Uncovering the Hidden Resource: Groundwater Law, Hydrology, and Policy in the 1990s (Summer Conference, June 15-17)

1992

6-15-1992

Fundamental Groundwater Hydrology and Well Hydraulics

E. D. Gutentag

E. D. Gutentag, *Fundamental Groundwater Hydrology and Well Hydraulics*, *in* UNCOVERING THE HIDDEN RESOURCE: GROUNDWATER LAW, HYDROLOGY, AND POLICY IN THE 1990S (Natural Res. Law Ctr., Univ. of Colo. Sch. of Law 1992).

FUNDAMENTAL GROUNDWATER HYDROLOGY AND WELL HYDRAULICS

E. D. Gutentag
Hydrologist
U.S. Geological Survey
Denver, Colorado

UNCOVERING THE HIDDEN RESOURCE:
GROUNDWATER LAW, HYDROLOGY AND POLICY LAW
IN THE 1990s

Natural Resources Law Center
University of Colorado
School of Law
Boulder, Colorado

June 15-17, 1992

E.D. Gutentag
U.S.G.S - WRD
YMP - HIP
Box 2504 MS 421
Lakewood, CO 80225

Definitions for Ground-Water Hydrology
Copies of slide Presentation

Outline of June 15 Presentation

E. D. Gutentag

FIGURES

Aquifer

An *aquifer* is a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

The term aquifer was defined by O.E. Meinzer from a geological concept in which water bodies are classified in accordance with stratigraphy or rock types. Meinzer clearly intended that an aquifer include the unsaturated part of the permeable unit.

Artesian

Artesian is synonymous with confined. Artesian water and artesian water body are equivalent respectively to confined ground water and confined water body.

An artesian well is a well deriving its water from an artesian or confined water body. The water level in an artesian well stands above the top of the artesian water body it taps.

If the water level in an artesian well stands above the land surface the well is a flowing artesian well. If the water level in the well stands above the water table, it indicates that the artesian water can and probably does discharge to the unconfined water body. It should be noted also that in ground water discharge areas wells having heads higher than the water table, or even flowing wells, may exist without confinement of the water body, owing to vertical components of gradient in the flow field.

Capillary fringe

The capillary fringe is the zone immediately above the water table in which all or some of the interstices are filled with water that is under less that atmospheric pressure and that is continuous with the water below the water table. The water is held above, the water table by interfacial forces (for example, surface tension). The capillary fringe is typically saturated to some distance above its base at the water table ; upward from the saturated part only progressively smaller pores are filled and the upper limit is indistinct. In some quantitative studies it is convenient to define the upper limit more or less arbitrarily. For instance, this limit may be defined as the level at which 50 percent of the pore space is filled with water.

Some lateral flow generally occurs throughout the capillary fringe, but because the effective hydraulic conductivity decreases rapidly with moisture content, the lateral flow in the capillary fringe generally is negligible compared with that in the saturated zone, except where the capillary fringe and the saturated zone are of comparable thickness.

Capture

Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in the recharge, or a combination of these changes. The decrease in discharge plus the increase in recharge is termed capture. Capture may occur in the form of decreases in the ground-water discharge into streams, lakes, and the ocean, or from decreases in that component of evapotranspiration derived from the saturated zone. After a new artificial withdrawal from the aquifer has begun, the head in the aquifer will continue to decline until the new withdrawal is balanced by capture.

Conductivity, hydraulic, K [LT^{-1}]

Hydraulic conductivity, K, replaces the term †"field coefficient of permeability," P_f, which embodies the inconsistent units gallon, foot, and mile. If a porous medium is isotropic and the fluid is homogeneous, the hydraulic conductivity of the medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic conductivity can have any units of LT^{-1} suitable to the problem involved. In data tabulations of the Geological Survey, hydraulic conductivity may be expressed in feet per day and, so that the work of the Geological Survey may be readily interpreted in other countries, also in meters per day. Thus,

$$K=-\frac{ft^3}{day\ ft^2(-ft\ ft^{-1})}=ft\ day^{-1} \qquad (1)$$

$$K=-\frac{m^3}{day\ m^2(-m\ m^{-1})}=m\ day^{-1} \qquad (2)$$

Hydraulic conductivity is dependent primarily on the nature of the pore space, the type of liquid occupying it, and the strength of the gravitational field. For comparing the hydraulic conductivities of aquifers at different localities that contain water of appreciably different kinematic viscosity, it is only necessary to relate them by the dimensionless ratio of the kinematic viscosities and values of the acceleration due to gravity.

In anisotropic media the direction of the specific discharge q is not generally parallel to that of the gradient (dh/dl) of the head.

Confining bed

Confining bed is a term which will now supplant the terms †"aquiclude," †"aquitard," and †"aquifuge" in reports of the Geological Survey and is defined as a body of "impermeable" material stratigraphically adjacent to one or more aquifers. In nature, however, its hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the aquifer. Its conductivity relative to that of the aquifer it confines should be specified or indicated by a suitable modifier such as slightly permeable or moderately permeable.

Flow, steady

Steady flow occurs when at any point the magnitude and direction of the specific discharge are constant in time. (See also "Flow, unsteady.")

Flow, uniform

A property is uniform if, at a given instant, it is the same at every point. Thus, *uniform flow* occurs if at every point the specific discharge has the same magnitude and direction.

Flow, unsteady

Unsteady, or *nonsteady, flow* occurs when at any point the magnitude or direction of the specific discharge changes with time. (See also "Flow, steady".)

The word *transient* is used in reference to the temporary features of unsteady flow. Thus, in unsteady flow, the specific discharge, the head, and perhaps other factors consist of a steady component plus a transient component.

Ground water, confined

Confined ground water is under pressure significantly greater than atmospheric, and its upper limit is the bottom of a bed of distinctly lower hydraulic conductivity than that of the material in which the confined water occurs.

Ground water, perched

Perched ground water is unconfined ground water separated from an underlying body of ground water by an unsaturated zone. Its water table is a *perched water table*. It is held up by a *perched bed* whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure.

Perched ground water may be either *permanent*, where recharge is frequent enough to maintain a saturated zone above the perching bed, or *temporary*, where intermittent recharge is not great or frequent enough to prevent the perched water from disappearing from time to time as a result of drainage over the edge of or through the perching bed.

Ground water, unconfined

Unconfined ground water is water in an aquifer that has a water table.

Head, static, $h[L]$

The *static head* is the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

The static head is the sum of the elevation head, h_e, and the pressure head, h_p; that is, $h=h_e + h_p$. (See "Head, total".) Under conditions to which Darcy's Law may be applied, the velocity of ground water is so small that the velocity head, $h_v = v^2/2g$ negligible. *Head*, when used alone, is understood to mean static head. Head is proportional to the fluid potential; therefore, the head is a measure of the potential.

Head, total, *H[L]*

The *total head* of a liquid at a given point is the sum of three components: (1) *elevation head,* h_e, which is equal to the elevation of the point above a datum, (2) *pressure head,* h_p, which is the height of a column of static water that can be supported by the static pressure at the point, and (3) *velocity head,* h_v, which is the height the kinetic energy of the liquid is capable of lifting the liquid.

