Ground-Water Resources of the Florida Mesa Area, La Plata County, Colorado

by S.G. Robson and Winfield G. Wright

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	0.4047	hectare
acre foot (acre-ft)	1,233	cubic meter
acre foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot (ft^3)	28.32	liter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Other abbreviations used:

microgram per liter (µg/L)

milligram per liter (mg/L)

Sea level: In this report "sea level" refers to the 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 Sea Level Datum of 1929.

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Abstract

Rapid population growth in La Plata County, Colorado, has increased the demand for ground water in the Florida Mesa area. This report was prepared in cooperation with La Plata County to provide needed information about the geology, extent, thickness, and depth of the aquifers in the area; sources of ground-water recharge and discharge; direction of ground-water movement; water-level changes; and water quality in the alluvial and bedrock aquifers.

Ground water in the study area is present in bedrock formations and in terrace deposits on Florida Mesa. Porous or fractured sandstone beds that contain bedrock aquifers are present near land surface along the northern margin of the study area and are present at depths less than 3,000 feet throughout the study area. Terrace deposits as much as 200 feet thick and consisting of gravel, sand, silt, and clay are present on Florida Mesa. The terrace deposits and the upper part of the underlying Animas and Nacimiento Formations form the principal aquifer under the mesa.

Ground water under the mesa is supplied from precipitation and irrigation water. A small part of the precipitation and irrigation water on the mesa percolates to depth in the soil and recharges the aquifer. Irrigation water is the largest source of this recharge.

Water levels in the aquifer can decline because of a reduction in irrigation recharge, or because of an increase in well pumping. Because irrigation recharge is so much larger than pumping, changes in recharge can have a much larger effect on ground-water levels than can changes in pumping. Factors that tend to increase ground-water recharge and thereby increase or maintain ground-water levels include: maintaining large rates of surface-water diversion onto Florida Mesa, reducing surface flow off the mesa, increasing use of ponds and spreading basins to promote infiltration, and irrigating by use of flood irrigation.

The general direction of ground-water movement on the mesa is from the northern part of the mesa to the south, southwest, and southeast. Most ground water discharges from the mesa to the Animas and Florida Rivers through seeps and springs along the margin of the mesa. Winter water levels in wells generally are lower than summer water levels because of the lack of irrigation recharge during the fall and winter. Potable water of low dissolved-solids concentration is present in the shallow parts of most aquifers.

INTRODUCTION

Rapid population growth in La Plata County, Colorado, has caused increased reliance on ground water as a source of supply for suburban and rural residents. In the Florida Mesa area to the southeast of Durango, water is pumped from a complex series of alluvial aquifers in shallow terrace deposits and from deeper bedrock aquifers. In much of the area, the alluvial aquifers are thin and can be dewatered by moderate water-level declines. Knowledge of the nature and extent of the alluvial and bedrock aquifers, the sources of recharge and discharge for the aquifers, and the effects of ground-water withdrawal on water levels in the aquifers is vital, if management of the area's water resources is to ensure continued availability of a dependable water supply.

Purpose and Scope

This report presents the results of a study of the geohydrology of the Florida Mesa area undertaken by the U.S. Geological Survey in 1994 and 1995 in cooperation with La Plata County. The study was designed to provide information on geology, extent, thickness, and depth of various water-bearing formations in the area, sources of ground-water recharge and discharge, direction of ground-water movement, water-level changes, and water quality of the aquifers. The study includes alluvial aquifers on terraces (Florida Mesa) and bedrock aquifers in consolidated rocks.

Location of Study Area

The 182-mi^2 study area is in southwestern Colorado (fig. 1) within the drainage area of the Florida and Animas River Valleys. The eastern, western, and southern boundaries of the study area are arbitrary; the irregular northern boundary is the northern extent of the oldest rock unit that is considered here to be an aquifer (the Dakota Sandstone). The Florida Mesa extends over an approximate 39-mi^2 area and is a principal topographic feature in the study area. The hogback ridges and intervening valleys along the northern margin of the study area form the northern rim of the San Juan Basin of Colorado and New Mexico.

GEOHYDROLOGIC UNITS

Ground water in the study area is present in consolidated rocks of Cretaceous and Tertiary age and in unconsolidated sediments of Quaternary age (table 1). Cretaceous rocks crop out in a series of northeast-southwest-trending hogback ridges and intervening valleys (fig. 2) along the northern margin of the study area and dip southward into the northern rim of the San Juan Basin. Sandstones tend to be more resistant to weathering than shales; as a result, sandstone units commonly form ridges and steep hillslopes with shale units forming the intervening valleys. Younger (Tertiary) rocks crop out or subcrop under unconsolidated sediments in most of the central and southern part of the study area and are relatively flat lying. The Cretaceous and Tertiary rocks consist of interlayered beds of sandstone, siltstone, and shale; porous or fractured sandstones form the principal water-yielding units (aquifers); relatively impermeable shales form confining units between aquifers.

Beds of water-yielding sandstone are present in the Dakota Sandstone, Point Lookout Sandstone, Cliff House Sandstone, Pictured Cliffs Sandstone, Farmington Sandstone Member of the Kirtland Shale, and in the Animas, Nacimiento, and San Jose Formations. The sandstones in the Dakota, Point Lookout, Cliff House, and Pictured Cliffs Sandstones are of marine or beach origin, having been deposited during the transgression (advance) or regression (withdrawal) of the shallow inland sea that occupied the central United States during Cretaceous time. These sandstones tend to be thicker, more extensive, and better sorted than the fluvial sandstones of the Farmington Sandstone Member and the Animas, Nacimiento, and San Jose Formations. These fluvial sandstones were deposited in a stream environment and are interbedded with siltstone, shale, and coal.

Thick confining units that are almost impermeable and generally do not yield water to wells are formed by the marine shales of the Mancos Shale and the Lewis Shale. Thinner confining units of slightly more permeable fluvial shale, coal, and thin sandstone beds are present in the Menefee Formation, Fruitland Formation, lower and upper shale members of the Kirtland Shale, and in numerous local shaly beds in the Animas, Nacimiento, and San Jose Formations.

The bedrock formations exposed in the northern part of the study area dip southward and extend into the subsurface under the Florida Mesa and into New Mexico. The subsurface shape and altitude of these formations are indicated by the structural contours drawn on the top of the Dakota Sandstone (fig. 3), the top of the Cliff House Sandstone (fig. 4), the top of the Pictured Cliffs Sandstone (fig. 5), and the base of the Farmington Sandstone Member (fig. 6). More closely spaced contours indicate steeply dipping rocks; widely spaced contours indicate more flat-lying rocks. Porous or fractured sandstones in the Dakota, Point Lookout, Cliff House, Pictured Cliffs, and Farmington Sandstones could be important sources of ground water if the sandstones are shallow enough to be tapped by a water well and contain potable water.

The depth to the sandstones mapped in figures 3–5 is indicated by the isobath line on each figure. North of the isobath, the sandstones generally are less than 3,000 ft below land surface and might be shallow enough to be reached by a water well. South of the isobath, the sandstones generally are deeper than 3,000 ft. The older sandstone units crop out farther to the north and dip to greater depths in the basin than do the younger sandstone units. Thus, the Dakota Sandstone is less than 3,000 ft deep only in a narrow band along the northernmost part of the study area (fig. 3). By contrast, the younger Farmington Sandstone Member of the Kirtland Shale crops out farther south in the study area and is less than 3,000 ft deep almost everywhere in the study area (fig. 6). The Animas, Nacimiento, and San Jose Formations overlie the Kirtland Shale and also are present at depths less than 3,000 ft. Figures 3–6 indicate that potential bedrock aquifers are present at depths less than 3,000 ft everywhere in the study area.

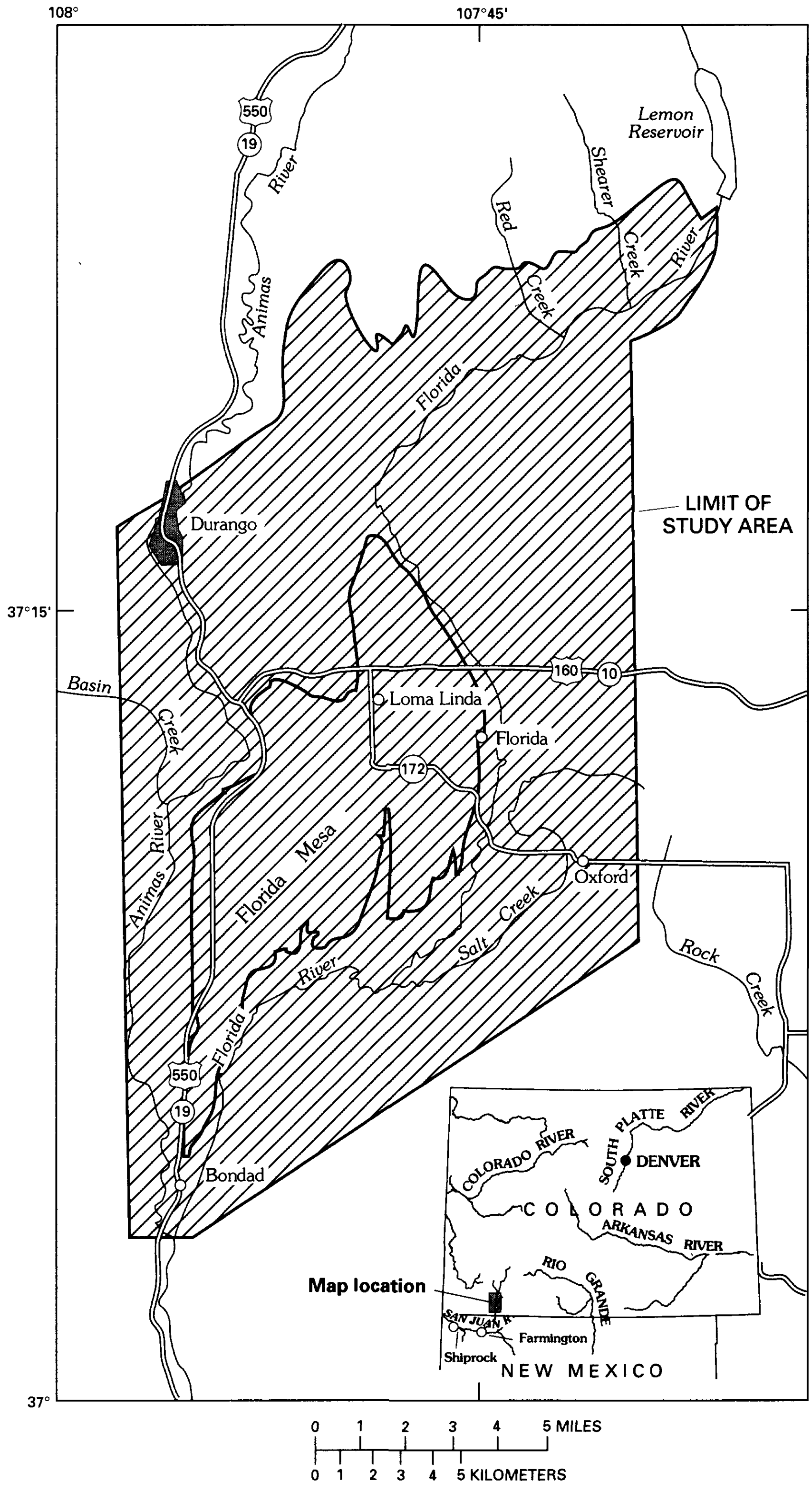

Figure 1. Location of the study area.

