EFFECTS OF PAVED SURFACES ON RECHARGE TO THE FLORIDAN AQUIFER IN EAST-CENTRAL FLORIDA- A CONCEPTUAL MODEL

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CECIL D. ANDRUS, Secretary

U.S. GEOLOGICAL SURVEY
H. WIlliam Menard, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Suite 3015
227 N. Bronough Street
Tallahassee, FL 32301

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EFFECTS OF PAVED SURFACES ON RECHARGE TO THE FLORIDAN AQUIFER IN EAST-CENTRAL FLORIDA -- A CONCEPTUAL MODEL

By C.H. Tibbals

ABSTRACT

The proportionate amount of surface area that can be paved in Floridan aquifer recharge areas in east-central Florida without reducing the net recharge to the Floridan aquifer is a function of many variables that include rainfall, depth to water table, depth to potentiometric surface of the Floridan, evaporation from paved areas, evapotranspiration from unpaved areas, runoff, pattern of paving, and leakance coefficient of the confining beds. Equations that incorporate those variables, except pattern of paving, are developed and coupled to produce a conceptual model that estimates relative amounts of water available for recharge and percentage of unpaved area below which Floridan aquifer recharge rates must increase. An assumption inherent in the use of the model is that the excess water that runs off from the paved areas is placed in the nonartesian aquifer in the unpaved area so that the water table rises and thus increases the hydraulic head difference between the nonartesian and Floridan aquifers. Thus, water is driven across the confining beds and into the Floridan at a rate that is sufficiently increased so as to make up for the reduced area due to paving under which recharge actually occurs. Many assumptions and stipulations are made to simplify the model. The model is not intended to be used as a basis for engineering design. Rather, its purpose is to show approximate mathematical interrelations of rainfall, runoff, evapotranspiration, percentage of paving, and Floridan aquifer recharge, and to make quantitative estimates of amounts of water available for Floridan aquifer recharge before and after paving. The allowable percentage of paving calculated in 4 examples ranges from 86.8 percent to 3.6 percent.

INTRODUCTION

The east-central Florida region is an area of 7,051 square miles comprising Lake, Volusia, Seminole, Orange, Brevard, Osceola, and Indian River Counties (fig. 1). Continuing growth and development in the region is increasing demand for its ground-water resources. Except for Brevard and Indian River Counties, all the counties of the region depend entirely on ground water from the Floridan aquifer for public water supplies. The Floridan aquifer is an areally extensive limestone aquifer that underlies all of Florida and parts of Alabama, Georgia and South Carolina. In Brevard and Indian River Counties, the Floridan contains brackish water so, except for the cities of Melbourne and Cocoa, public supplies are obtained from shallow, nonartesian (unconfined) aquifers. Melbourne obtains water from Lake Washington (fig. 1) and Cocoa imports water from a Floridan aquifer wellfield in east Orange County.

In east-central Florida, water in the Floridan aquifer is confined under artesian pressure and is derived from overlying nonartesian aquifers. Where the water levels in nonartesian aquifers are above the artesian pressure surface (potentiometric surface) of the Floridan aquifer, water from the nonartesian aquifers leaks downward through confining beds and into the Floridan. The amount of water available for downward leakage depends upon amounts of rainfall, runoff and evapotranspiration.

Increasing urbanization reduces downward leakage and increases runoff by increasing the impervious areas associated with development. When the increased runoff from these areas is intercepted and disposed of by whatever means (sewers, streams, and so forth), the amount of water available for ground-water recharge is reduced. A balancing effect is that of reduced evapotranspiration under the impervious surface.