Homogeneity

Homogeneity is synonymous with uniformity. A material is homogeneous if its hydrologic properties are identical everywhere. Although no known aquifer is homogeneous in detail, models based upon the assumption of homogeneity have been shown empirically to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

Hydraulic diffusivity, *T/S or K/S, $[L^2T^{-1}]$*

The *hydraulic diffusivity* is the parameter *T/S or* K/S_s. It is the conductivity of the saturated medium when the unit volume of water moving is that involved in changing the head a unit amount in a unit volume of medium. By analogy with Maxwell's nomenclature in heat conduction theory (thermometric conductivity), it may be considered potentiometric conductivity. Similar diffusivities, having dimensions L_2T_{-1}, characterize the flow of heat and of electricity by conduction and the movement of a dissolved substance in a liquid by diffusion. The parameter arises from the fundamental differential equation for liquid flow in a porous medium.

In any isotropic homogeneous system the time involved for a given head change to occur at a particular point in response to a greater change in head at another point is inversely proportional to the diffusivity. As a common example the cone of depression affects moderately distant wells by measurable amounts in a short time in confined ground-water bodies for which the diffusivities are commonly large and only after a longer time in unconfined water bodies for which the diffusivities are commonly much smaller.

Hydraulic gradient [dimensionless]

The *hydraulic gradient* is the change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Isotropy

Isotropy is that condition in which all significant properties are independent of direction. Although no aquifers are isotropic in detail, models based upon the assumption of isotropy have been shown to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

Permeability, intrinsic, k,*[L^2]*

Intrinsic permeability is a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement. It is a property of the medium that is dependent upon the shape and size of the pores.

If a porous medium is isotropic and the fluid is homogeneous, the *intrinsic permeability* of the medium is the volume of liquid of unit kinematic viscosity that will move in unit time under a unit potential gradient through a unit area, measured at right angles to the direction of flow.

Porosity, n [dimensionless]

The *porosity* of a rock or soil is its property of containing interstices or voids and may be expressed quantitatively as the ratio of the volume of its interstices to its total volume. It may be expressed as a decimal fraction or as a percentage. With respect to the movement of water only the system of interconnected interstices is significant. Specific yield plus specific retention equals porosity.

Porosity, effective, n_e [dimensionless]

Effective porosity refers to the amount of interconnected pore space available for fluid transmission. It is expressed as a percentage of the total volume occupied by the interconnecting interstices. Although effective porosity has been used to mean about the same thing as specific yield, such use is discouraged.

Potentiometric surface

The *potentiometric surface*, which replaces the term †"piezometric surface," is a surface which represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased cells. Where the head varies appreciably with depth in the aquifer, a potentiometric surface is meaningful only if it describes the static head along a particular specified surface or stratum in that aquifer. More than one potentiometric surface is then required to describe the distribution of head. The water table is a particular potentiometric surface.

Pressure, static, [$ML^{-1}T^{-2}$]

Static pressure is the pressure exerted by the fluid. It is the mean normal compressive stress on the surface of a small sphere around a given point.

The static pressure does not include the *dynamic pressure*, $pv^2/2$, and therefore is distinguished from the *total pressure*. The velocity of ground water ordinarily is so small that the dynamic pressure is negligible. Pressure, when used alone, is understood to mean static pressure.

Specific capacity $[L^2T^{-1}]$

The *specific capacity* of a well is the rate of discharge of water from the well divided by the drawdown of water level within the well. It varies slowly with duration of discharge which should be stated when known. If the specific capacity is constant except for the time variation, it is roughly proportional to the transmissivity of the aquifer.

The relation between discharge and drawdown is affected by the construction of the well, its development, the character of the screen or casing perforation, and the velocity and length of flow up the casing. If the well losses are significant, the ratio between discharge and drawdown decreases with increasing discharge; it is generally possible roughly to separate the effects of the aquifer from those of the well by step drawdown tests. In aquifers with large tubular openings the ratio between discharge and drawdown may also decrease with increasing discharge because of a departure from laminar flow near the well, or in other words, a departure from Darcy's law.

Specific discharge, or specific flux $q[LT^{-1}]$

The *specific discharge*, or *specific flux*, for ground water is the rate of discharge of ground water per unit area of the porous medium measured at right angles to the direction of flow. Specific discharge has the dimensions of velocity, as follows:

$$q=Q/A$$

where Q equals Q equals *total discharge, or total flux,* through area A.

Specific discharge has sometimes been called the bulk velocity or the Darcian velocity. Specific discharge is a precise term and is preferred to terms involving "velocity" because of possible confusion with actual velocity through the pores if a qualifying term is not constantly repeated.

Specific retention, S_r, [dimensionless]

The *specific retention* of a rock or soil is the ratio of (1) the volume of water which the rock or soil, after being saturated, will retain against the pull of gravity to (2) the volume of the rock or soil.

Ideally, the definition implies that gravity drainage is complete. However, the amount of water held in pores above the water table during gravity drainage is dependent upon particle size, distance above the water table, time of drainage, and other variables. Lowering of the water table and infiltration occur over such short periods of time that gravity drainage is rarely or never complete. Thus the concepts embodied in specific retention do not recognize adequately the highly complex set of interacting conditions that regulate moisture retention. Nevertheless, specific retention is a useful though approximate measure of the moisture holding capacity of the unsaturated zone in that region above the capillary fringe. (See also "Specific yield.")

Specific yield, S_y [dimensionless]

The *Specific yield* of a rock or soil is the ratio of (1) the volume of water which the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil. The definition implies that gravity drainage is complete.

In the natural environment, specific yield is generally observed as the change that occurs in the amount of water in storage per unit area of unconfined aquifer as the result of a unit change in head. Such a change in storage is produced by the draining or filling of pore space and is therefore dependent upon particle size, rate of change of the water table, time, and other variables. Hence, specific yield is only an approximate measure of the relation between storage and head in unconfined aquifers. It is equal to porosity minus specific retention.

Storage, bank [L^3]

The change in storage in an aquifer resulting from a change in stage of an adjacent surface-water body is referred to as *bank storage*.

Storage, Specific, S_s [L^{-1}]

In problems of three-dimensional transient flow in m compressible ground-water body, it is necessary to consider the amount of water released from or taken into storage per unit volume of the porous medium. The *specific storage*, S_s, is the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

Storage coefficient, S [dimensionless]

The *storage coefficient* is the volume of water an aquifer releases from or takes into storage per unit surface ares of the aquifer per unit change in head.

In a confined water body the water derived from storage with decline in head comes from expansion of the water and compression of the aquifer; similarly, water added to storage with a rise in head is accommodated partly by compression of the water and partly by expansion of the aquifer. In an unconfined water body, the amount of water derived from or added to the aquifer by these processes generally is negligible compared to that involved in gravity drainage or filling of pores; hence, in an unconfined water body the storage coefficient is virtually equal to the *specific yield*.

Stream, gaining

A *gaining stream*, which replaces the term †"effluent stream," is a stream or reach of a stream whose flow is being increased by inflow of ground water.

Stream, losing

A *losing stream*, which replaces the term †"influent stream," is a stream or reach of a stream that is losing water to the ground.

Transmissivity, T $[L^2T^{-1}]$

Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It replaces the term †"coefficient of transmissibility" because by convention it is considered a property of the aquifer, which is transmissive, whereas the contained liquid is transmissible. However, though spoken of as a property of the aquifer, it embodies also the saturated thickness of the aquifer (b) and the properties of the contained liquid. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths.