Table 1. Description of geologic units and their physical and hydrologic properties

System	Series	Geologic unit	Symbol	Maximum thickness (feet)	Physical characteristics	Hydrologic characteristics
QUATERNARY	Holocene	Flood-plain deposits	Qa	50	Clay, silt, sand, gravel, and boulders. Generally poorly sorted and confined to present-day stream valleys. Includes low-level terraces, alluvial fans, and eolian materials.	Reported well yields are as much as 25 gal/min, but average 10 gal/min. Water quality is variable, depending on underlying rock and sources of alluvial material. Dissolved-solids concentrations range from about 300 to 1,000 mg/L, but 400 mg/L is common.
		Landslide deposits	Ql	Unknown	Unsorted, shattered rock mass and soil largely derived from slope failure of the Dakota Sandstone.	No data.
	Pleistocene	Terrace deposits	Qt	200	Clay, silt, sand, gravel, and boulders. Sediments are poorly sorted, with coarser materials being well rounded. Includes higher level stream valleys, eolian materials, and remnants of alluvial fans.	Reported well yields are as much as 50 gal/min, but generally range from 5 to 10 gal/min. Dissolved-solids concentrations range from about 300 to 1,000 mg/L, but 400 mg/L is common.
TERTIARY	Eocene	San Jose Formation	Tsj	2,500	Sandstone, shale, and conglomerate. Sandstones are arkosic and massive and are interbedded with red, maroon, and gray shales.	Reported well yields are as much as 75 gal/min; yields of 1 to 10 gal/min are more common. Dissolved-solids concentrations range from 800 to 1,600 mg/L.
	Paleocene	Nacimiento Formation	Tn	1,300	Sandstone and shale. Sandstones are arkosic, white, medium to coarse grained, and are interbedded with black and gray shale.	Reported well yields commonly range from 2 to 15 gal/min. Dissolved-solids concentrations range from 200 to 2,500 mg/L, but 500 mg/L is common.
TERTIARY / CRETACEOUS	Paleocene / Upper Cretaceous	Animas Formation	TKa	1,400	Varicolored shale, with interbedded breccia, conglomerate, and tuffaceous sandstone. The sandstone varies from light to rusty brown and contains abundant silicified wood and clay balls. Upper part grades into Nacimiento Formation.	Reported well yields are as much as 75 gal/min, but yields of 1 to 10 gal/min are more common. Dissolved-solids concentrations range from 200 to 2,500 mg/L, but 500 mg/L is common.
CRETACEOUS	Upper Cretaceous	Kirtland Shale: Upper shale member	Kk	500	Sandy shale and interbedded light-gray sandstone.	No data.
		Kirtland Shale: Farmington Sandstone Member	Kk	500	Sandstone, light gray, fine to medium grained, massive, interbedded with siltstone and shale.	Reported well yields of 10 gal/min.
		Kirtland Shale: Lower shale member	Kk	500	Shale, dark gray.	No data.
		Fruitland Formation	Kf	300	Varying proportions of interbedded sandstone, shale, and coal. The fine- to medium-grained sandstone beds, which are gray, brown, and olive in color, grade laterally and vertically into shales and siltstones. The upper sandstone beds are well indurated and form resistant ledges.	Well yields are estimated to be less than 5 gal/min. Dissolved-solids concentrations range from 400 to 6,000 mg/L.

Table 1. Description of geologic units and their physical and hydrologic properties--Continued

System	Series	Geologic unit	Symbol	Maximum thickness (feet)	Physical characteristics	Hydrologic characteristics
CRETACEOUS	Upper Cretaceous	Pictured Cliffs Sandstone	Kpc	300	Sandstone, light-olive gray to grayish orange and orange, well sorted. Fine to medium grained, medium to thick bedded, and cliff-forming. Interbedded with small amounts of shale and siltstone.	Reported well yields are as much as 5 gal/min. Dissolved-solids concentrations range from 222 to 1,830 mg/L.
		Lewis Shale	Kl	1,800	Shale, light to dark gray and black. Marine origin. Contains interbeds of light-gray sandstone, sandy to silty limestone, and several calcareous concretions.	Reported well yields are as much as 3 gal/min. Dissolved-solids concentrations range from 428 to 3,370 mg/L.
		Mesaverde Group: Cliff House Sandstone	Kch	350	Gray, calcareous, marine sandstone, and silty shale; crossbedded and massive in places. Sandstones are very fine to fine grained and well sorted.	Reported well yields are as much as 17 gal/min, but yields of 5 to 10 gal/min are more common. Dissolved-solids concentrations range from 250 to 3,500 mg/L.
		Mesaverde Group: Menefee Formation	Kmf	350	Varying proportions of light-gray sandstone, siltstone, and shale with several interbedded coal seams.	Reported well yields are as much as 15 gal/min. Dissolved-solids concentrations range from 210 to 7,170 mg/L.
		Mesaverde Group: Point Lookout Sandstone	Kpl	400	Light-gray to brown marine sandstone, massive and cliff-forming. Contains interbedded siltstone and shale in the lower part.	No data; well yields and water quality may be similar to well yields and water quality from Cliff House Sandstone.
		Mancos Shale	Km	1,900	Dark-gray silty and sandy marine shale. Contains some interbedded sandstones and limestone. Lower 200 ft is calcareous and locally fossiliferous.	Yield from one well reported as 1 gal/min. Dissolved-solids concentrations range from 600 to 5,000 mg/L.
	Upper and Lower Cretaceous	Dakota Sandstone	Kd	200	Sandstone, light gray to yellowish brown, with interbedded siltstone, black carbonaceous shale, and coal. Contains many conglomerate lenses near the base.	Reported well yields are as much as 5 gal/min. Dissolved-solids concentrations may range from 270 to 440 mg/L.

Modified from Brogden and others (1979)

The Animas Formation, its approximate lateral equivalent the Nacimiento Formation, and the San Jose Formation are exposed at land surface throughout most of the central and southern parts of the study area beyond the Florida Mesa (fig. 2). On the mesa, terrace deposits overlie the Animas and Nacimiento Formations, which were eroded prior to deposition of the terrace deposits. The eroded surface of the top of the Animas and Nacimiento Formations slopes to the south and southwest and ranges in altitude from about 7,150 to 6,250 ft (fig. 7). An upper bench on the bedrock surface extends over most of the central and eastern parts of the mesa; a lower bench extends along the southwestern margin of the mesa near Highway 550.

Unconsolidated sediments consisting of cobbles, gravel, sand, silt, and clay are present on numerous terraces formed by the ancestral Animas and Florida Rivers. The Florida Mesa is capped by the largest and oldest of these terrace deposits, parts of which are saturated and yield water to wells. The terrace deposits on the mesa range in thickness from zero at the edge of the mesa to as much as 200 ft in the west-central part of the mesa (fig. 8). Most of the terrace deposits on the eastern part of the mesa are less than 50 ft thick.

Many smaller terraces that are topographically lower (and thus, younger) than the Florida Mesa are located along the margins of the Animas and Florida River Valleys. The youngest terraces merge with the flood-plain deposits in the valley bottoms and have been mapped (Zapp, 1949; Barnes, 1953; Barnes and others, 1954; Moore and Scott, 1981) as part of the flood-plain deposits (fig. 2). Most of the terrace deposits above the valley bottoms are not important sources of ground water because the deposits are small and generally are unsaturated. Flood-plain deposits consist of unconsolidated cobbles, gravel, sand, silt, and some clay and commonly are 10 to 50 ft thick. These deposits are important sources of ground water only in local areas where they are close enough to a stream to have a large saturated thickness. Most of the wells drilled in flood-plain deposits also are completed in the underlying Animas or Nacimiento Formations.

GROUND-WATER CONDITIONS

Ground water in the study area moves through the aquifers from areas of recharge to areas of discharge. Changes in recharge or discharge can cause fluctuations in the water levels in wells and can cause changes in the direction of ground-water movement and in the saturated thickness of an aquifer.

EXPLANATION

QUATERNARY	Qa	FLOOD-PLAIN DEPOSITS
	Ql	LANDSLIDE DEPOSITS
	Qt	TERRACE DEPOSITS
TERTIARY	Tsj	SAN JOSE FORMATION
	Tn	NACIMIENTO FORMATION
TERTIARY AND CRETACEOUS	TKa	ANIMAS FORMATION
CRETACEOUS	Kk	KIRTLAND SHALE
	Kf	FRUITLAND FORMATION
	Kpc	PICTURED CLIFFS SANDSTONE
	Kl	LEWIS SHALE
	Kch	CLIFF HOUSE SANDSTONE
	Kmf	MENEFEE FORMATION
	Kpl	POINT LOOKOUT SANDSTONE
	Km	MANCOS SHALE
	Kd	DAKOTA SANDSTONE

——— CONTACT

Figure 2. Geology of the study area.

Recharge and Discharge

Rainfall and snowmelt are the principal sources of natural recharge to aquifers in the study area. However, these sources generally supply only small volumes of water to the aquifers because annual precipitation is small and runoff, evaporation, and transpiration divert much of the water before it can percolate to sufficient depth to recharge an aquifer. However, the small rates of natural recharge are the principal source of recharge to the confined aquifers present in the deeper sandstone units. Recharge to the deeper confined aquifers (such as those in the interval from the Dakota Sandstone to the Farmington Sandstone Member) occurs only near the area of outcrop of the sandstone, as indicated by the precipitation arrows shown in figure 9A. In deeper parts of the basin, thick confining layers above and below the aquifers prevent most direct water movement to or from the land surface. On Florida Mesa and in the outcrop of the Animas, Nacimiento, and San Jose Formations, the shallow aquifer is not overlain by thick confining layers, and precipitation recharges the aquifer over a broad area, as indicated by the widespread precipitation arrows shown in figure 9B.

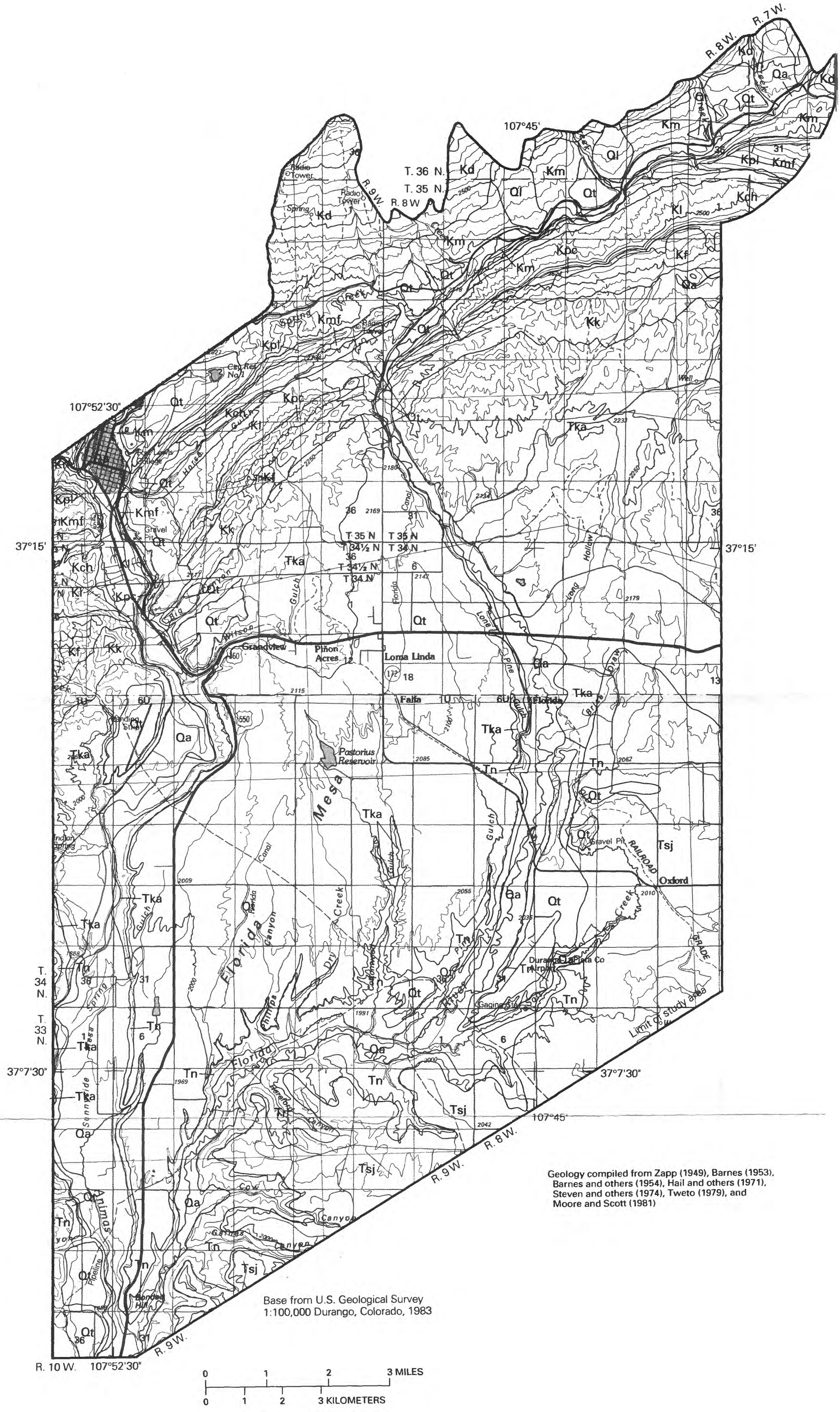

Figure 2. Geology of the study area--Continued.

