 were checked by using Monterey County transportation studies that inventory housing and population by traffic zones within census tracts.

During the 9 years between 1970 and 1979 the population increased by 46 percent to a total of 19,000, and the domestic water demand increased to 2,700 acre-ft/yr. In the early 1970's the California Department of Water Resources had estimated that the population would reach 19,000 by the year 2020. Most of the growth occurred in the southern hilly part of North Monterey County along State Highway 156, and off San Miguel Canyon Road and U.S. Highway 101 near Prunedale.

Commercial-Industrial

Commercial-industrial water demands are summarized in table 3. Most commercial establishments are retail or grocery stores, service stations, restaurants, or offices. Churches, schools, and hospitals were also considered as commercial-industrial. A substantial part of the industrial water demand is used for processing agricultural products. The largest industrial users of ground water from the study area are Kaiser Refractories and Pacific Gas and Electric Company, both located outside the study area at Moss Landing. However, their wells draw water from subareas E_2 and M.

TABLE 3. - Population, and domestic and commercial-industrial water demand

Subarea (pl. 3)	Population 1979	Water demand, in thousands of acre-feet per year: Domestic	Water demand, in thousands of acre-feet per year: Commercial-industrial
P_1	960	0.18	0.01
P_2	158	.02	.13
P_3	731	.10	.001
P_4	586	.08	.02
S	1,166	.16	.24
E_1	2,700	.38	.14
E_2	324	.05	.03
E_3	227	.03	.0
E_4	16	.002	.0
E_5	1,556	.22	.50
E_6	721	.10	.02
M	3,736	.53	.54
G	32	.004	.001
T_1	2,794	.39	.15
T_2	2,378	.34	.02
T_3	964	.14	.01
Total	19,049	2.7	1.8

GROUND-WATER YIELDS

Estimates of ground-water recharge that can be used by county planners to better evaluate ground-water supplies within subareas were made on the basis of few data. Although some assumptions may not be entirely substantiated at this time, as future data on stream discharge and other hydrologic data become available these figures can be revised.

The California Department of Water Resources (1977) has estimated the amount of ground water in storage in the geologic formations of the Quaternary deposits in the North County area. The Department's estimates of storage are shown in table 4 by subarea.

Regional ground-water storage in the Quaternary and younger Tertiary deposits of the North County area makes up a substantial surplus reservoir from which regional pumping sustains annual demands. The regional storage within the Quaternary deposits is about 80 times the current gross water demand and is located principally in the western part of the North County area. Continued withdrawal of this stored water without freshwater replacement, however, will result in lower water levels, smaller well yields, and, in many places, replacement of freshwater by saltwater. An area where ground-water storage is deficient in meeting local pumping stress is the granitic ridge area where thin Quaternary deposits overlie the granitic basement. The granitic ridge comprises about 20 percent of the North County area but contains less than 6 percent of the computed storage. Recoverable ground-water storage is substantially less in the underlying granitic basement rock or older Tertiary units than in the Quaternary deposits as it is limited principally to fracture storage.

In determining whether the North County can meet its current or projected water needs from its ground-water supply, it is necessary to evaluate ground-water recharge over many years. This long-term average annual recharge includes years of both excessive and deficient recharge and provides the best estimate of whether the ground-water system will continue to sustain existing water demands or meet potential ones. The greater the variation in the amount of recharge from year to year, the larger the storage capacity of the ground-water system must be to accommodate pumping stress during the deficient years. In California the ideal storage capacity is generally accepted as being at least three times the annual pumpage (Arvey Swanson, California Department of Water Resources, written commun., 1972; also see "Technical Considerations in Crystalline Rock," fig. 2 of this report). Without substantial storage potential, the estimated ground-water yield cannot equal the average annual recharge, but must approach the minimum annual recharge.

TABLE 4. - Water storage in Quaternary deposits by subarea

Subarea (pl. 3)	Storage (acre-feet)	Subarea (pl. 3)	Storage (acre-feet)
P_1	357,000	E_4	3,200
P_2	[1]196,100	E_5	312,400
P_3	225,300	E_6	[1]135,500
P_4	[1]76,100	M	495,400
S	618,500	G	10,200
E_1	653,100	T_1	117,300
E_2	25,200	T_2	39,800
E_3	5,800	T_3	12,800
Total			2,876,000
			[2]3,283,700

[1]Not included in estimate by California Department of Water Resources (1977).

[2]Includes additional subareas not included in the California Department of Water Resources estimate.