Velocity, average interstitial, v_i[LT^{-1}]

Although the *specific discharge*, q, has the dimensions of a velocity, it expresses the average volume rate of flow rather than the particle velocity. In order to determine the average interstitial velocity, v_i, it is necessary to know also the effective porosity, n_e.

Water table

The *water table* is that surface in a ground-water body at which the water pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists. (See also "Ground water, perched.")

Zone, saturated

The *saturated zone* is that part of the earth's crust beneath the deepest water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric. The saturated zone may depart from the ideal in some respects. A rising water table may cause entrapment of air in the upper part of the zone of saturation, and the lower part may include accumulations of other natural fluids. The saturated zone has been called the † phreatic zone by some.

The foregoing definition is virtually that given by Meinzer. Later, other authors, emphasizing that ordinary interstices somewhat above the water table in porous media are filled with capillary water, extended the term "saturated zone" to include this water. However, this capillary water cannot be distinguished in the field without special instrumentation. Hence, the definition accepting the water table as the top of the saturated zone is standard for reports of the Geological Survey.

Zone, unsaturated

The *unsaturated zone*, which replaces the terms † "zone of aeration" and † "vadose zone," is the zone between the land surface and the deepest water table. It includes the *capillary fringe*. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies the water pressure locally may be greater than atmospheric.