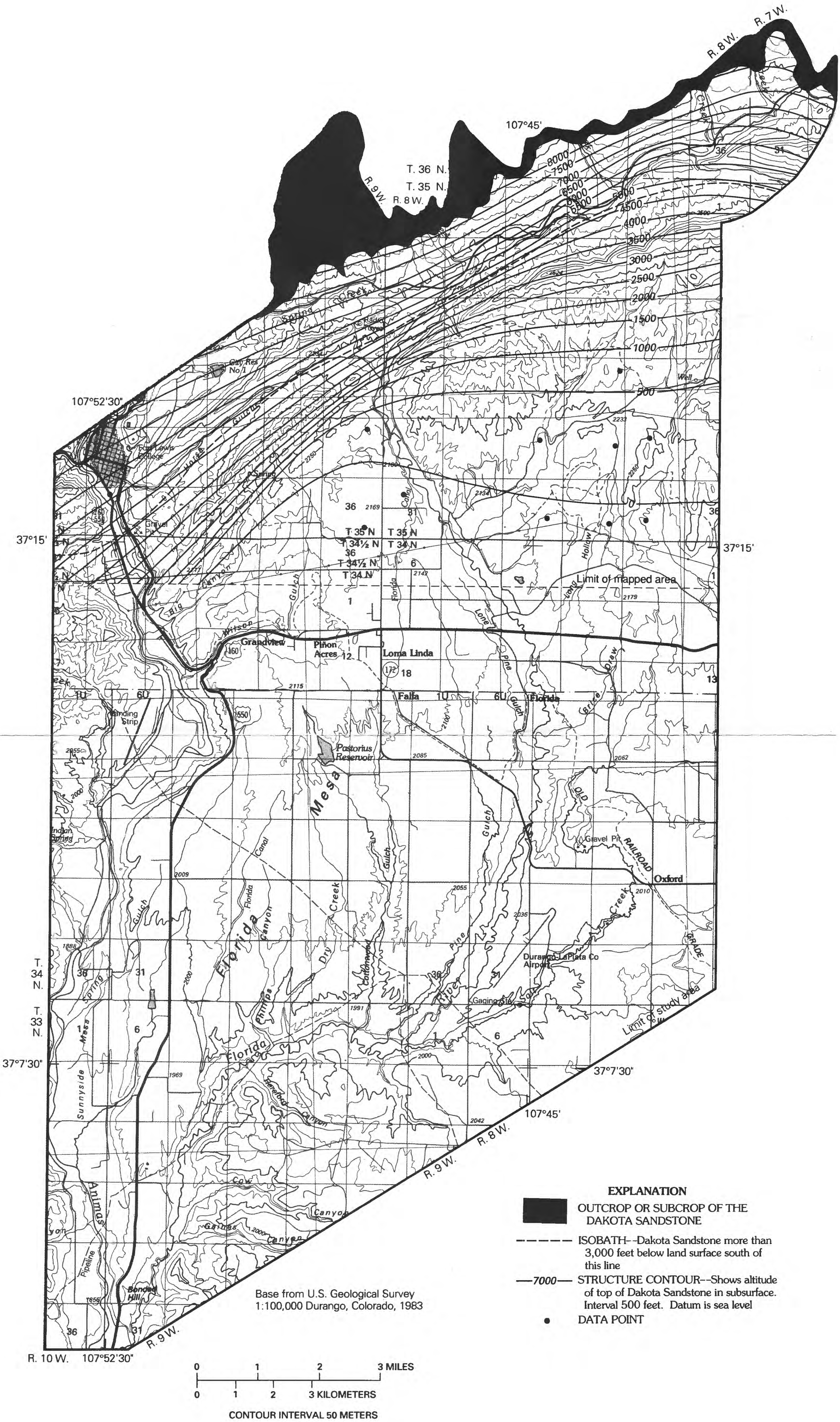

Figure 3. Altitude and configuration of the top of the Dakota Sandstone.

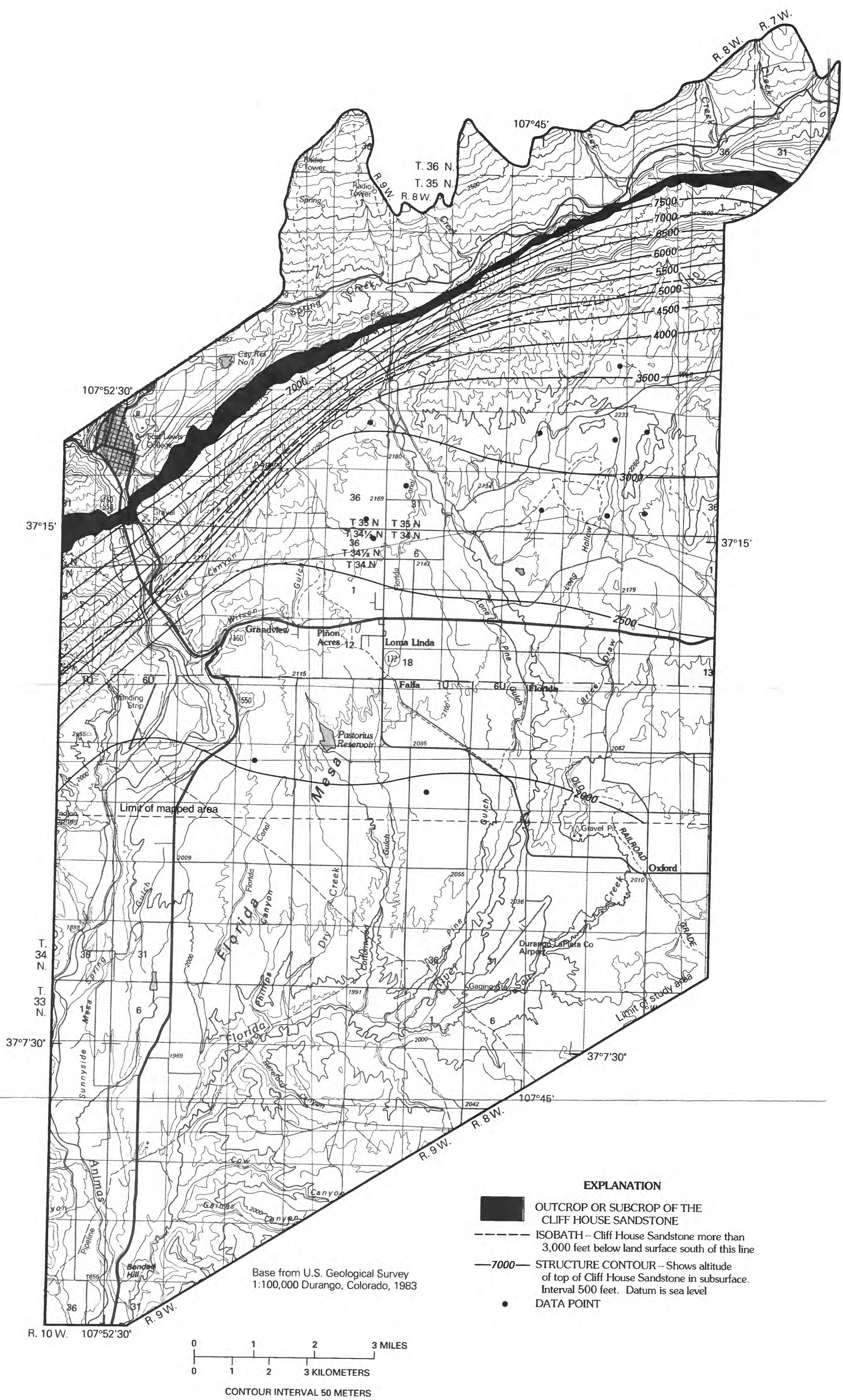

Figure 4. Altitude and configuration of the top of the Cliff House Sandstone.

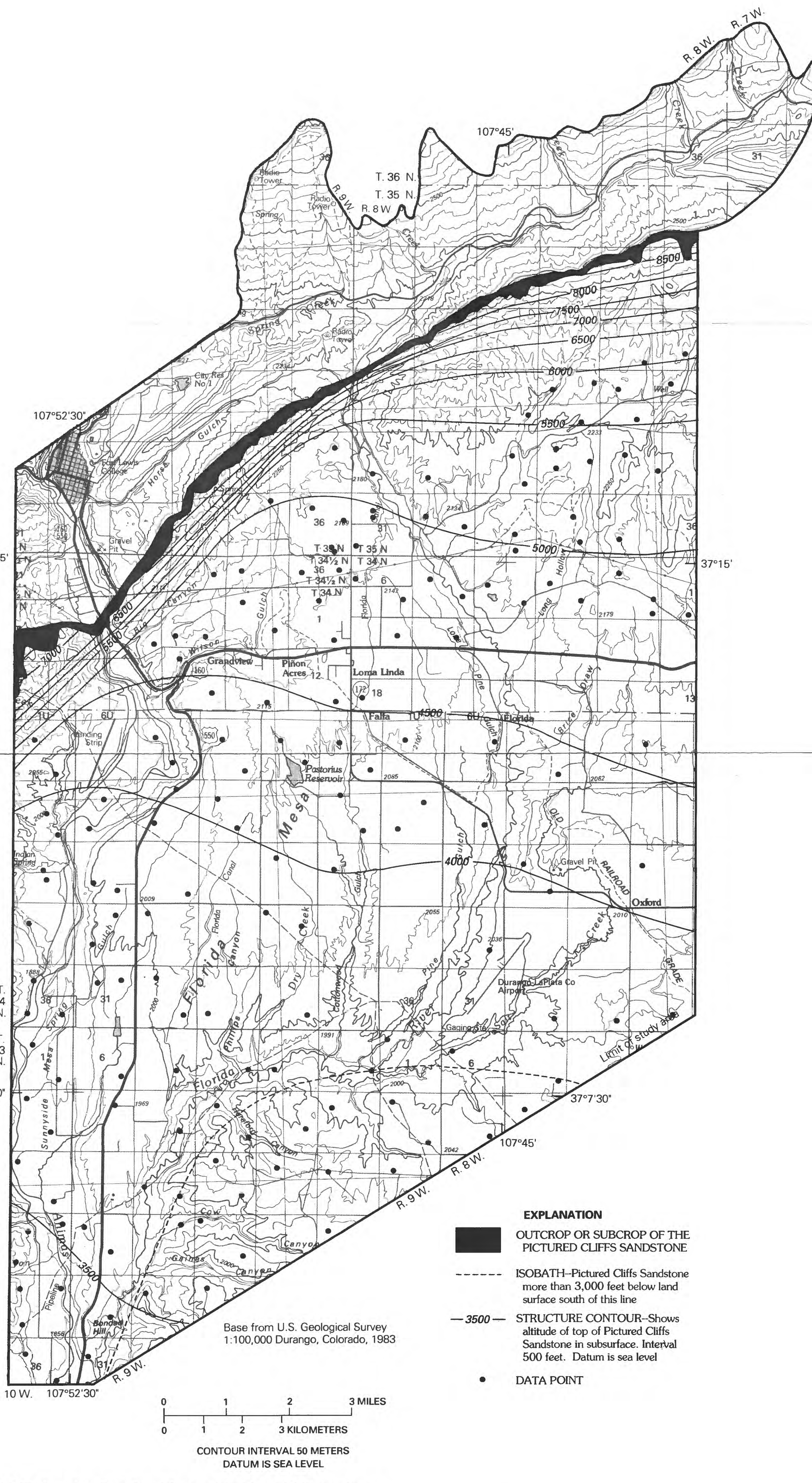

Figure 5. Altitude and configuration of the top of the Pictured Cliffs Sandstone.

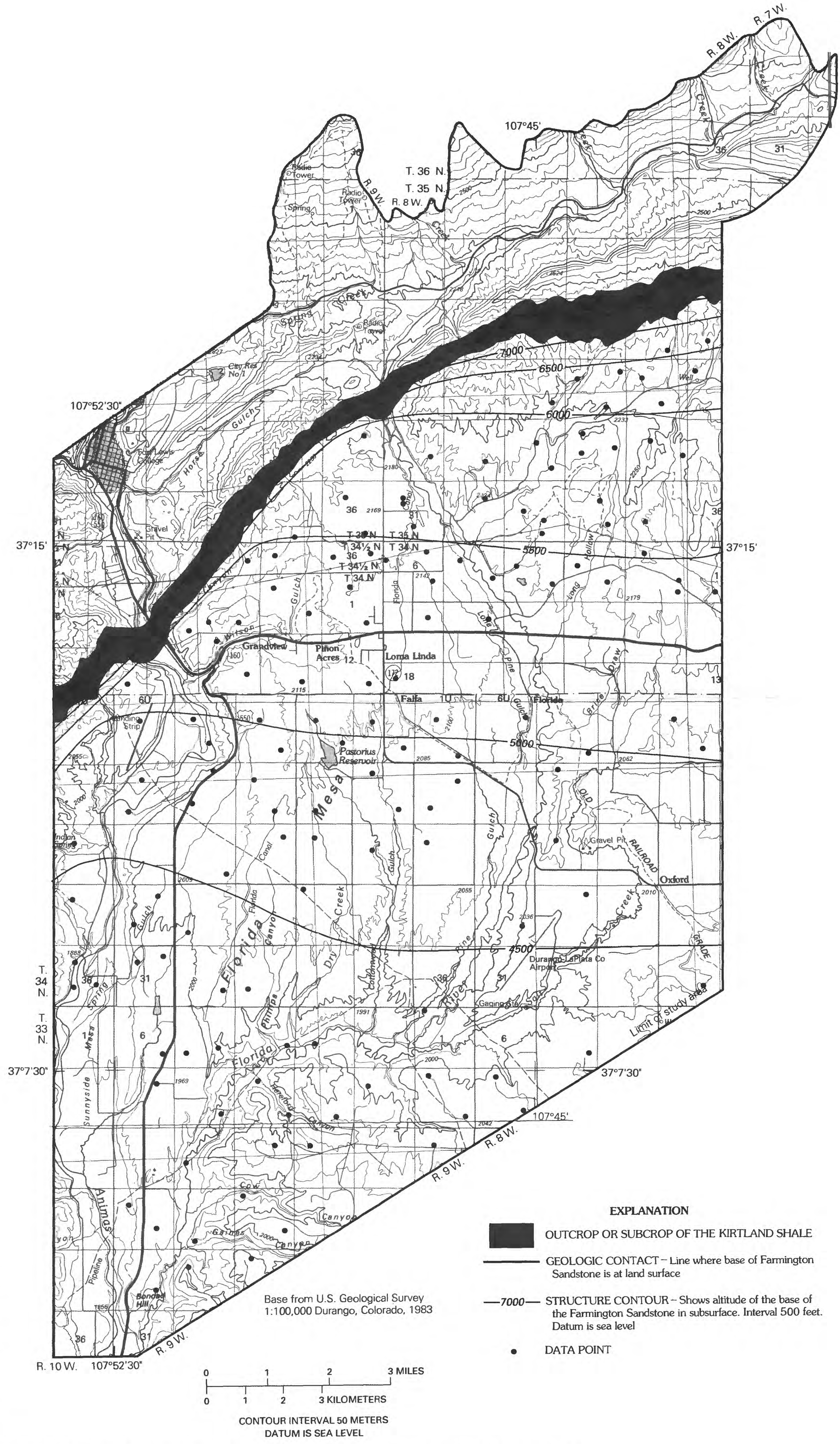

Figure 6. Altitude and configuration of the base of the Farmington Sandstone Member of the Kirtland Shale.