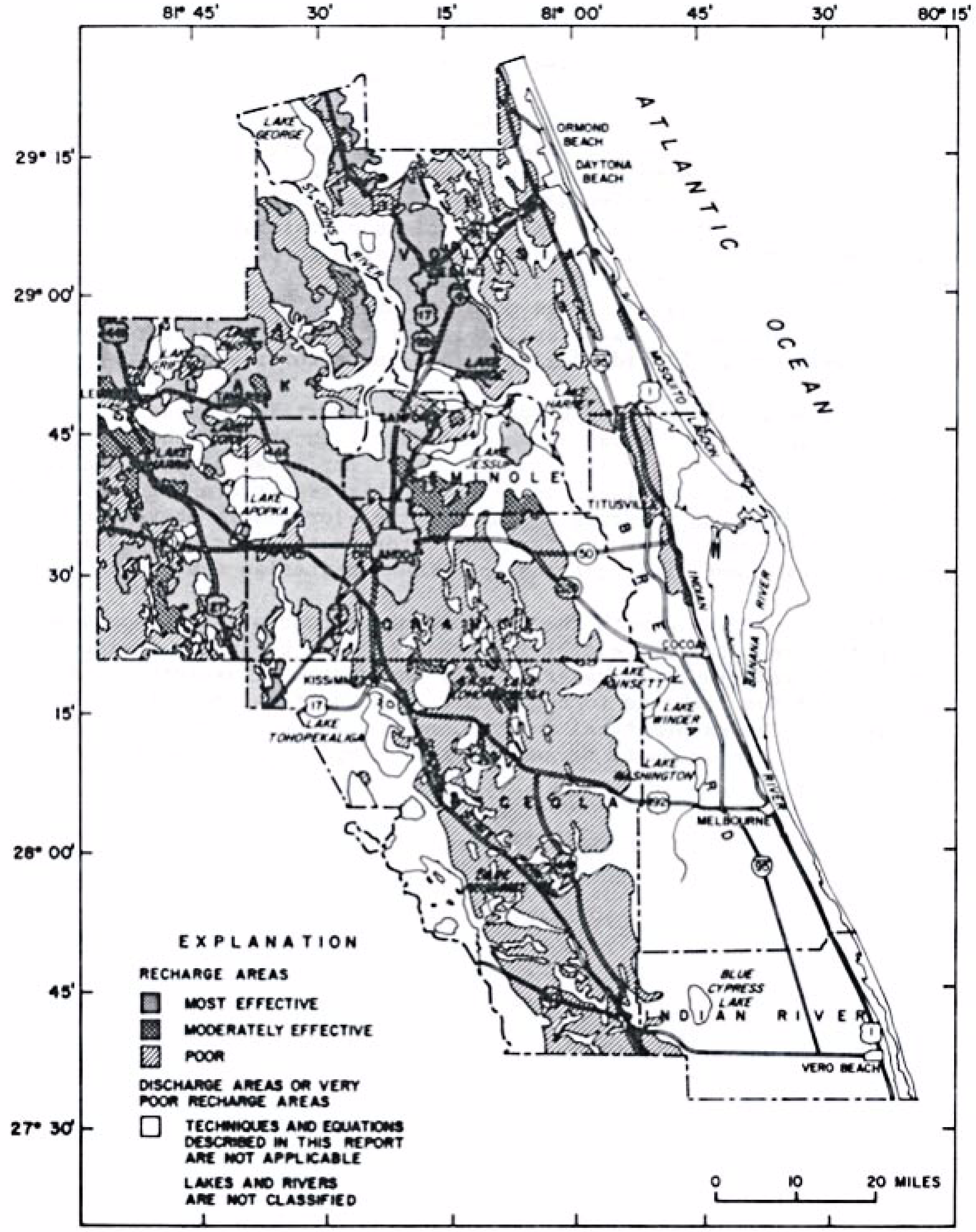


Figure 1.--Recharge and discharge areas of the Floridan aquifer in east-central Florida (adapted from Lichtler, 1972).

Purpose and Scope

The purpose of this report is to illustrate that recharge to the Floridan aquifer need not be reduced by development, providing that a means of emplacing increased runoff into the nonartesian aquifer is available. Based on simplified concepts, a mathematical model is developed to show approximate interrelations of rainfall, runoff, evapotranspiration, depth to water table, depth to potentiometric surface of the Floridan aquifer, percent impervious (paved) area, and Floridan aquifer recharge. This model is used to make quantitative estimates of amounts of water available for Floridan aquifer recharge in the east-central Florida region before and after paving.

The conceptual model developed in this report is considered applicable in all land areas shown on figure 1 except for those shown as discharge areas of the Floridan aquifer. For those discharge areas, the techniques and equations described in this report are not applicable because the artesian pressure surface of the Floridan is above the water levels in the nonartesian aquifers and water in the Floridan leaks upward through confining beds and into the nonartesian aquifers.

This report deals with the development of concepts and should not be regarded as either a feasibility study or as a basis for engineering design. In addition, the water quality and aesthetic aspects of using runoff water for recharge to the nonartesian aquifers are not considered. The mathematical derivations for the conceptual model are inelegant but are adequate because of many simplifying assumptions or stipulations.