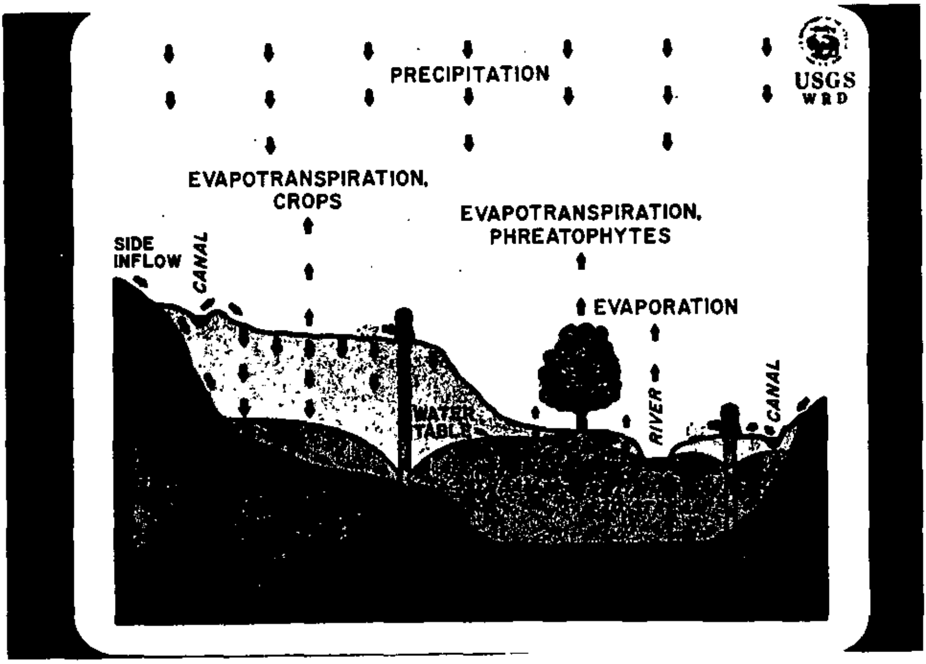


Figure 1

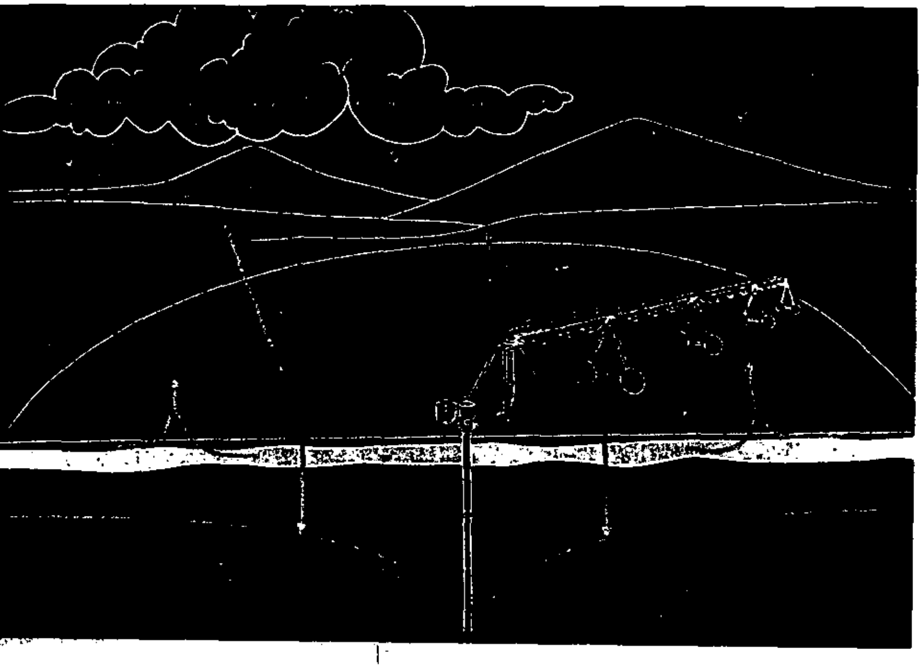


Figure 2

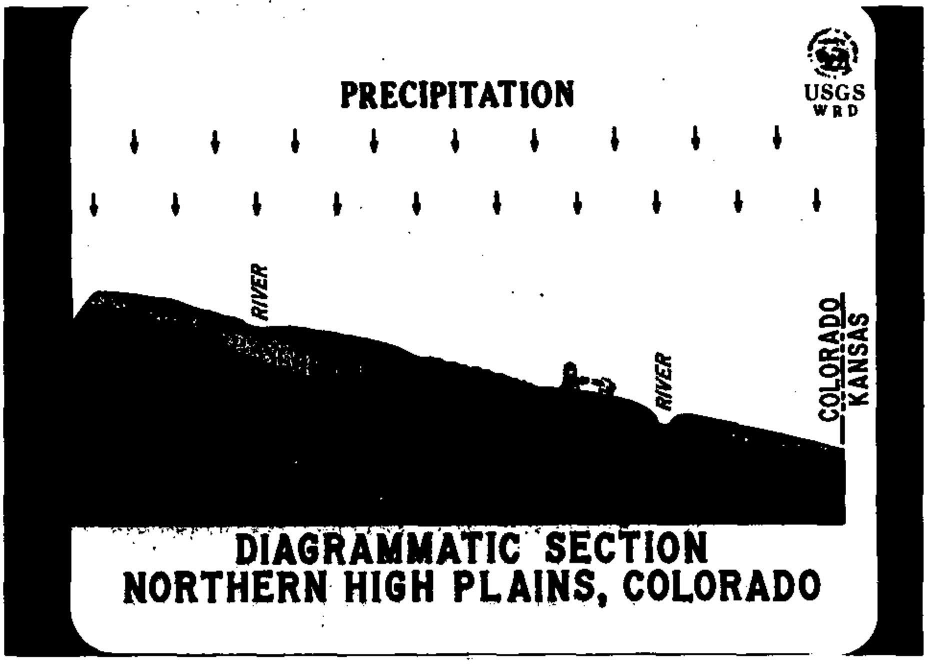


Figure 3

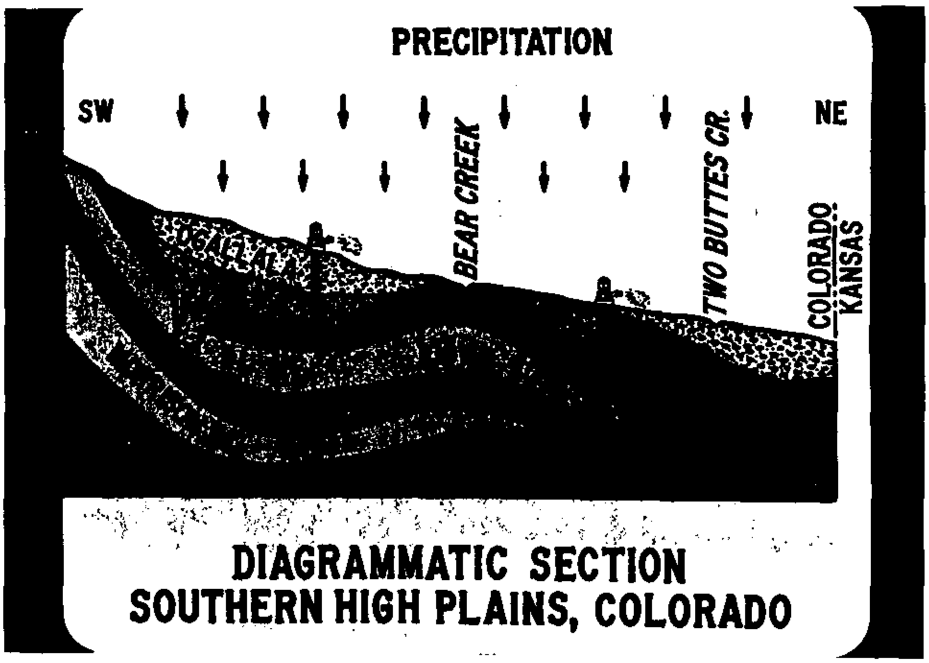


Figure 4