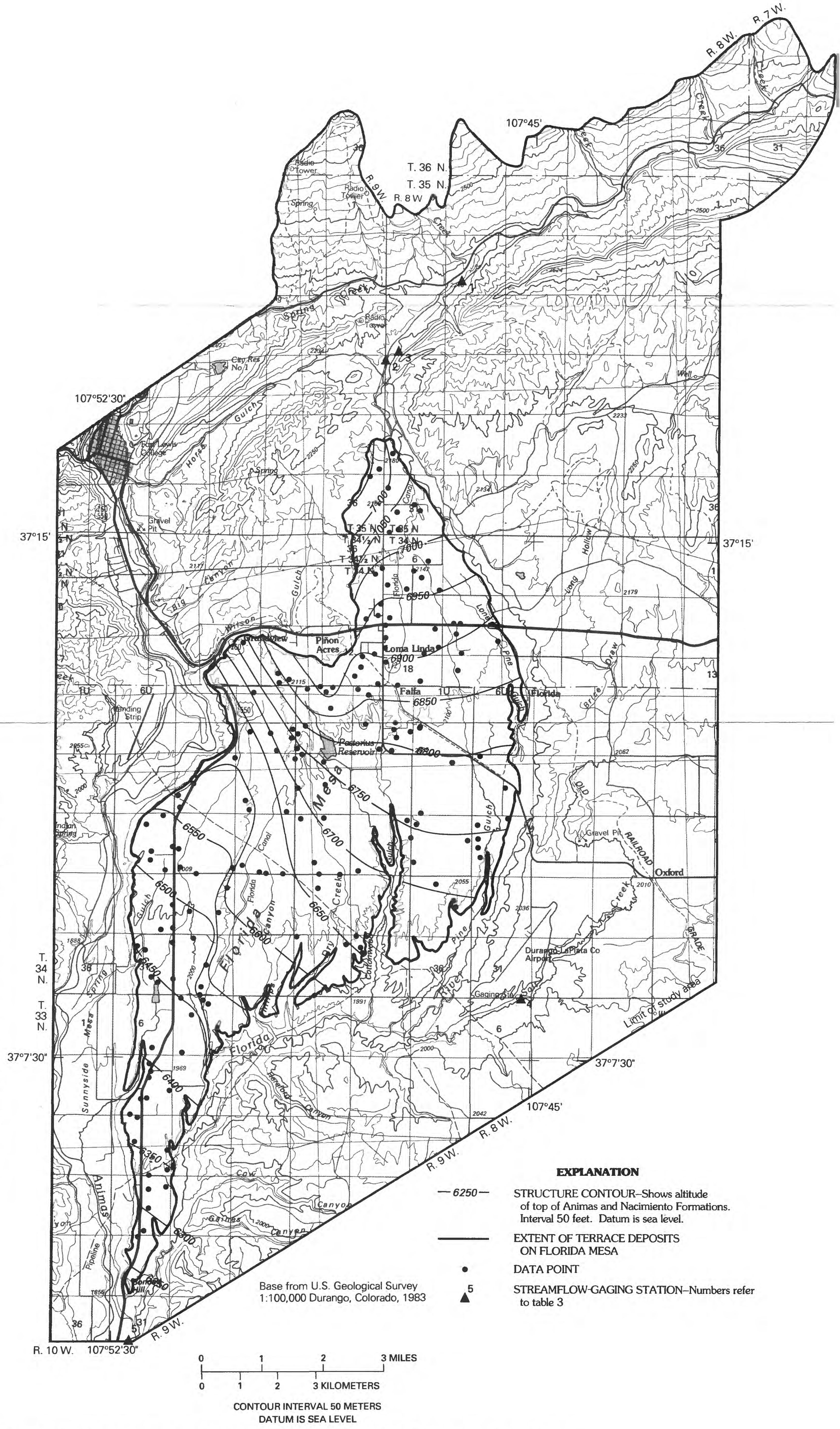

Figure 7. Altitude and configuration of the top of the Animas and Nacimiento Formations on Florida Mesa.

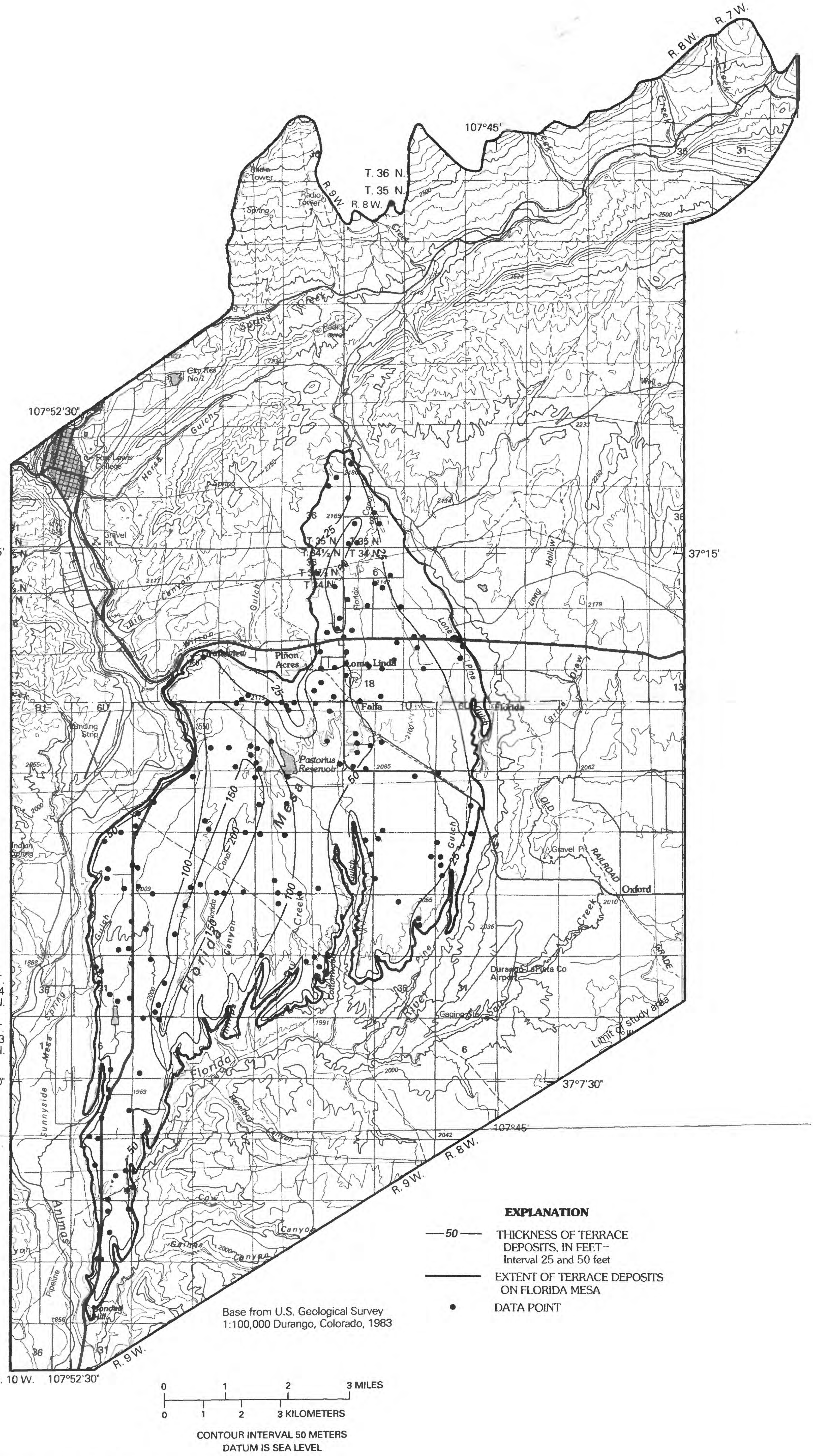

Figure 8. Thickness of the terrace deposits on Florida Mesa.

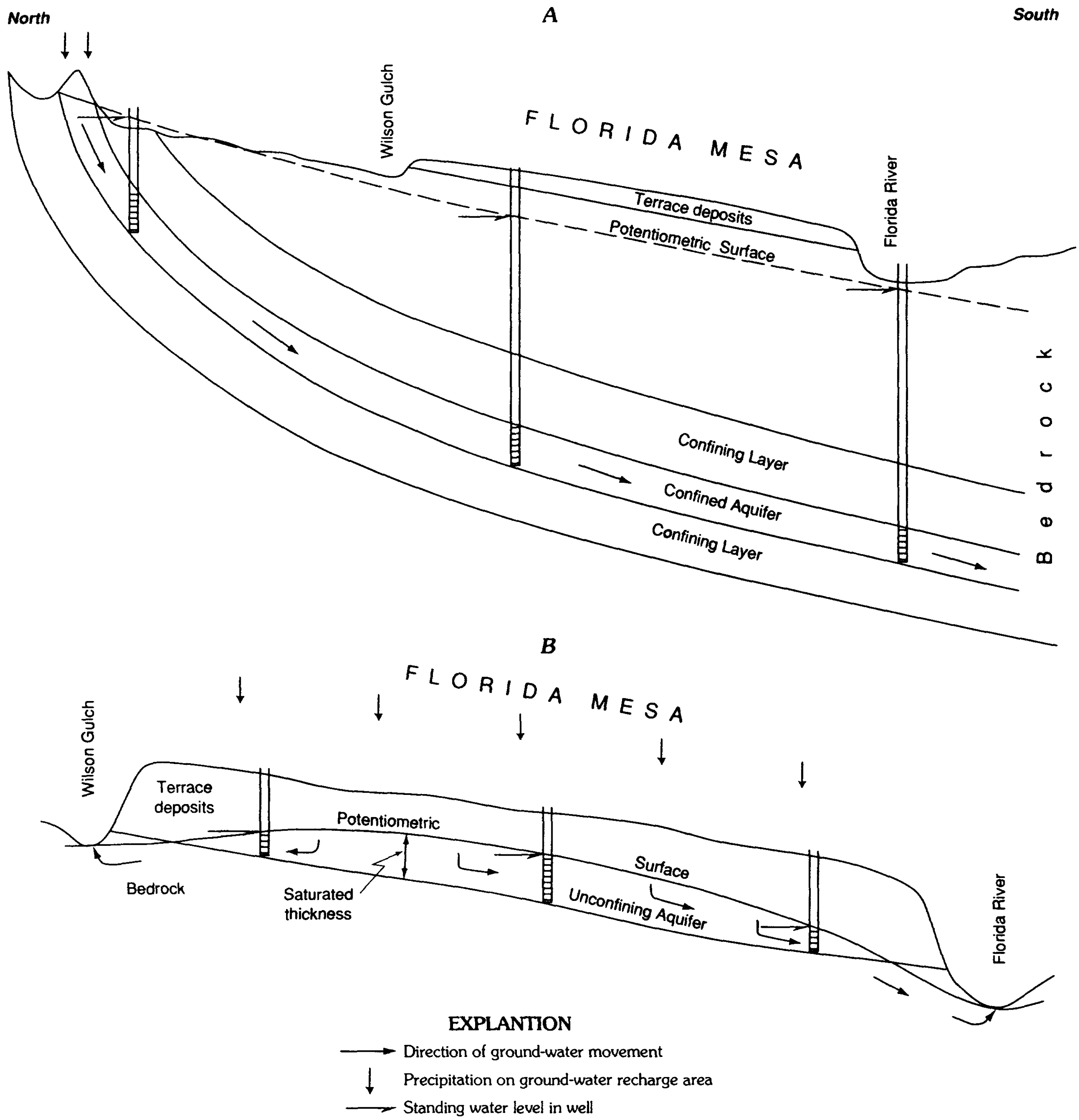

Figure 9. Generalized geohydrologic sections extending north to south in the study area for (A) confined aquifer, and (B) unconfining aquifer.