The source of most of the ground water in the near-surface sediments is local rainfall. Figure 6 shows the mean monthly rainfall and the monthly potential evapotranspiration in the North County area. The mean monthly rainfall was determined by distributing the estimated average annual precipitation throughout the year in direct proportion to the mean monthly precipitation recorded over many years at the Watsonville Waterworks weather station. The average annual precipitation for the North County area was estimated within subareas by the Thiessen Method, using existing rainfall stations near the study area, and by drawing lines of equal precipitation (Rantz, 1971). The annual precipitation in each subarea was multiplied by its surface area, and the sum of the product was divided by the total area to obtain an average annual rainfall of 18.3 inches for the North County area. Previous reports have used an average annual rainfall of as much as 19.2 inches. The potential evapotranspiration was obtained by taking the potential as determined by the California Department of Water Resources (1975, table 6), and correlating it with the North County area by using A-pan evaporation measurements at the Santa Rita station and allowing for local climatic variations (California Department of Water Resources, 1975, appendix D). The average annual potential evapotranspiration for the North County area was determined to be 34.1 inches.

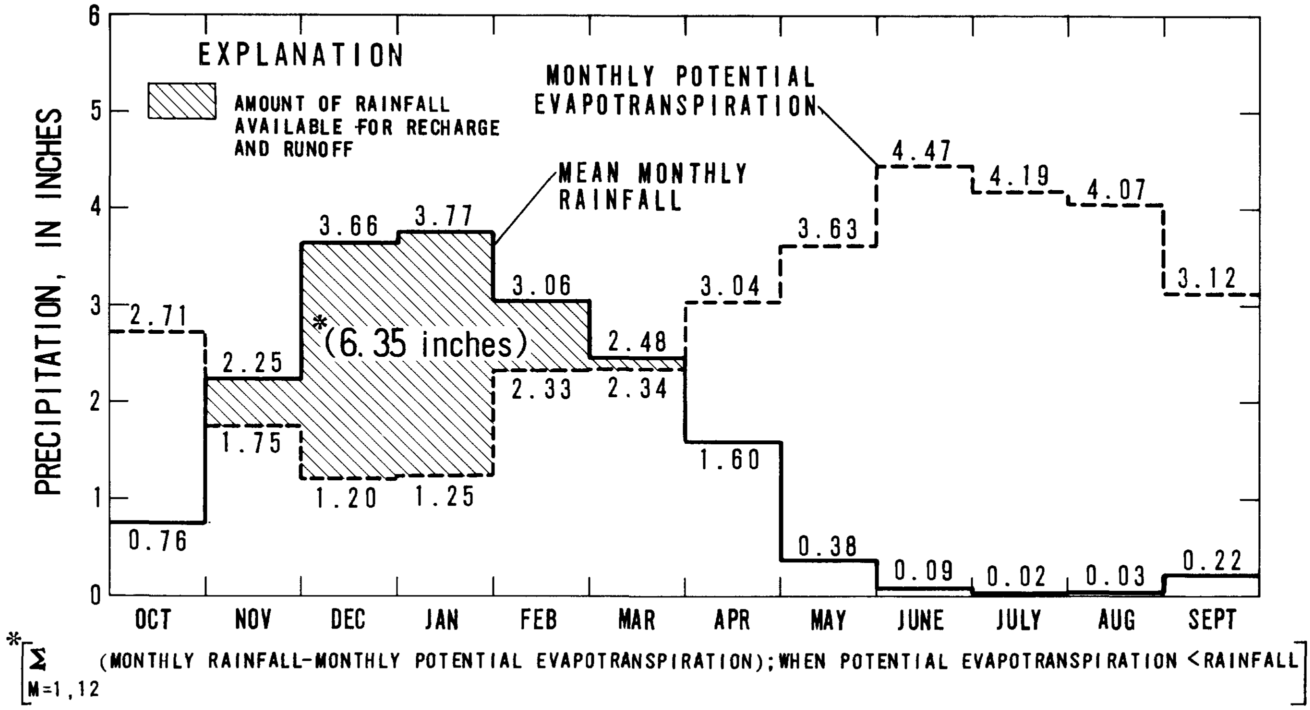


FIGURE 6.—Mean monthly rainfall and monthly potential evapotranspiration in the North County area.