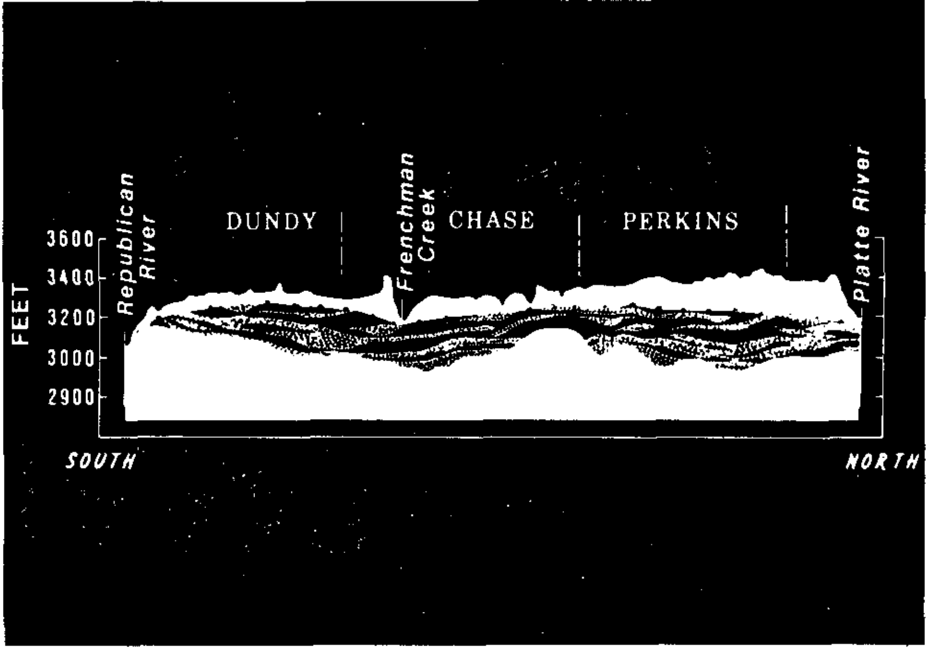


Figure 5

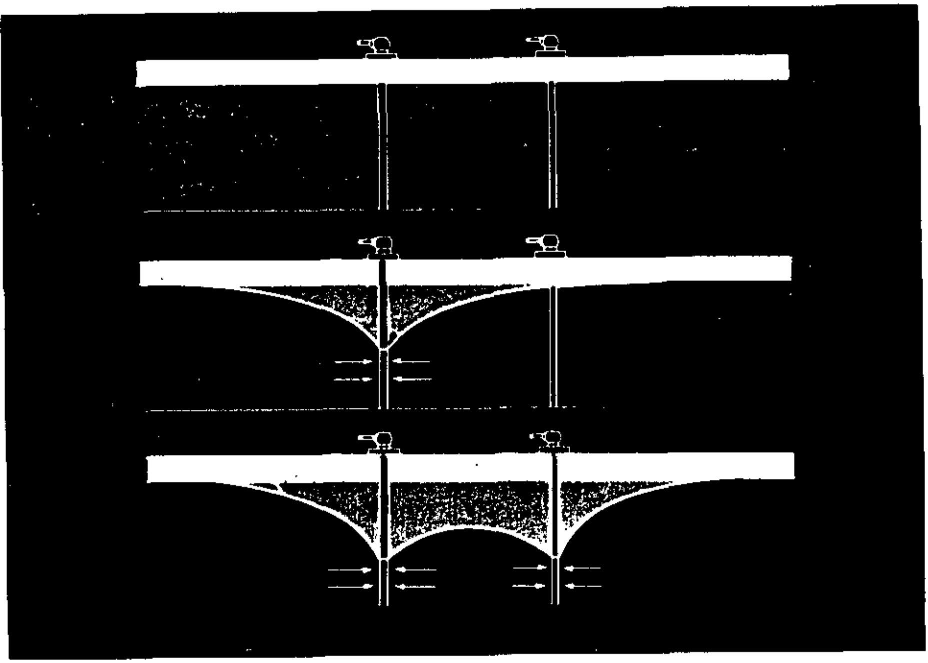


Figure 6

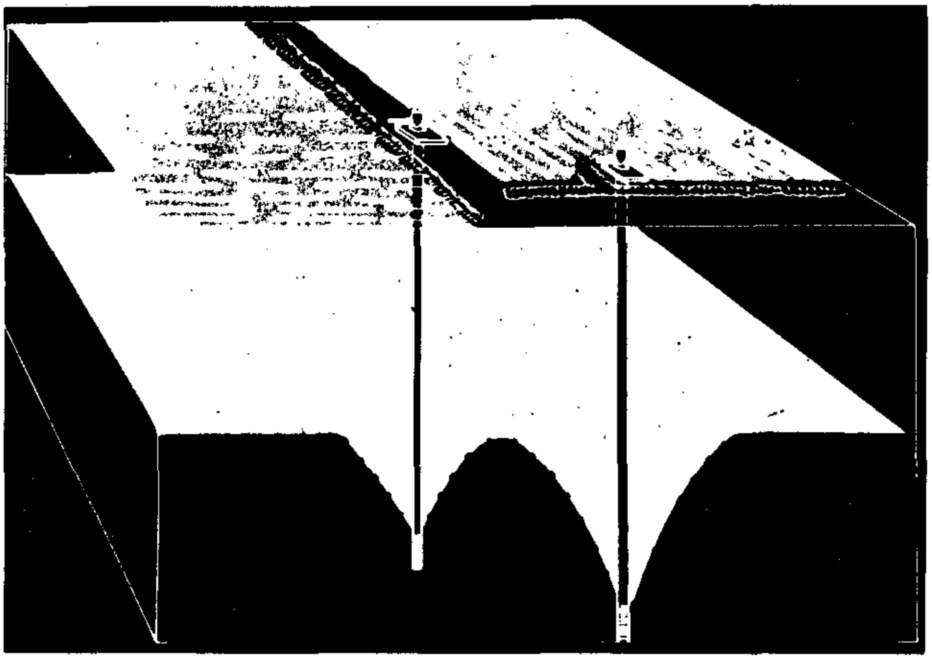


Figure 7

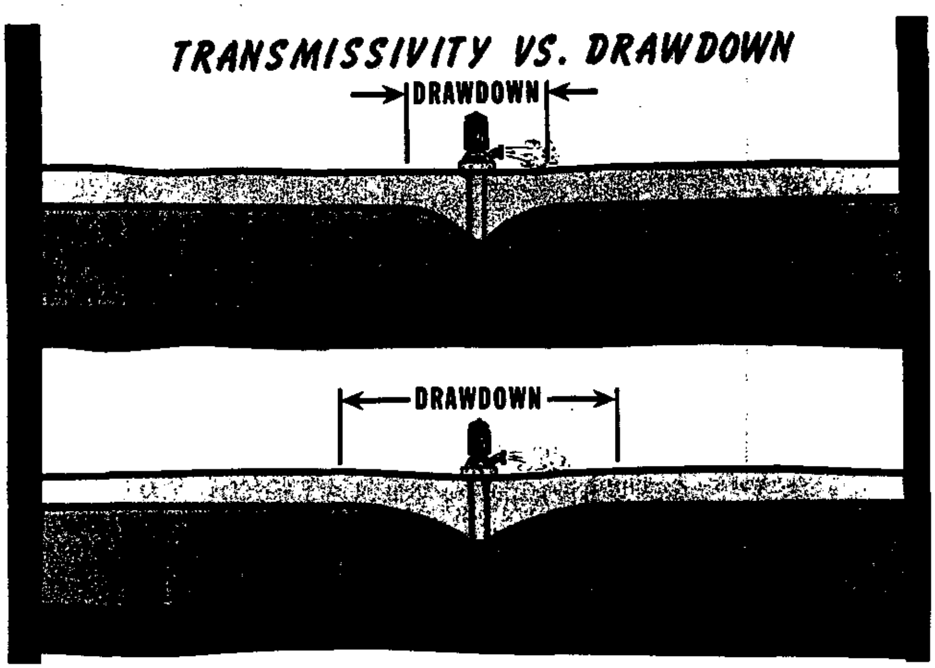
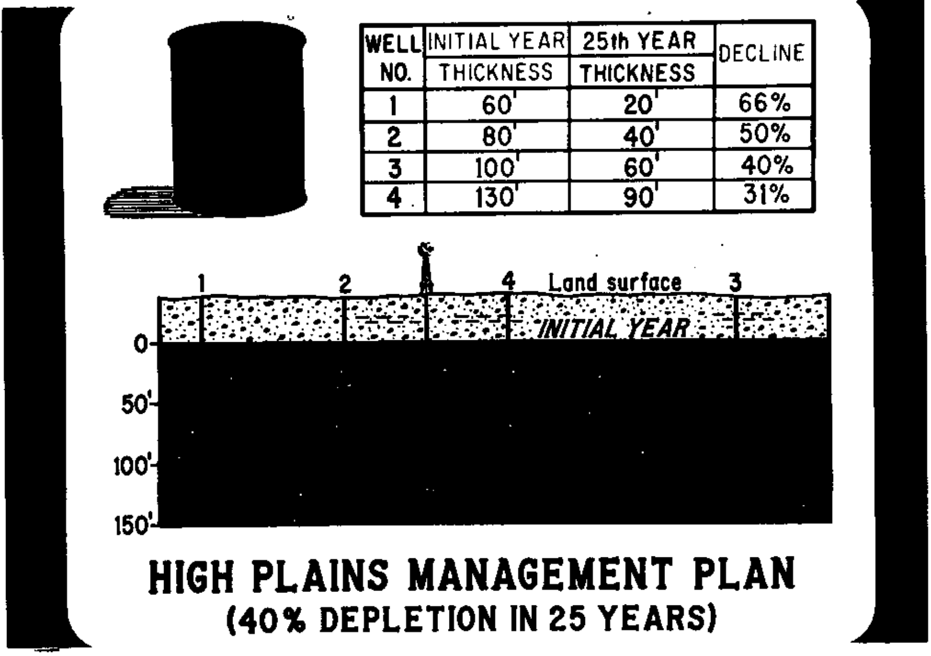