Studies of precipitation recharge in other areas of western Colorado that have climate and geology similar to that of the study area (Robson and Stewart, 1990, fig. 32) indicate that the mean annual precipitation of about 19 in. in the study area would produce about 0.8 in. of ground-water recharge. This rate is equivalent to about 2,000 acre-ft/yr of recharge to the deeper aquifers (those in the interval from the Dakota Sandstone to the Farmington Sandstone Member) in the 46-mi^2 area of outcrop along the northern margin of the study area. About 4,000 acre-ft/yr of recharge would occur in the 97-mi^2 area of outcrop and subcrop of the Animas, Nacimiento, and San Jose Formations (excluding the area of the Florida Mesa). About 2,000 acre-ft/yr of this recharge ultimately discharges to the base flow of the Florida River (see the "Supplemental Information" section at the back of this report); the remaining 2,000 acre-ft/yr discharges to the base flow in the Animas River or flows through the formations to the south out of the study area. The complex irrigation system on Florida Mesa requires a more detailed water-budget analysis to estimate the recharge and discharge on the mesa.

Florida Mesa Water Budget

A water budget is a detailed accounting of the principal means of water movement into or out of a hydrologic system. Results of the water-budget analyses are summarized in this section and in figure 10. Procedures used to estimate the components of the budget are discussed in the "Supplemental Information" section.

Precipitation and surface-water diversions are the principal sources of water movement onto Florida Mesa (fig. 10). The mean annual precipitation of about 19 in. in the area provides about 39,000 acre-ft/yr of water to the approximate 39-mi^2 area of the mesa. (The area of Florida Mesa is defined by the limit of the terrace deposits on the mesa [fig. 2].) Surface water diverted from the Florida River through the Florida Canal and Florida Farmers Ditch supplies about an additional 45,000 acre-ft/yr of water to the mesa. Total water inflow to the mesa is about 84,000 acre-ft/yr.

Part of this total water inflow to the mesa is lost to the atmosphere through evapotranspiration (fig. 10), or infiltrates into the ground-water system (recharge, fig. 10), or flows off the mesa in the form of irrigation tailwater or stormwater runoff (runoff, fig. 10). The water budget is assumed to balance—total water entering the mesa equals the total water leaving the mesa (about 84,000 acre-ft/yr).

Evapotranspiration totals about 59,000 acre-ft/yr and is the largest component of water outflow from the mesa. Evapotranspiration consists of (1) evaporation from open water such as ponds, puddles, wet soil, and wet vegetation; and (2) transpiration from crops and vegetation. Evapotranspiration from nonirrigated areas is 33,300 acre-ft/yr, evapotranspiration from irrigated crops is about 25,600 acre-ft/yr, and evapotranspiration of water withdrawn from wells (consumptive use) is about 300 acre-ft/yr.

Ground-water recharge on the Florida Mesa totals about 15,000 acre-ft/yr and is the second largest component of outflow from the mesa (fig. 10). Ground-water recharge from irrigated fields is about 12,000 acre-ft/yr; recharge due to seepage from unlined canals and ditches is 2,200 acre-ft/yr; and recharge from infiltration of precipitation on nonirrigated areas is 700 acre-ft/yr. Most of the ground water that is recharged on Florida Mesa flows through the aquifer to the south, east, and west and ultimately discharges from seeps and springs into the Animas and Florida Rivers. Ground-water discharge into the Animas and Florida Rivers totals 14,600 acre-ft/yr.

Surface-water runoff from the mesa totals about 10,000 acre-ft/yr and includes irrigation tailwater runoff (about 4,900 acre-ft/yr), spring runoff of snow and ice meltwater (3,200 acre-ft/yr), and waste flow from irrigation ditches (about 2,500 acre-ft/yr). Runoff from the mesa flows into the Florida and Animas Rivers.

Three important findings from the water-budget analyses are:

1. Surface water diverted onto the Florida Mesa through the Florida Canal and the Florida Farmers Ditch is the largest source of water on the mesa.

2. Infiltration of water from irrigated fields and leakage from unlined canals and ditches is by far the largest source of ground-water recharge on the mesa.

3. Consumptive use of ground water withdrawn from wells on the mesa is a small part of the total ground-water discharge from the mesa; most ground water is discharged through springs and seeps into the Florida and Animas Rivers.

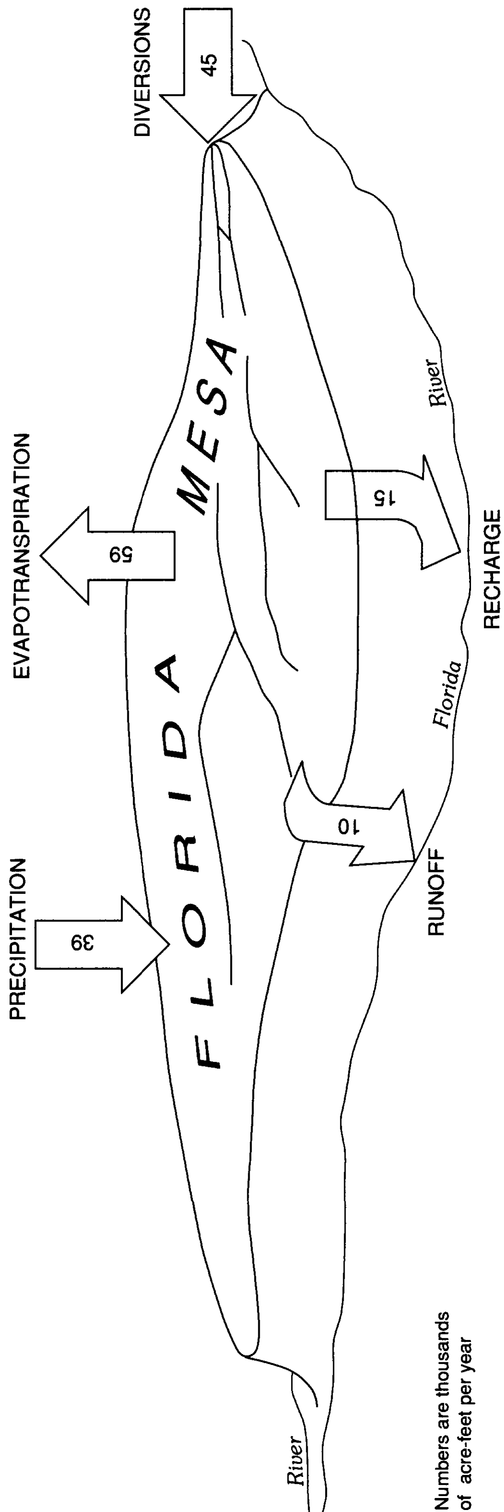

Figure 10. Summary water budget for Florida Mesa.

Two human activities that affect the ground-water levels on Florida Mesa are the withdrawal of ground water from wells and recharge of ground water from irrigated areas. Changes in irrigation recharge have had a much larger effect on ground-water levels than have changes in the rate of withdrawal. During 1968–93, the difference between the maximum and minimum rate of irrigation diversion onto the mesa was 29,000 acre-ft/yr. This difference in diversion rate caused a 9,000-acre-ft/yr change in the rate of irrigation recharge (based on the water-budget ratio of irrigation diversion to irrigation recharge). During 1968–93, about 500 new wells were constructed on the mesa, and consumptive use of pumped water increased by about 300 acre-ft/yr. The historical change in irrigation recharge (9,000 acre-ft/yr) was 30 times larger than pumping (about 300 acre-ft/yr).

Factors That Affect Ground-Water Recharge

As irrigated land on Florida Mesa becomes more urbanized, ground-water recharge may be reduced and cause a decline in water levels. Knowledge of factors affecting ground-water recharge are important if future land-use practices are to be managed to ensure continued availability of the ground-water supply.

Factors that would tend to increase ground-water recharge and, thus, increase or maintain ground-water levels include:

1. Maintaining large rates of surface-water diversion onto Florida Mesa.
2. Decreasing surface flow off the mesa as tailwater and as waste from irrigation ditches.
3. Increasing use of structures such as lakes, ponds, and spreading basins to promote infiltration.
4. Irrigating by use of flood irrigation.
5. Using leach fields rather than surface ponds for disposal of septic-system effluent.

Factors that would tend to decrease ground-water recharge and, thus, cause water-level declines include:

1. Reducing the size of the irrigated area on the mesa.
2. Converting from flood irrigation to more water-efficient irrigation practices.
3. Lining of irrigation ditches and canals or installation of pipelines.
4. Converting to more drought-tolerant crops that require less irrigation.
5. Converting the agricultural water supply to local municipal use with a central sewage system that discharges water off the mesa.

Many of the above factors have social, economic, and legal aspects that are beyond the scope of this report.

Potentiometric Surface and Direction of Ground-Water Movement

Every aquifer has a unique potentiometric surface, just as every lake has a unique water surface. A potentiometric surface is defined by the altitude of the standing water level in many wells and slopes in the general direction of ground-water movement. Water-level measurements in water wells and drill-stem tests in oil and gas wells indicate that the potentiometric surfaces in the deep bedrock aquifers decrease from north to south across the study area (fig. 9A). The general slope of the potentiometric surfaces, and, thus, the principal direction of ground-water movement, is from the outcrops along the northern margin of the study area toward the San Juan River near and downstream from Farmington, New Mexico. Precipitation that infiltrates the outcrops of permeable sandstone beds ultimately moves down the dip of the beds, under Florida Mesa, south out of the study area, and into New Mexico. Water-level data that define the altitudes of the potentiometric surfaces are available for selected wells in the San Jose, Nacimiento, and Animas Formations (Levings and others, 1990b), the Kirtland Shale and Fruitland Formation (Kernodle and others, 1990), the Pictured Cliffs Sandstone (Dam and others, 1990), the Cliff House Sandstone (Thorn and others, 1990), the Menefee Formation (Levings and others, 1990a), and the Dakota Sandstone (Craigg and others, 1989).

The shape of the potentiometric surface in the terrace deposits and the upper part of the Animas, Nacimiento, and San Jose Formations (fig. 11) is complex because of the effects of topography. When a potentiometric surface is broadly recharged from the land surface, ground water tends to move from areas of higher topography to areas of lower topography where ground water discharges to streams (fig. 9B). The Animas and Florida Valleys are topographically low and are the principal areas of ground-water discharge. As a result, the potentiometric surface is strongly affected by the altitude of the stream valleys and is somewhat affected by the altitude of the intervening upland areas.

On Florida Mesa, the potentiometric surface ranges in altitude from about 7,100 to 6,300 ft and slopes gently to the south, southwest, and southeast (fig. 11). A ground-water divide extending through the central part of the mesa separates the eastern 56 percent of the mesa where ground water drains to the Florida River from the western 44 percent of the mesa where ground water drains to the Animas River. Broadly spaced potentiometric contours indicate a relatively flat potentiometric surface; closely spaced contours indicate a steeper potentiometric surface. The areas of steepest potentiometric surface are at the margins of the mesa where ground water either flows downslope to the Animas or Florida Rivers or discharges from numerous seeps and springs.

East of the ground-water divide, ground water generally moves to the southeast; west of the divide, ground water generally moves to the southwest (fig. 12). The direction of ground-water movement differs little from the summer (irrigation season) to the winter (nonirrigation season), even though there are seasonal changes in water level caused by seasonal variations in recharge from precipitation and irrigation.

The saturated thickness of the terrace deposits is less than 25 ft on most of the mesa (fig. 13) and is less than 10 ft in much of this area. Saturated thickness exceeds 50 ft only in the southwestern part of the mesa. Beyond the line of zero saturated thickness (fig. 13), the potentiometric surface is below the base of the terrace deposits (in the Animas and Nacimiento Formations, fig. 9B), and the terrace deposits generally are unsaturated and do not yield water to wells. The areas of small saturated thickness near the margins of the terrace deposits are particularly susceptible to dewatering caused by water-level declines.

Water-Level Changes

Water levels were measured in 41 wells near the Florida Mesa during August and September 1994 and during January 1995 in an effort to determine if seasonal changes in ground-water recharge or discharge had an effect on ground-water levels. During summer, water levels may decline because of increased pumping to supply domestic needs or because of decreased precipitation recharge. Conversely, water levels may rise during summer because of increased recharge from canals and irrigated fields. During winter, water levels may decline because of cessation of irrigation, but may rise because of decreased pumping or greater precipitation recharge. Because these factors can have a greater or lesser effect on water levels in individual wells, a comparison of summer and winter water levels can indicate a varied pattern of rise or decline.

A comparison of the water-level measurements taken during August and September 1994 and January 1995 (fig. 14) indicated that water levels on the mesa generally were lower in winter than in summer. The decline likely was due to the loss of irrigation recharge during winter, which is in agreement with the water budget, that indicated that irrigation was the principal source of ground-water recharge on the mesa. It is important to note that the loss of irrigation recharge for a period of only a few months was apparently enough to produce measurable water-level declines over large parts of the mesa.