In figure 6, the shaded area under the rainfall curve but above the potential evapotranspiration curve represents rainfall in excess of the actual evapotranspiration each of those months. This excess monthly rainfall generally occurs from November through March and is available for ground-water recharge and runoff to streams. On the average, the amount of rainfall available for recharge and runoff is about 6.35 inches, or 34.7 percent of the total 18.3 inches of average annual precipitation, during a year of normal rainfall and normal monthly distribution. It should be pointed out, however, that deviations from the average are common in this area where annual rainfall at Watsonville, for example, has been within plus or minus 6 inches of its average annual value only 66 years of the last 101 years. Yet, for a long-term estimate of ground-water recharge it is reasonable to make estimates using average values of precipitation.

Few measurements of stream discharge in the North County study area have been recorded. Hydrographs of storm runoff in 1978 have been obtained for a 25.39-square-mile drainage area of Los Carneros Creek by the University of California at Berkeley for a Sea Grant study (Prof. Thomas Dickart, written commun., 1980). Using these partial hydrographs, a hydrograph for the 1978 water year was synthesized for Los Carneros Creek at Johnson Road, based on the annual hydrograph from Pescadero Creek near Chittenden, Calif. The 1978 runoff for Los Carneros Creek at Johnson Road was estimated at 4,100 acre-ft, or 3.0 inches of precipitation during a year having 138 percent of average annual rainfall. It is estimated that during an average rainfall year there would be at most 2.2 inches of runoff in the area, or 12 percent of the average annual precipitation. The Los Carneros drainage area is approximately one-fourth of the total drainage area in the North County.

Hydrograph records were also available for Prunedale Creek at Reese Circle, a much smaller drainage area of 7.33 mi², representing approximately

8 percent of the drainage area in the North County. Although station control was poor for some years, runoff was estimated to be at least 1.0 inch during an average rainfall year, or 5.8 percent of the average annual rainfall.

With consideration of differences in surface geology, topography, and land use, the average annual runoff for the entire North County area is estimated from available stream discharge data to be between 1.0 inch and 2.2 inches of the annual precipitation. The remaining 4.15 to 5.35 inches or 22.7 to 29.2 percent of the total 18.3 inches of average annual precipitation is available for ground-water recharge. Within the elevated hilly region only (fig. 1), the average annual runoff may approach the lowest 1.0-inch value because of losses into the highly porous Aromas Sand.

Based on 2.2 inches of runoff, the minimum annual ground-water recharge from precipitation available to maintain long-term sustained yields from the Quaternary deposits is shown in table 5. For comparison, the estimated net ground-water demand was calculated and subtracted from the minimum annual ground-water recharge from precipitation to determine the amount of excess recharge from precipitation available for underground storage or outflow to other areas. The net water demand was calculated from the gross water demand by assuming: 20 percent of applied irrigation water becomes return flow; 50 percent of domestic water is used for ground-surface applications with a 20 percent return flow; 50 percent of domestic water passes through septic systems with 80 percent return flow; and 35 percent of commercial-industrial water is return flow.

As shown in table 5 the net ground-water demand exceeds the minimum available ground-water recharge from precipitation alone by a maximum of 8,000 acre-ft/yr (or a minimum of 1,500 acre-ft/yr). The most probable estimate of this excess demand is 3,400 acre-ft/yr where the net ground-water recharge from precipitation is realistically 24,600 acre-ft/yr. The most probable value of the ground-water recharge was obtained by assuming that the subareas within the elevated hilly region (fig. 1) have an average annual runoff of 1.0 inch, and the subareas outside the elevated hilly region have an average annual runoff of 2.2 inches.

Over the granitic ridge, subareas E_2, E_3, E_4, T_2, and T_3 have virtually no alternative recharge sources other than local precipitation, whereas subareas T_1 and G might receive some subsurface recharge from the Gabilan Creek drainage area. All these subareas have some excess recharge water to export to adjacent subareas and are, therefore, not considered to be in a state of overdraft. However, concentrated pumping stress (caused by many wells close together) and limited storage result in continued local deficiencies throughout the area even with sufficient recharge from precipitation.

Total combined pumpage north and west of the granitic ridge in subareas P_1, P_2, P_3, P_4, S, E_1, E_5, and M is, however, generally exceeding recharge from precipitation. The pumpage is sustained by the large storage capacity in the subareas. Pumping in these areas is slowly depleting ground-water storage and lowering water levels to sea level or below, causing saltwater intrusion. Recharge by underflow from the Pajaro River valley or the Salinas Valley could supply sufficient water from the Aromas Sand to meet the ground-water demand in these subareas, provided water-level gradients were favorable. In the Pajaro Valley, however, water levels in subareas P_1, P_2, P_3, and P_4 are as low as those in the subareas near the coast. In the Castroville area in the Salinas Valley, water levels are even lower.