Figure 8



WELL NO.	INITIAL YEAR THICKNESS	25th YEAR THICKNESS	DECLINE
1	60'	20'	66%
2	80'	40'	50%
3	100'	60'	40%
4	130'	90'	31%

Figure 9

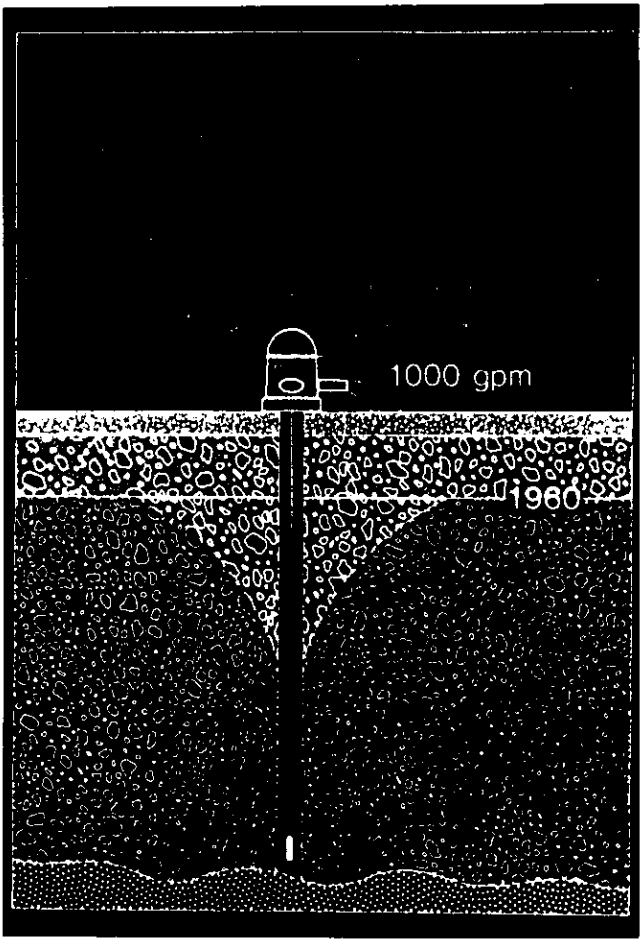


Figure 10

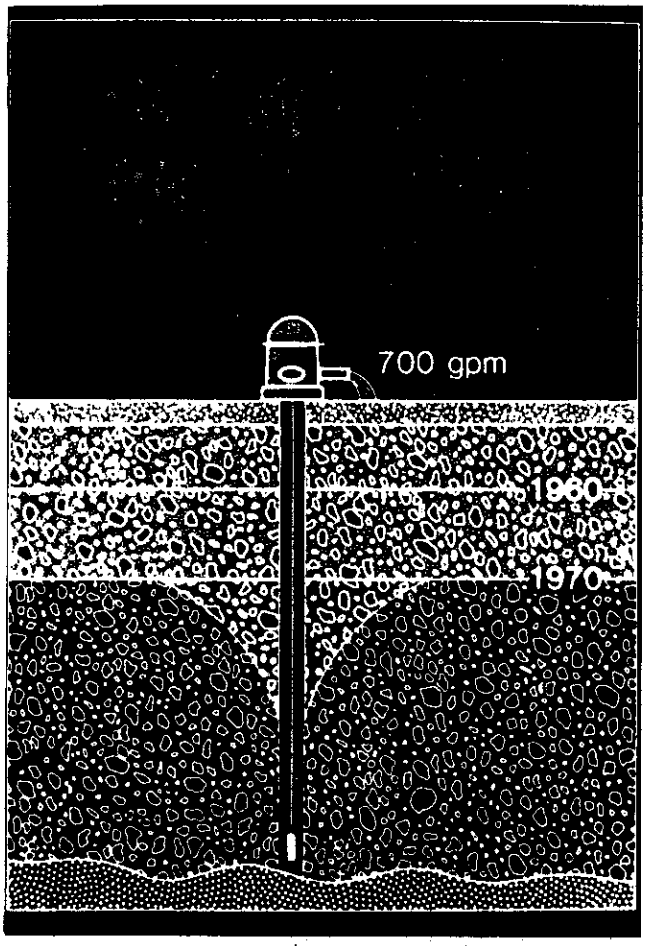


Figure 11