The water-level changes shown in figure 14 undoubtedly also are affected by pumping. Pumping, which generally is greater in summer than winter, markedly lowers the water level in the pumped well and could more readily affect the summer water-level measurement than the winter measurement, in spite of efforts to avoid measuring water levels in pumping or recently pumped wells. Increased summer pumping could lower the summer water level in the measured well and would cause the declines shown on figure 14 to be too small and the rises to be too large.

WATER-QUALITY CHARACTERISTICS

Ground water in the study area is of varied chemical quality. Potable water is present in the shallow parts of most of the aquifers, but nonpotable or saline water is present in the deeper parts of many of the aquifers. Wells in the outcrop of the Dakota Sandstone, along the northern margin of the study area, generally yield water of 300 to 400 mg/L dissolved solids. The water is of a calcium or sodium bicarbonate type, hard to very hard, and is used as a domestic water supply. In the west-central part of the San Juan Basin west of Shiprock, New Mexico, water in the Dakota Sandstone is of a sodium sulfate type and has 3,000 to 5,000 mg/L dissolved solids (Craigg and others, 1989), which is an order of magnitude higher than drinking-water standards (table 2).

Wells in the outcrop of the Mesaverde Group (Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone) near the study area yield water of a sodium bicarbonate or sulfate type and generally have dissolved-solids concentrations from 300 to 1,200 mg/L (Butler, 1986). Wells in the outcrop generally are less than 500 ft deep and yield water of widely varied hardness ranging from soft to very hard. Dissolved-solids concentrations increase with depth of the aquifer; in the west-central part of the San Juan Basin near Farmington, New Mexico, dissolved-solids concentrations of 39,000 and 76,000 mg/L have been measured in two deep wells (Levings and others, 1990a; Thorn and others, 1990).

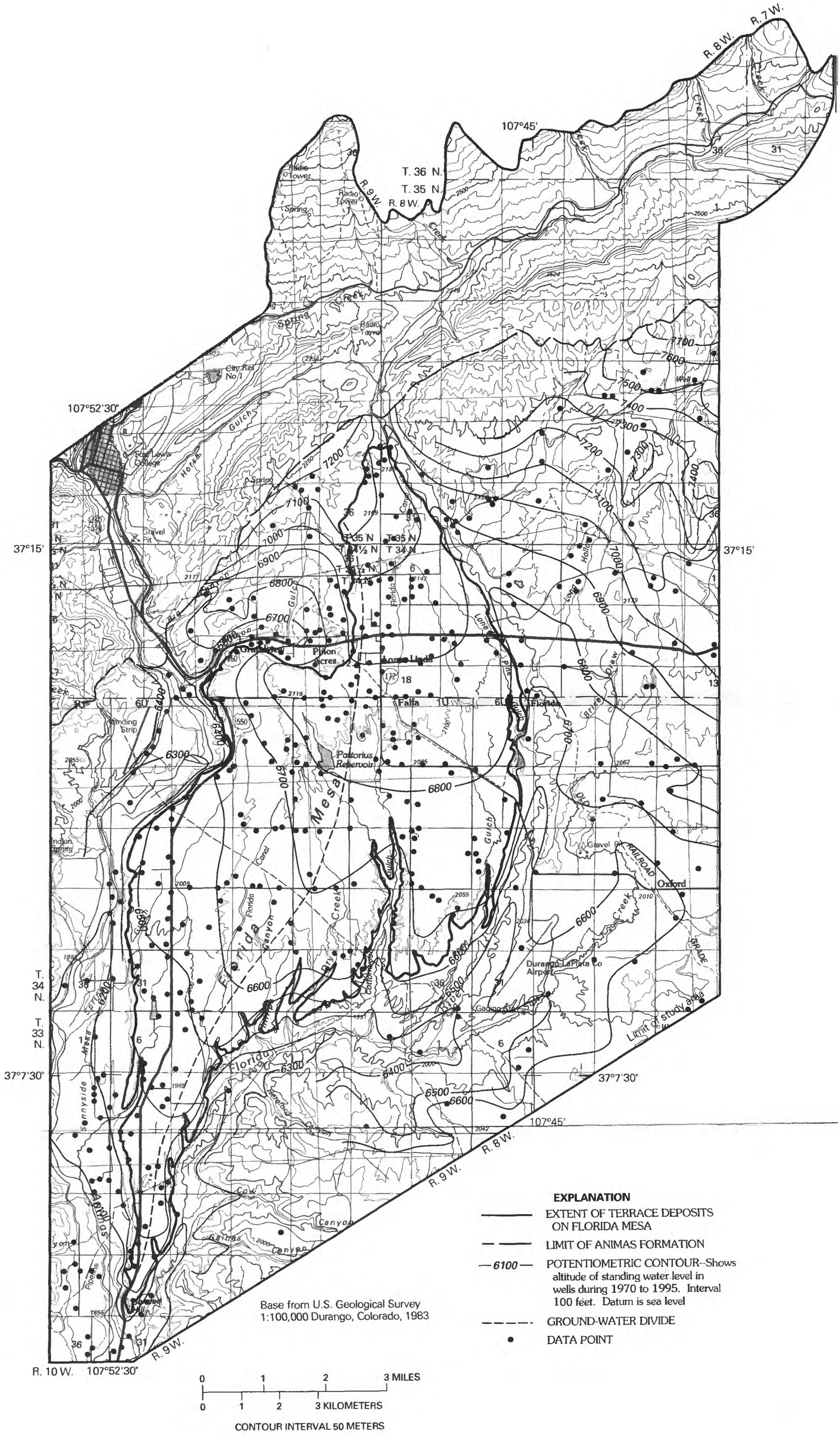

Figure 11. Potentiometric surface in the terrace deposits and the upper Animas, Nacimiento, and San Jose Formations near Florida Mesa.

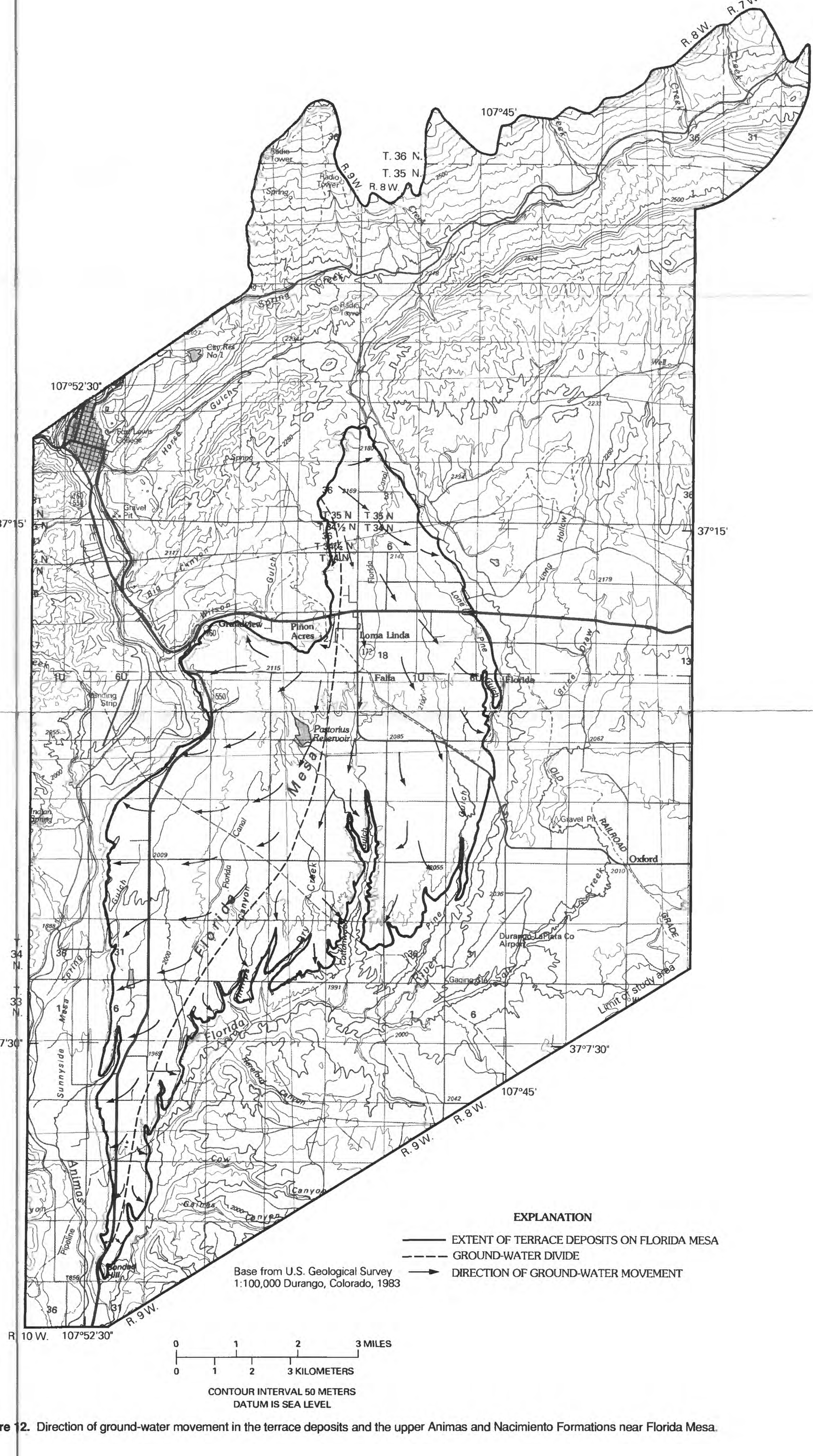

Figure 12. Direction of ground-water movement in the terrace deposits and the upper Animas and Nacimiento Formations near Florida Mesa.

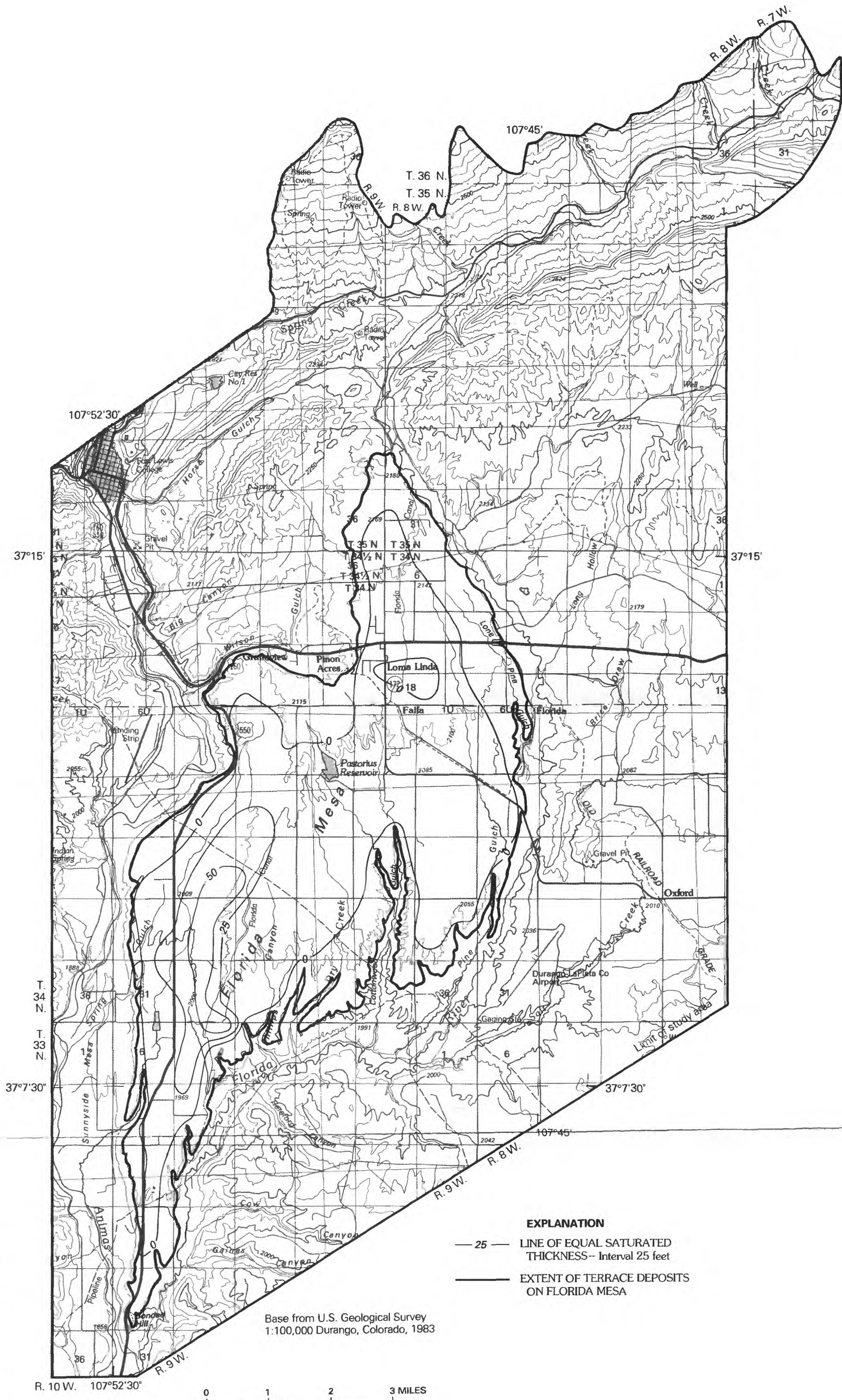

Figure 13. Saturated thickness of the terrace deposits on Florida Mesa.