Few quantitative data are available for the pre-Quaternary formations which extend under North Monterey County; therefore, no estimates of underground flow were made for these deposits.

TABLE 5. - Minimum ground-water recharge from precipitation during an average water year, gross and net ground-water demand, recharge in excess of demand, estimated storage, and other available sources of recharge in the Quaternary deposits

Subarea (pl. 3)	Minimum ground-water recharge from precipitation	Gross ground-water demand	Net ground-water demand	Recharge in excess of demand available for underground storage or outflow	Estimated storage	Other sources of recharge[1]
	Thousands of acre-feet					
P_1	1.3	6.6	5.3	-4.0	357	Ocean, Pajaro River and Valley recharge, adjacent subareas.
P_2	.9	5.3	4.2	-3.3	196	Pajaro River and Valley recharge; adjacent subareas.
P_3	.8	.4	.3	.5	225	Adjacent subareas.
P_4	.4	.7	.5	-.1	76	Adjacent subareas.
S	2.7	7.9	6.2	-3.5	619	Ocean, adjacent subareas.
E_1	2.5	5.1	4.0	-1.5	653	Ocean, adjacent subareas.
E_2	.6	.7	.5	.1	25	Some storage in adjacent subareas.
E_3	.3	.1	.1	.2	6	Some storage in adjacent subareas.
E_4	.3	<.1	<.1	.3	3	Some storage in adjacent subareas.
E_5	2.0	2.8	2.1	-.1	312	Ocean, adjacent subareas.
E_6	1.3	.5	.3	1.0	136	Adjacent subareas.
E_7	2.1	--	--	<1.5	No est.	Some storage in adjacent subareas.

See footnote at end of table.

TABLE 5. - Minimum ground-water recharge from precipitation during an average water year, gross and net ground-water demand, recharge in excess of demand, estimated storage, and other available sources of recharge in the Quaternary deposits--Continued

Subarea (pl. 3)	Minimum ground-water recharge from precipitation	Gross ground-water demand	Net ground-water demand	Recharge in excess of demand available for underground storage or outflow	Estimated storage	Other sources of recharge[1]
	Thousands of acre-feet					
M	2.2	5.0	3.7	-1.5	495	Ocean, adjacent subareas, and limited recharge from Salinas Valley drainages.
G	.3	<.1	<.1	.3	10	Some storage in adjacent subareas and limited recharge from Salinas Valley drainages.
T_1	1.7	.6	.4	1.3	117	Some storage in adjacent subareas and limited recharge from Salinas Valley drainages.
T_2	.9	.4	.2	.7	40	Some storage in adjacent subareas.
T_3	.3	.3	.2	.1	13	Some storage in adjacent subareas.
Total	20.6	36.3	28.0	-8.0	3,284	Ocean, Pajaro Valley, Salinas Valley.
	[2]26.5			(-1.5)		

[1]See storage interaction, plate 3.
[2]Maximum ground-water recharge from average annual precipitation based on 1.0 inch of runoff.

SUMMARY AND CONCLUSIONS

Ground-water recharge to the Quaternary formations, which include terrace deposits, alluvium, and the upper part of the Aromas Sand, is supplied principally by local rainfall and subsequent underground movement between local subareas. Unfavorable ground-water gradients minimize regional ground-water flow into the North Monterey County area from the Pajaro and Salinas Valleys. Basement features and fault zones preclude any significant ground-water flow into the area from the east. Saltwater is increasingly replacing depleted fresh ground water along the coast where water levels remain below sea level throughout most of the year. Recharge to the granitic rock is from downward movement of water from the overlying Quaternary sediments and from rainfall on the granitic exposure. Water storage in the granitic ridge is limited to the 200-foot-thick weathered zone of the granitic rocks and to an additional 200-foot-thick fractured zone in the solid granitic rock that is hydraulically connected to the surface or overlying sediments.