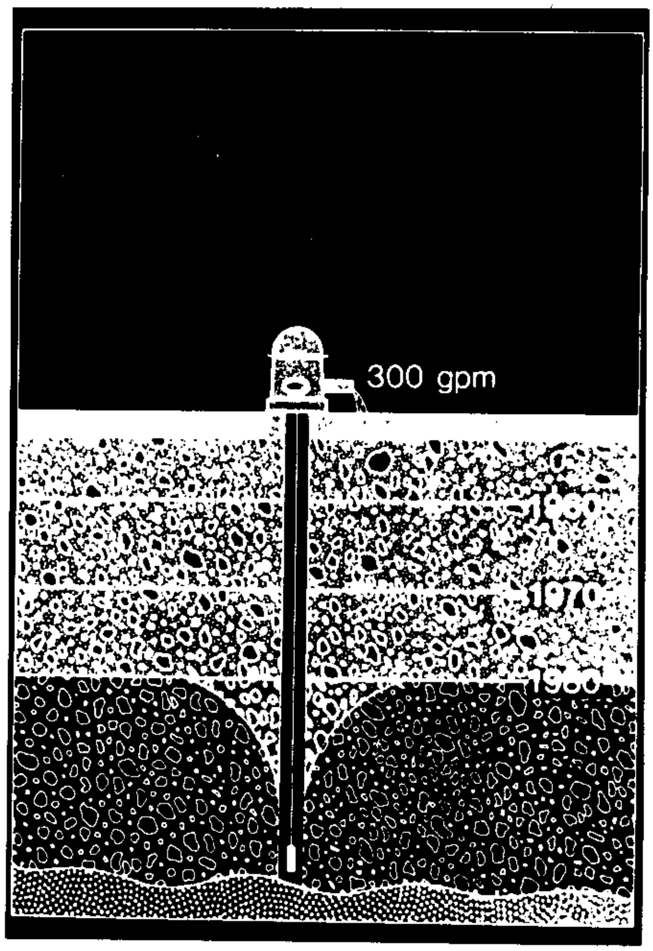


Figure 12

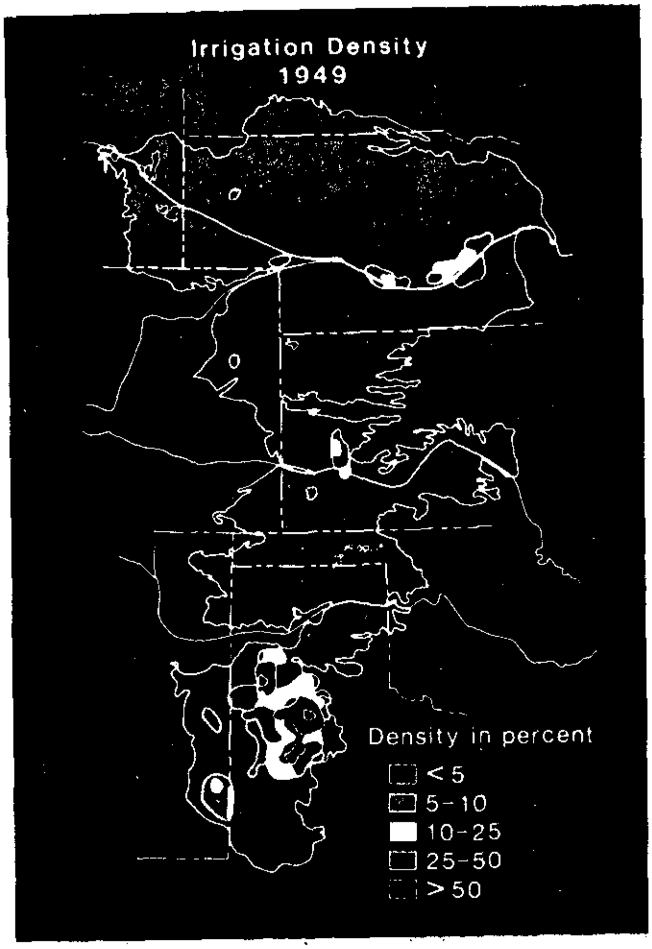


Figure 13

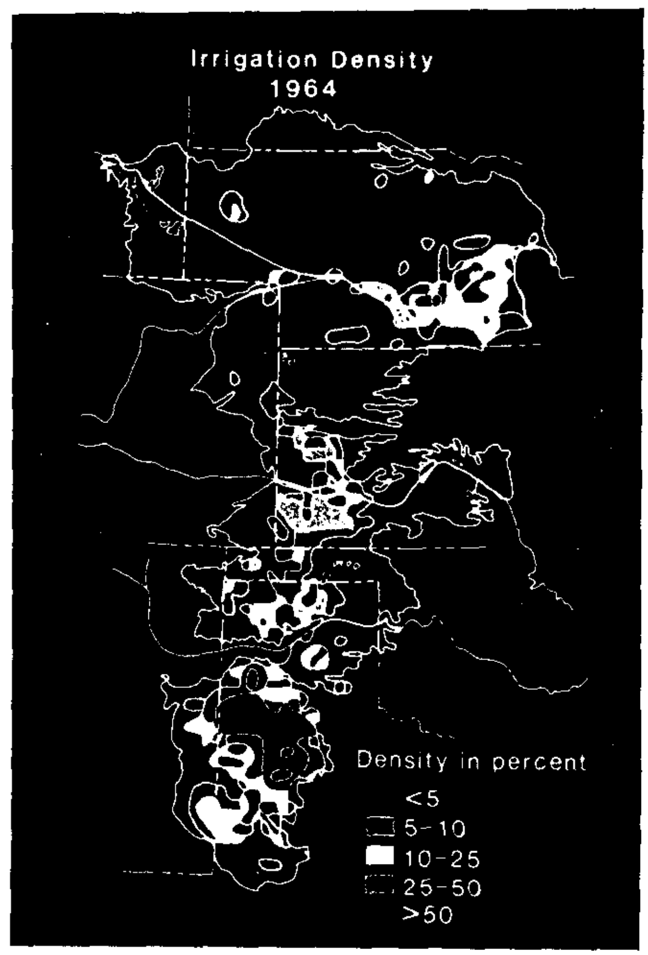


Figure 14

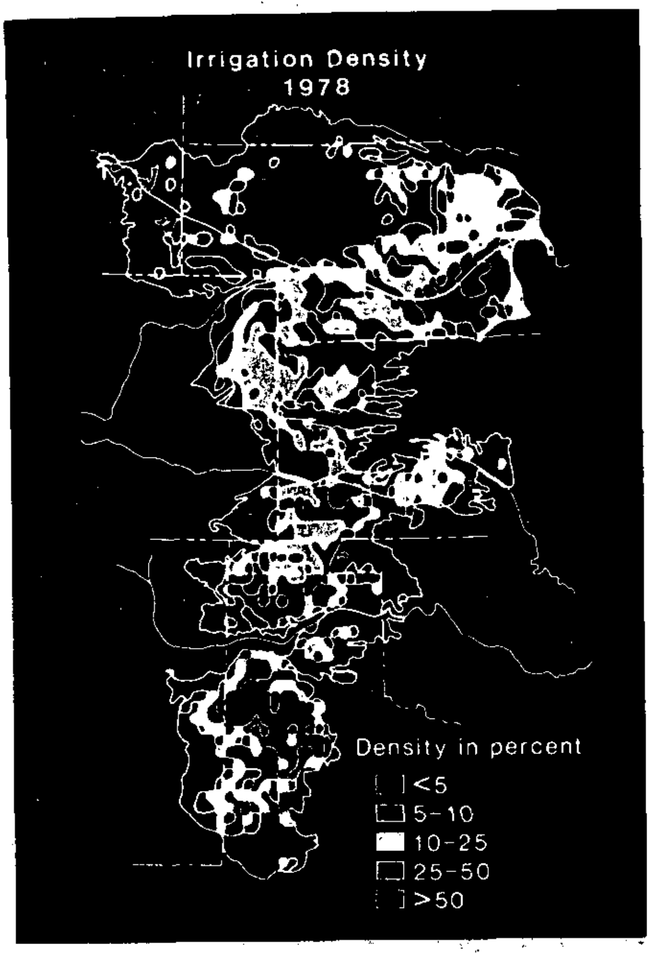


Figure 15

Figure 16

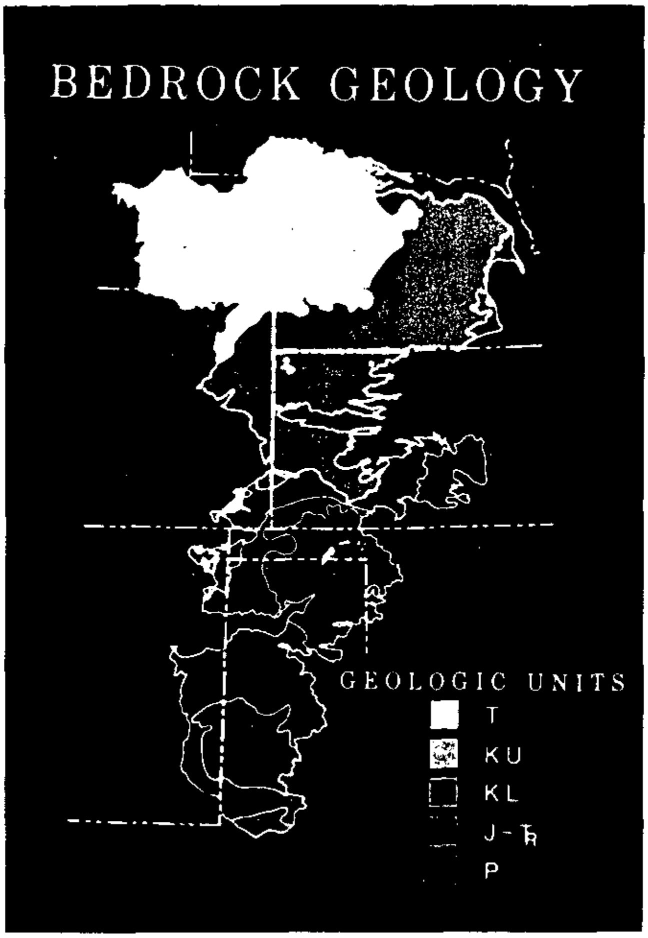


Figure 17

Figure 18