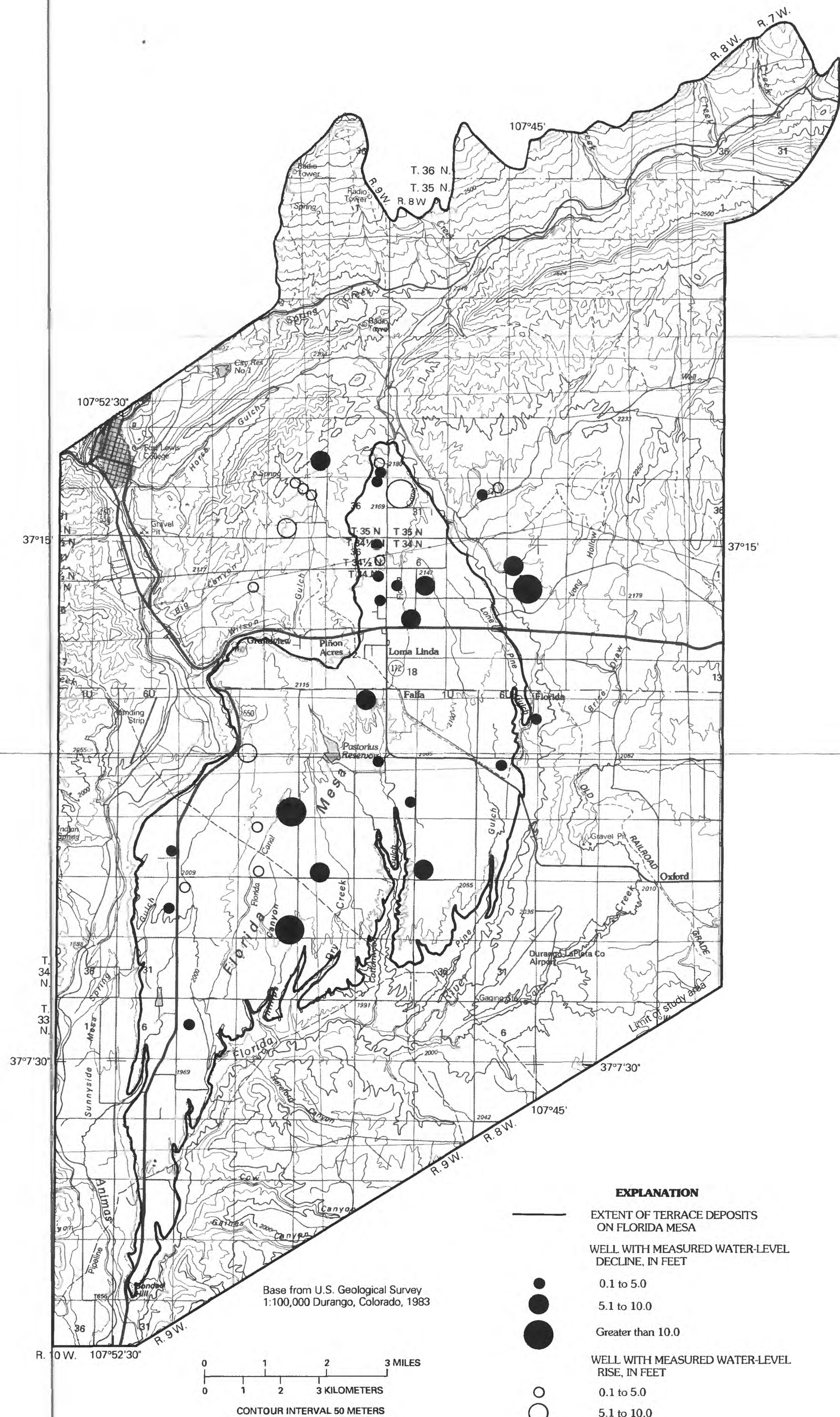

Figure 14. Water-level changes near Florida Mesa from August and September 1994 to January 1995.

Table 2. Water-quality standards for selected constituents

Water-quality characteristic or constituent	National and Colorado drinking-water standards (U.S. Environmental Protection Agency, 1986a, b; Colorado Department of Health, 1981)
	Major inorganic constituents (mg/L)
Sulfate	[1]250
Chloride	[1]250
Fluoride	[2]4.0
Dissolved solids	[1]500
Nitrate (as nitrogen)	[2]10
	Trace elements (μg/L)
Arsenic	[2]50
Barium	[2]1,000
Iron	[1]300
Lead	[2]50
Manganese	[1]50
Selenium	[2]10
Zinc	[1]5,000

[1]Secondary maximum contaminant level. These control contaminants in drinking water that primarily affect the aesthetic qualities relating to the public acceptance of drinking water. The regulations are not Federally enforceable, but are intended as guidelines for the States.

[2]Primary maximum contaminant level. These are the maximum permissible levels of a contaminant in water at the tap, are health related, and are legally enforceable.

Wells in the Pictured Cliffs Sandstone, Fruitland Formation, or Kirtland Shale in the outcrop near the study area yield water of a calcium bicarbonate type that is hard to very hard. Dissolved-solids concentrations generally range from 300 to 500 mg/L (Butler, 1986), but can be much larger in intervals where coal has degraded the water quality. Water coproduced from coal-bed methane wells in the Fruitland Formation near the study area is of a sodium bicarbonate type and ranges from about 1,000 to 6,000 mg/L dissolved solids (Bureau of Economic Geology, 1991). In the deeper central part of the San Juan Basin east of Farmington, New Mexico, dissolved-solids concentrations of 10,000 to 40,000 mg/L are common (Dam and others, 1990; Kernodle and others, 1990).

Water produced from fractured shale or thin sandstone beds in thick shale units, such as the Mancos Shale or the Lewis Shale, generally is of a sodium bicarbonate type near the outcrop, ranges from soft to very hard, and has dissolved-solids concentrations that commonly range from 300 to 1,200 mg/L. At depth, the shale generally is less fractured than at the outcrop and contains water of larger dissolved-solids concentrations.

The Animas, Nacimiento, and San Jose Formations are present at the surface or underlie thin alluvium throughout the southern part of the study area (fig. 2). Ground water in the upper parts of these formations is readily recharged from surface sources and is of better chemical quality than water in the deeper parts of the formations. Where saturated alluvium overlies the formations, wells commonly yield water from both units. Results from about 130 chemical analyses of water from the alluvium and the shallow formations (Butler, 1986; Levings and others, 1990b; Chafin and others, 1993; Bureau of Land Management, 1994; Bureau of Land Management and Colorado Oil and Gas Conservation Commission, 1995) indicate that the water quality in the alluvium is similar to the water quality in the upper Animas, Nacimiento, and San Jose Formations.

Water in the alluvium and the upper Animas, Nacimiento, and San Jose Formations is of a sodium bicarbonate type, ranges from soft to very hard, and has a mean dissolved-solids concentration of about 470 mg/L. Dissolved-solids concentrations commonly range from 300 to 900 mg/L in these geologic materials. Mean concentrations of chloride are about 50 mg/L; sulfate, 100 mg/L; fluoride, 1.5 mg/L; iron, 80 μg/L; manganese, 30 μg/L; nitrate plus nitrite, 0.5 mg/L; and selenium, 5 μg/L. The wide distribution of potable ground water at relatively shallow depths has led to extensive development of the alluvium and the Animas, Nacimiento, and San Jose Formations, which form the principal aquifer in the study area; however, potable water in these shallow formations is maintained by irrigation recharge.

Natural gas historically has been produced from the Dakota Sandstone, Mesaverde Group, Pictured Cliffs Sandstone, and Fruitland Formation of the San Juan Basin. The Fruitland Formation alone has estimated coal-bed natural gas resources between 43 and 49 trillion cubic feet and is the largest source of coal-bed natural gas production in the United States (Bureau of Economic Geology, 1991). The natural gas resources in the bedrock units of the study area sometimes can hinder or preclude development of the ground-water resources of gas-bearing formations. Even shallow aquifers that do not yield commercial quantities of natural gas can be degraded by the presence of small concentrations of natural gas.

Natural gas dissolved in ground water can adversely affect the taste, odor, or appearance of the water, and gas released from solution in the water can cause fire or explosion hazards in confined or poorly ventilated spaces. Although methane (the principal component of natural gas) is tasteless, odorless, colorless, and nontoxic to humans, its presence in ground water can cause geochemical reactions in the aquifer that adversely affect taste, odor, and appearance of the pumped water. When water containing dissolved natural gas is exposed to the air, gas is released from solution and can dissipate rapidly with adequate ventilation. However, in confined or poorly ventilated spaces, natural gas may rise (methane is less dense than air) and accumulate, creating a fire or explosion hazard. Because natural gas is tasteless, odorless, and colorless, the presence of hazardous accumulations can be difficult to detect.

Dissolved-methane concentrations were measured in water samples from about 150 wells in the study area (Chafin and others, 1993; Bureau of Land Management, 1994; Bureau of Land Management and Colorado Oil and Gas Conservation Committee, 1995). Sampled wells primarily are completed in the upper Animas or Nacimiento Formations and in the floodplain or terrace deposits. The average methane concentration was about 4 mg/L; however, most wells had less than 1 mg/L, and only 16 wells had more than 10 mg/L. Concentrations varied greatly from well to well, and repeated sampling of selected wells (Bureau of Land Management, 1994) indicated that methane concentrations varied considerably with time. The 16 wells with concentrations in excess of 10 mg/L are located in two general areas: (1) In the Animas River Valley between La Posta and Bondad, and (2) to the east of the Florida River north and east of Florida. Only one sampled well on Florida Mesa (near Bondad) had dissolved-methane concentrations greater than 10 mg/L.

SUMMARY

Increasing demand for ground water in the area of rapid suburban growth near Florida Mesa has caused concern about the continued availability of a dependable ground-water supply. This study was conducted in cooperation with La Plata County to provide needed information about the geology, extent, thickness, and depth of the aquifers; sources of ground-water recharge and discharge; direction of ground-water movement; water-level changes; and water quality in the alluvial and bedrock aquifers.

Bedrock aquifers are present in porous or fractured sandstone beds of many geologic formations that are exposed at land surface along the northern margin of the study area. The formations dip steeply into the subsurface and extend at depth under Florida Mesa and into New Mexico. Beds of nearly impermeable shale separate sandstone beds and retard vertical water movement between aquifers. The Animas, Nacimiento, and San Jose Formations are present at shallow depths in the central and southern parts of the study area and immediately underlie terrace deposits on Florida Mesa. Bedrock aquifers are present at depths less than 3,000 ft throughout the study area, although the deeper parts of the aquifers are more likely to contain water of poor chemical quality. Wells completed in the bedrock aquifers may yield as much as 75 gal/min, but yields of 1 to 10 gal/min are more common.

Terrace deposits as much as 200 ft thick are present on Florida Mesa and are an important source of ground water. Younger terrace deposits and floodplain deposits along the Animas and Florida Rivers are sources of ground water only in local areas where the deposits have adequate saturated thickness. Saturated thickness of terrace deposits on Florida Mesa is less than 25 ft in most of the mesa, but exceeds 50 ft in a small area.

Rainfall and snowmelt on the narrow outcrops of bedrock formations in the northern part of the study area are the principal sources of ground-water recharge to the deeper bedrock aquifers. On Florida Mesa, and in the outcrop of the Animas, Nacimiento, and San Jose Formations, precipitation recharge is widespread. The water budget for Florida Mesa is complex because of extensive irrigation on the mesa. On average, about 84,000 acre-ft/yr of water flows onto Florida Mesa. Surface water diverted from the Florida River for irrigation use is the largest source of water on the mesa (about 45,000 acre-ft/yr); precipitation (about 39,000 acre-ft/yr) is the second largest source of water. Water outflow from the mesa is by means of evapotranspiration (about 59,000 acre-ft/yr), ground-water recharge (about 15,000 acre-ft/yr), and surface-water runoff (about 10,000 acre-ft/yr). The water budget indicates that (1) infiltration of water from irrigated fields and leakage from unlined irrigation canals is the largest source of ground-water recharge on the mesa, and (2) consumptive use of water withdrawn from wells is only a small part of the total ground-water discharge from the mesa. Historical changes in the rate of recharge from irrigation have had a much larger effect on water levels in the shallow aquifer than have increases in withdrawal from wells.