Estimates of ground-water recharge by subareas indicate that precipitation during average rainfall years is adequate to meet existing pumping needs regionally in the granitic ridge area. Limited ground-water storage makes the area heavily dependent on seasonal rains to maintain local pumping levels. Because of this limited local storage and seasonally fluctuating well yields, the main ground-water concern in the granitic ridge area is one of recharge distribution versus pumping stress distribution coupled with the effective rate of water movement. In a normal rainfall year total recharge within the granitic ridge area can satisfy the total existing pumping needs, but locally concentrated pumping could exceed available recharge. In a dry or drought year, inadequate local storage and a loss of seasonal recharge tend to intensify well-yield problems and may increase well interference between adjacent wells when efforts are made to meet water needs. Individual well yields are reduced as limited ground water stored in the fractured granitic rock is being removed quicker than it can be replaced. In an area such as the granitic ridge, the most efficient use of the water resources is to limit water development to a large number of properly spaced low-yielding wells, such as domestic wells, and to carefully monitor wastewater to prevent degradation. Well density might be limited according to local recharge capabilities on an area-by-area basis. Well density could be determined by controlled development and close monitoring of ground-water conditions regionally, or by engineering studies for individual areas, or both.

In contrast, ground-water recharge is not adequate to meet the water demands in the more heavily pumped areas west of the granitic ridge (see unshaded valleys and coastal areas on pl. 3), though ground-water storage is plentiful. Most of the ground-water storage is in this part of the North County. The main ground-water concern in the areas west of the granitic ridge is the gradual removal of fresh ground water in storage and its replacement with saltwater as water levels drop below sea level. This causes higher concentrations of chloride and dissolved solids in wells along the coast. Saltwater marshes, estuaries, and sloughs are the major sources of saltwater recharge used to maintain ground-water storage levels at or below sea level in the shallow aquifers. In deeper Quaternary aquifers with deteriorating water quality, it is not known whether vertical percolation of overlying saltwater through sediments and corroded well casings is the major source of contamination or whether saltwater is principally advancing from the aquifer outcrop areas under Monterey Bay. At greater depths the older Tertiary units are known to contain high concentrations of salts.

Hydrologic information collected in the granitic ridge area, such as water-level measurements, applies only to the immediate area monitored. The area has complex ground-water hydrology. Water-level differences ranging from more than 100 feet to less than a foot can occur locally between adjacent wells completed in granitic rocks and overlying Quaternary deposits. Pumping stress between adjacent wells may be partially or completely isolated due to variations in vertical permeabilities. Recharge sources to adjacent wells might also be separate or distantly coupled. The nature of the hydraulic relationship between the granitic rocks and the overlying Quaternary deposits is a local relationship that can be understood by monitoring selected sites to deduce basic hydrolgic principles that may apply regionally throughout the granitic ridge area. Therefore, in designing a well network in the granitic ridge area, it is better to obtain limited hydrologic information at a few selected sites with a higher degree of certainty, then to take a more statistical regional approach with large quantities of less meaningful data. Changes in water levels within and between units can be best determined by frequently monitoring water levels at specific sites in defined areas. Some wells could be equipped with continuous water-level recorders to produce a detailed hydrograph. Cleaning and test-pumping of wells selected for monitoring purposes would increase the probabilty of good hydraulic coupling to the water-bearing formation.

Deeper geologic units of the late Tertiary and early Quaternary Periods, undeveloped at present, may have substantial potential for ground-water development west of the granitic ridge area provided that increased pumping stress does not cause water of unusable quality to migrate into these units. These geologic units consist of the upper part of the Purisima Formation and the lower part of the Aromas Sand west of the granitic ridge, which is known to contain large quantities of additional ground water. The reasons for presenting the upper Tertiary as a potential aquifer for the area even with its proximity to the ocean are several: First, the outcrop is several miles off shore (3 or 4 miles; Greene, 1970). Second, the unit is extensive and thick and extends inland up the Pajaro and Salinas Valleys to tap potential recharge from overlying aquifers, rivers, and direct precipitation at outcrops. Third, it is known to be a good aquifer north of Monterey Bay in the nearby Soquel-Aptos area. Fourth, some initial drilling and pumping indicates water of usable quality. All these reasons point to a cautious optimism. If the Tertiary units are explored and then developed for usable ground water until degradation results or other adverse impacts occur, estimates of recharge and transmissivity within the units could be documented during this development process. However, the proximity of the ocean and the remoteness of the recharge source areas up the river valleys may limit extensive development of water from these units in the study area. Another limiting factor is the uncertainty as to the degree of the hydraulic continuity of this unit with overlying aquifers or the ocean. Connate water of high salinity may also be a problem. Therefore, until additional well drilling and testing is completed in the upper part of the Purisima Formation and the lower part of the Aromas Sand, any statements about storage potential or sustained yields in these units would be speculative at best. The older Tertiary units are consolidated and for the most part deeply buried and have little potential other than for small yields from sandstone units.

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