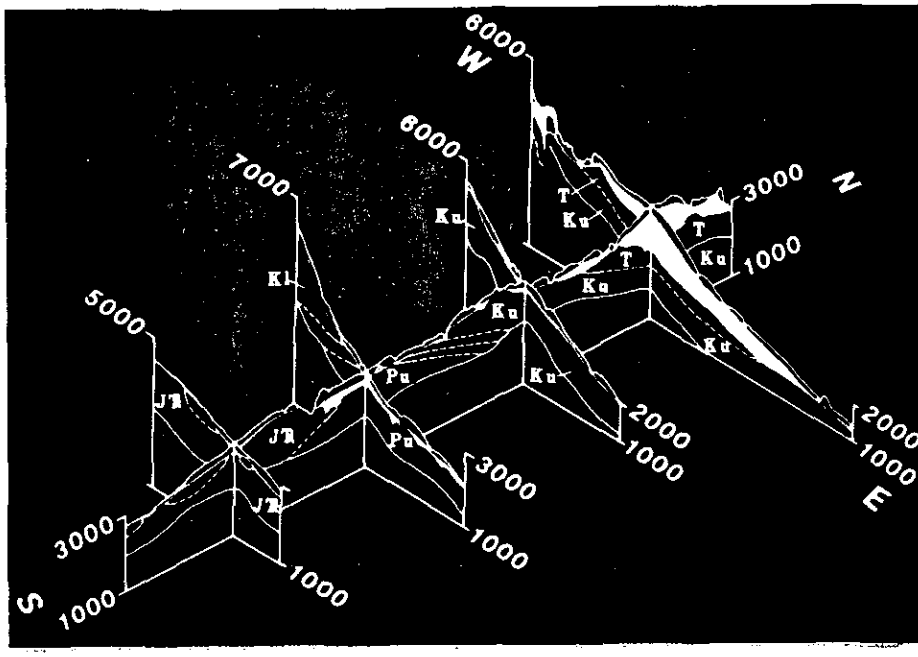


Figure 19

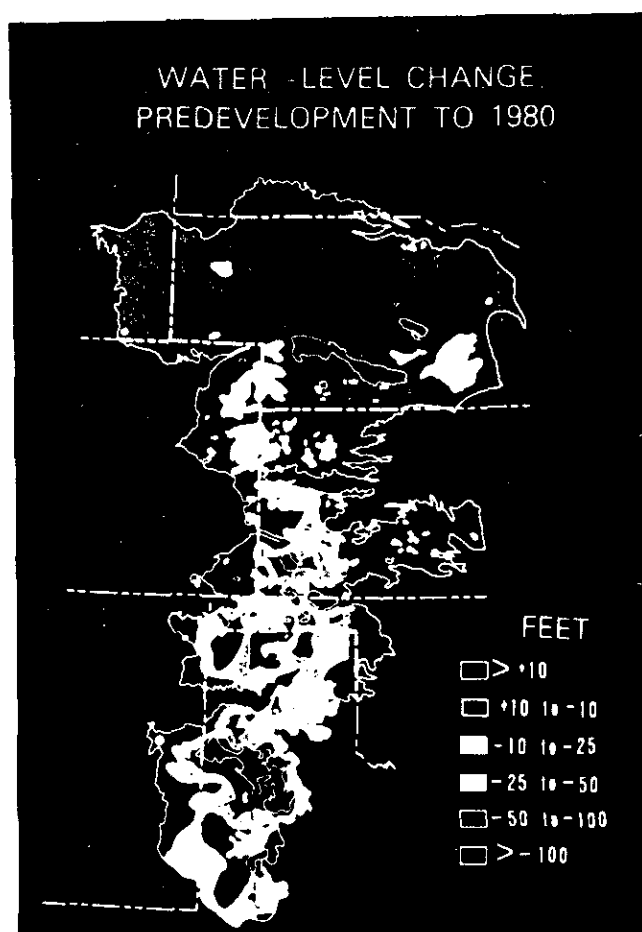


Figure 20

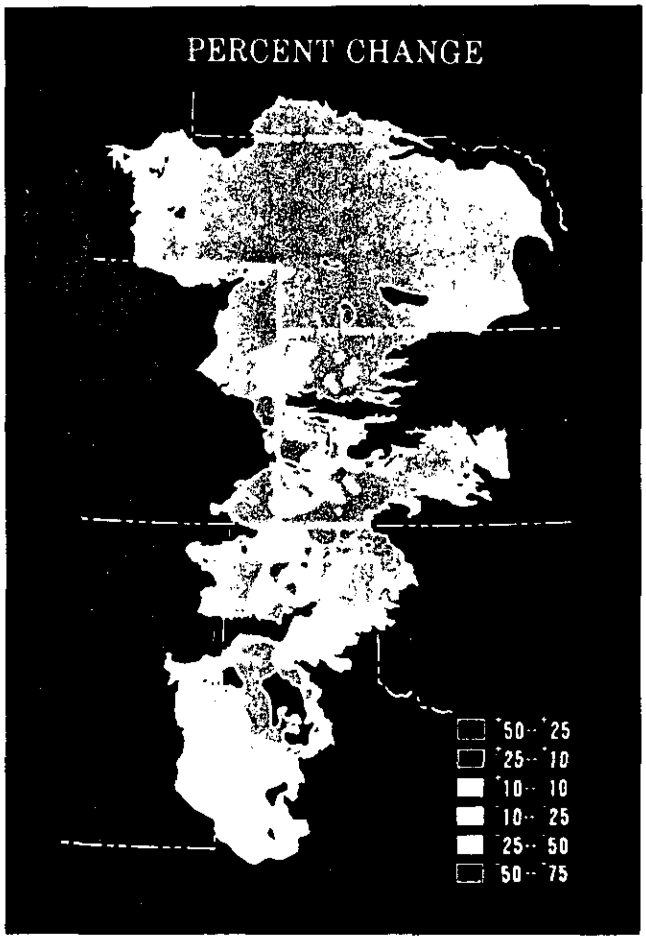


Figure 21

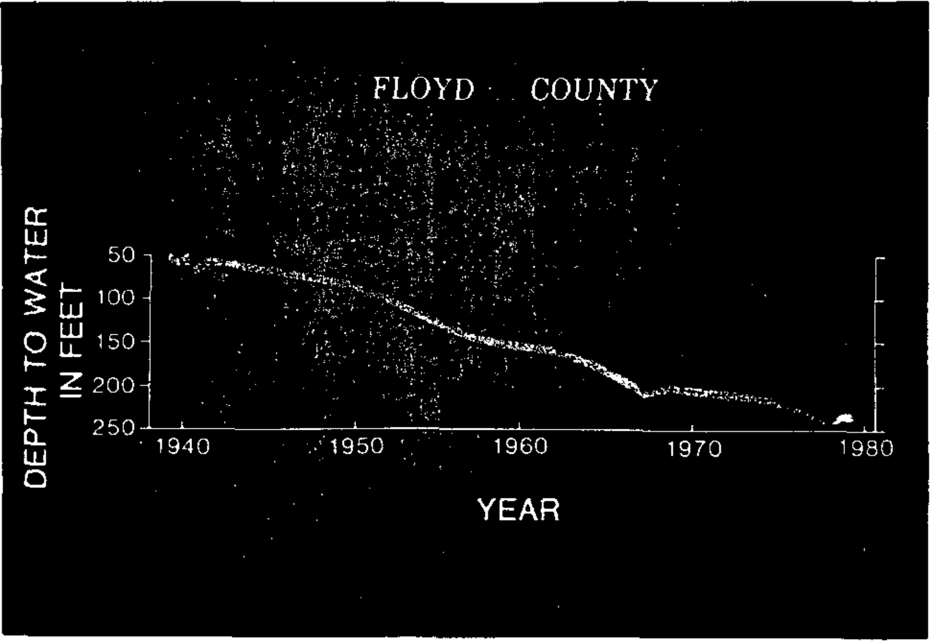


Figure 22

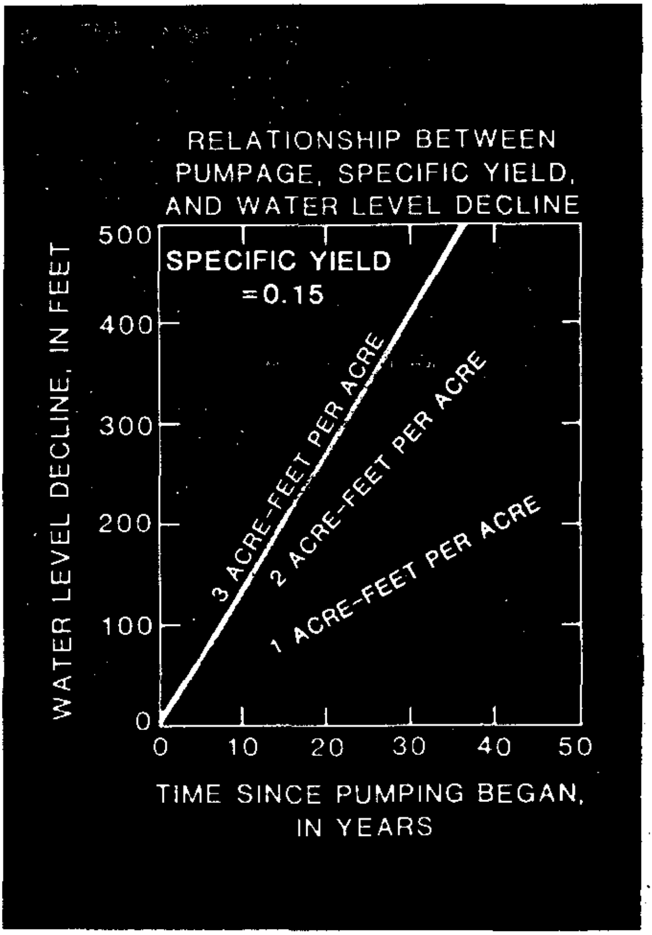


Figure 23