Factors that would tend to increase ground-water recharge and, therefore, increase or maintain ground-water levels include (1) maintaining large rates of surface-water diversion onto the mesa, (2) decreasing surface flow off the mesa, (3) using lakes and spreading basins to increase infiltration, (4) using flood irrigation to promote infiltration, and (5) using leach fields to dispose of septic-system effluent. Factors that would tend to decrease ground-water recharge and, therefore, cause water-level declines include (1) reduction in the size of the irrigated area on the mesa, (2) conversion from flood irrigation to more water-efficient irrigation practices, (3) lining of irrigation canals, (4) conversion to more drought-tolerant crops, and (5) conversion of the agricultural water supply to municipal use with sewage outfall off the mesa.

The potentiometric surfaces in the deep bedrock aquifers are highest near the outcrops in the northern part of the study area. The general slope of the surfaces and direction of ground-water movement is south from the outcrops, under Florida Mesa, and toward the San Juan River near Farmington, New Mexico. On Florida Mesa, the potentiometric surface is highest near the northern end of the mesa, and ground water flows to the south, southeast, or southwest where it discharges to the Animas and Florida Rivers.

Water-level measurements in wells during August and September 1994 and during January 1995 indicated that winter water levels were lower than summer water levels over most of the mesa. The lower winter water levels likely were due to loss of irrigation recharge during the fall and winter and indicated that even a brief cessation of irrigation recharge can affect water levels over large parts of the mesa.

Dissolved-solids concentrations of water in the deeper bedrock aquifers range from 300 to 500 mg/L in outcrop areas to as much as 76,000 mg/L in the deep parts of the aquifers in New Mexico. In the alluvium and shallow parts of the Animas, Nacimiento, and San Jose Formations, ground water generally ranges from 300 to 900 mg/L dissolved solids. The water typically is soft to very hard and of a sodium bicarbonate type. Dissolved-methane concentrations in the water varied greatly from well to well and with time. Only 16 of 150 sampled wells had dissolved-methane concentrations greater than 10 mg/L. These 16 wells were in two general areas: (1) Between La Posta and Bondad, and (2) to the east of the Florida River north and east of Florida.

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SUPPLEMENTAL INFORMATION

The water budget for Florida Mesa was estimated using hydrograph separation of the streamflow-gain data for the Florida River and the irrigation and crop data presented in a Bureau of Reclamation study of the surface-water budget of the mesa (Dyke, 1994). Some data were modified from Dyke (1994) to adjust for differences in the size of the study area. The approach used here to estimate the water budget differed from the approach used by Dyke (1994) in that gain in flow of the Florida River was analyzed rather than the gain in flow of the Animas River because (1) the Florida River has smaller streamflow than the Animas River, and water discharged to the river from the mesa is a larger percentage of flow in the Florida River; and (2) the Florida River has a smaller ungaged drainage area than does the Animas River, which would introduce less error into the water budget. A second water budget developed as part of a model of ground-water flow (Finch and others, 1994) was not used in the current analyses because of conceptual errors in the estimate of ground-water recharge. The following water budget was calculated to the nearest 100 acre-ft/yr and rounded to the nearest 1,000 acre-ft/yr for use in the summary water budget (fig. 10).

During 1968 through 1982, continuous records of streamflow are available for gaging stations on the Florida River at Bondad, the Florida River below the Florida Farmers Ditch diversion, Salt Creek near Oxford, the Florida Canal, and the Florida Farmers Ditch. Locations of streamflow-gaging stations are shown in figure 7 and are listed in table 3. The mean annual gain in streamflow (for 1968–82) in the Florida River along the east and south sides of the mesa was 15,900 acre-ft/yr and was calculated as:

$$G = B - F - S$$
$$15{,}900 = 53{,}200 - 28{,}300 - 9{,}000 \qquad (1)$$

where

G = gain in streamflow, in acre-feet per year;
B = streamflow at Florida River at Bondad, in acre-feet per year;
F = streamflow at Florida River below Florida Farmers Ditch, in acre-feet per year; and
S = streamflow at Salt Creek near Oxford, in acre-feet per year.

The hydrograph of the mean monthly gain in streamflow (fig. 15) was separated into base flow (4,300 acre-ft/yr), spring runoff (3,600 acre-ft/yr), and irrigation return flow (8,000 acre-ft/yr) components by fitting the low-flow data points to a recession curve typical of the exponential decay of base flow. Because about one-half of the drainage area of the Florida River between the Farmers Ditch and Bondad gaging stations is on Florida Mesa, about one-half of the gain in base flow (2,200 acre-ft/yr) and about one-half the gain in spring runoff (1,800 acre-ft/yr) were assumed to be from the Florida Mesa area. Most irrigated areas are on the mesa, except for about 1,500 acres (Dyke, 1994) of hay and pasture in the Florida Valley that are irrigated by streamflow diversions in the reach. The total irrigation return-flow gain to the Florida River from the mesa (12,300 acre-ft/yr) was calculated as the sum of measured return flow (8,000 acre-ft/yr), consumptive use from irrigation in the valley (2,100 acre-ft/yr) (Dyke, 1994), and one-half the base flow (2,200 acre-ft/yr).

Table 3. Name and number of streamflow-gaging stations in the study area

[*, station operated by Colorado Department of Natural Resources]

Number in figure 7	Station name	U.S. Geological Survey station number
1	Florida Canal	*
2	Florida Farmers Ditch	*
3	Florida River below Farmers Ditch near Durango	09363050
4	Salt Creek near Oxford	09363100
5	Florida River at Bondad	09363200

Total irrigation gain to the Florida and Animas Rivers from the mesa was estimated by use of the potentiometric surface map and an irrigated-area map of the mesa. The ground-water divide in the potentiometric surface on the mesa (fig. 11) closely corresponds to the location of the surface-drainage divide. Both divides separate the eastern part of the mesa where ground water and surface water flow toward the Florida River from the western part of the mesa where ground water and surface water flow toward the Animas River. About 56 percent of the irrigated area on the mesa is east of the two divides, and runoff and ground-water recharge in this area supply the 12,300 acre-ft/yr of gain in flow in the Florida River. Total irrigation gain to the Florida and Animas Rivers from the mesa (22,000 acre-ft/yr) was calculated as the total gain to the Florida River divided by 56 percent. Total spring runoff of 3,200 acre-ft/yr was calculated similarly.

Water enters the mesa area from surface-water diversions and precipitation. Records of diversions through the Florida Canal and the Florida Farmers Ditch (1968–82), provided by the Colorado Department of Natural Resources, State Engineers

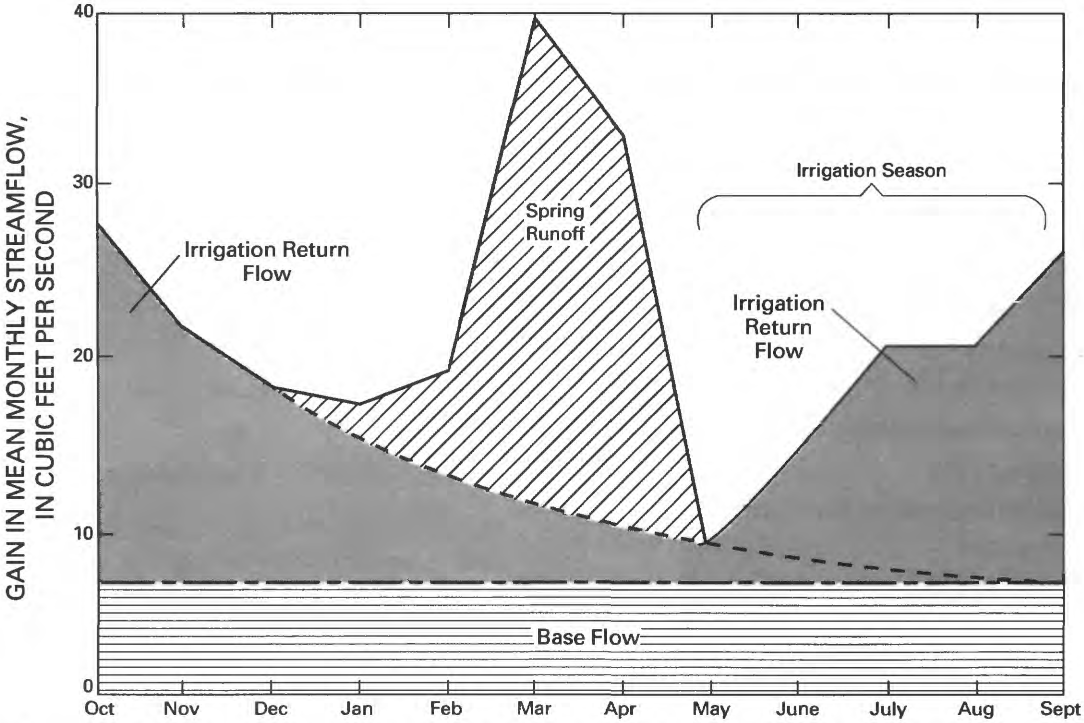

Figure 15. Separation of components of 1968–82 mean gain in streamflow in the Florida River.

Office (written commun., 1995), indicated that 45,000 acre-ft/yr of streamflow was diverted onto the mesa from the Florida River. Mean annual precipitation at Durango was 18.61 in. for the 96-year period of record (National Oceanic and Atmospheric Administration, 1989). Mean annual precipitation at Durango during 1968–82 was 18.92 in. A mean annual precipitation of 18.92 in. on the 39.4-mi^2 mesa will produce 39,400 acre-ft/yr of water. Total inflow was 84,400 acre-ft/yr and, in the absence of a large change in ground-water storage, also is equal to the total outflow from the mesa. Change in ground-water storage likely is negligeable because water-level measurements in various wells made at different times during 1970 to 1995 indicated an inconsistent pattern of small water-level rises or declines with no consistent trend in water-level change.

Dyke (1994) estimated that seepage loss from unlined irrigation canals and ditches was 5 percent of the diversion, or 2,200 acre-ft/yr. Administrative-waste runoff was about 5 percent, as estimated by ditch riders, or 2,500 acre-ft/yr (Dyke, 1994). Crop consumptive use during the growing season was about 25,600 acre-ft/yr (Dyke, 1994, table 5). Tailwater runoff was about 4,900 acre-ft/yr (Dyke, 1994, table 13). An estimated 500 domestic wells on the mesa have a consumptive use of about 0.57 acre-ft/yr per well (George Van Slyke, Colorado State Engineers Office, oral commun., 1995) and a total consumptive use of about 300 acre-ft/yr. Because pumping has not caused large water-level declines in the aquifer, it was assumed that well consumptive use was offset by captured discharge; that is, the effects of pumping ultimately are offset by a reduction in the rate of natural discharge from springs to seeps.

From the preceding data, the consumptive use from noncrop areas, fallow land, and cropped fields during the nongrowing season can be calculated as:

$$\begin{array}{cccccccccccc} NCU & = & IN & - & TIG & - & CCU & - & SR & - & DW & \\ 33{,}300 & = & 84{,}400 & - & 22{,}000 & - & 25{,}600 & - & 3{,}200 & - & 300 & (2) \end{array}$$

where

NCU = noncrop, fallow, and nonseasonal consumptive use, in acre-feet per year;

IN = total water inflow to the mesa, in acre-feet per year;

TIG = total irrigation gain to the Florida and Animas Rivers, in acre-feet per year;

CCU = crop consumptive use, in acre-feet per year;

SR = spring runoff, in acre-feet per year; and

DW = domestic well consumptive use, in acre-feet per year.

Precipitation recharge from the approximately 11,000 acres of nonirrigated land on the mesa was about 0.8 in. per year (Robson and Stewart, 1990) or 700 acre-ft/yr.

Ground-water recharge from irrigated fields can be calculated as:

$$\begin{aligned} IR &= TIG + DW - PR - SI - W - T \\ 12{,}000 &= 22{,}000 + 300 - 700 - 2{,}200 - 2{,}500 - 4{,}900 \end{aligned} \quad (3)$$

where

IR = ground-water recharge from irrigated fields, in acre-feet per year;

PR = precipitation recharge from nonirrigated areas, in acre-feet per year;

SI = seepage from irrigation canals, in acre-feet per year;

W = administrative-waste runoff, in acre-feet per year; and

T = tailwater runoff, in acre-feet per year.

Total ground-water recharge (TGR) is calculated as:

$$\begin{aligned} TGR &= IR + SI + PR \\ 14{,}900 &= 12{,}000 + 2{,}200 + 700 \end{aligned} \quad (4)$$

Total ground-water discharge (TGD) is calculated as:

$$\begin{aligned} TGD &= TIG + DW - W - T \\ 14{,}900 &= 22{,}000 + 300 - 2{,}500 - 4{,}900 \end{aligned} \quad (5)$$

Total surface runoff (TSR) is calculated as:

$$\begin{aligned} TSR &= W + T + SR \\ 10{,}600 &= 2{,}500 + 4{,}900 + 3{,}200 \end{aligned} \quad (6)$$

The value 10,600 was rounded to 10,000 for use in the summary water budget (fig. 10) in order to avoid a round-off error in the summary budget.

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