Notation and Units

The notation and units used in this report are as follows

Before Paving	After Paving	Definition
n.a	c	Fractional paving expressed as decimal fraction of a unit area,
Ω	Ω	Average rainfall (in/yr),
f_1	$\phi_2=\phi_1+\mu(1-c)$	Average net surface and subsurface runoff (in/yr),
T'_1	T'_2	Average evapotranspiration from unpaved area (in/yr),
$T_1=T'_1$	$T_2=T'_2(1-c)$	Average net evapotranspiration -- evapotranspiration rate from unpaved area prorated over entire unit area (in/yr),
n.a	ε'	Average evaporation from paved area (in/ yr),
n.a.	$e=e'c$	Average net evaporation -- evaporation rate from paved area prorated over entire unit area (in/yr),
T_α	T_α	Assumed transmissivity of Floridan aquifer (100,000 ft^2/d),
T	T	Actual transmissivity of Floridan aquifer (ft^2/d),
$\propto$	$\propto$	$T/T\alpha$ (dimensionless),
ρ_1	ρ_2	Average depth to potentiometric surface of Floridan aquifer (ft),
n.a	$\Delta\rho$	Buildup of potentiometric surface of Floridan aquifer under unpaved area ft assuming $T = T_\alpha$,
n.a	$\Delta\rho_\propto$	Buildup of potentiometric surface of Floridan aquifer under unpaved area corrected for actual transmissivity, $\Delta\rho_\propto = (\Delta\rho)/_\propto$ (ft),

Before Paving	After Paving	Definition
ω_1	ω_2	Average depth to water table in non-artesian aquifer under unpaved area
χ_1	χ_2	Average head difference between water table and potentiometric surface of Floridan aquifer under unpaved area (ft)
n.a.	$\chi_3=\chi_2-\chi_1$	Increase in head difference between water table and potentiometric surface of Floridan aquifer under unpaved area after paving (ft),
θ'_1	θ'_2	Average recharge to Floridan aquifer under unpaved area (in/yr),
$\theta_1=\theta'_1$	$\theta_2=\theta'_2(1-c)$	Average net recharge to Floridan aquifer -- recharge rate under unpaved area prorated over entire unit area (in/yr),
n.a.	μ	Increase in average surface and subsurface runoff after paving, expressed as rate for unpaved area only (in/yr),
ℓ	ℓ	Leakance coefficient of confining bed expressed as rate per foot of head (in/yr)/ft,
n.a.	N	Number of computer-model nodes used to define the simulated area in which n recharge well nodes are located; N = 1296,
n.a.	n	Number of recharge well nodes N nodes of the area simulated model,
n.a.	K’	Hydraulic conductivity of confining bed as used by computer model (ft/d).

For those readers who wish to use metric units rather than U.S. customary units, the conversion factors for the terms used in this report are listed below:

Multiply U.S. customary unit	By	To obtain metric unit
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
inch per year	83.33	millimeter per year per meter (mm/yr)/m
(in/yr)/ft square mile (m	2.5899	square kilometer km^2

HYDROLOGIC CYCLE

The elements of the hydrologic cycle in east-central Florida are rainfall, surface and subsurface runoff, evapotranspiration, leakage to or from the Floridan aquifer, pumpage, and changes in amounts of water in storage in the nonartesian and Floridan aquifers (fig. 2). In this report, all time-dependent hydrologic parameters including ground-water levels are considered to be long-term averages, therefore, short-term fluctuations in amounts of water in storage in the nonartesian and Floridan aquifers are neglected. Pumpage from the nonartesian aquifer in Floridan aquifer recharge areas (areas where the conceptual model is applicable) is so small that in this report, it is neglected.

In east-central Florida, average annual rainfall over the Floridan aquifer recharge areas (fig. 1) is about 52 in. and ranges from 50.92 in north Lake County to 53.32 in. at Sanford (U.S. Environmental Data Service, 1975). Annual runoff ranges from 0 to 20 in. (Kenner, 1966).

Evapotranspiration is a major item in the hydrologic cycle. It occurs in essentially three modes; (1) from plant surfaces and bare ground, (2) from the unsaturated zone (above the water table but beneath land surface), and (3) directly from the water table. The maximum potential evapotranspiration from a free water surface in east-central Florida is about 48 in/yr (Visher and Hughes, 1969). However, potential evapotranspiration is not maximum over all of east-central Florida because in much of the area the water table is below the land surface and, in many areas, below plant root zones. In areas where the water table is far below land surface, water in the nonartesian aquifer is less subject to uptake by plants (transpiration) or direct evaporation from the water table than where the water table is at land surface and acts as a free water surface.

No matter how far below land surface the water table stands, there most likely is some minimum or base rate of evapotranspiration. This base rate is determined by evaporation and transpiration that takes place before water that is residual from rainfall minus surface runoff can percolate to the water table. Estimates of this base rate of evapotranspiration range from 25 to 35 in/yr (Warren Anderson, oral commun., October 13, 1975). In this report, 30 in/yr (Knochenmus and Hughes, 1976, p.15) is used as the base rate of evapotranspiration.

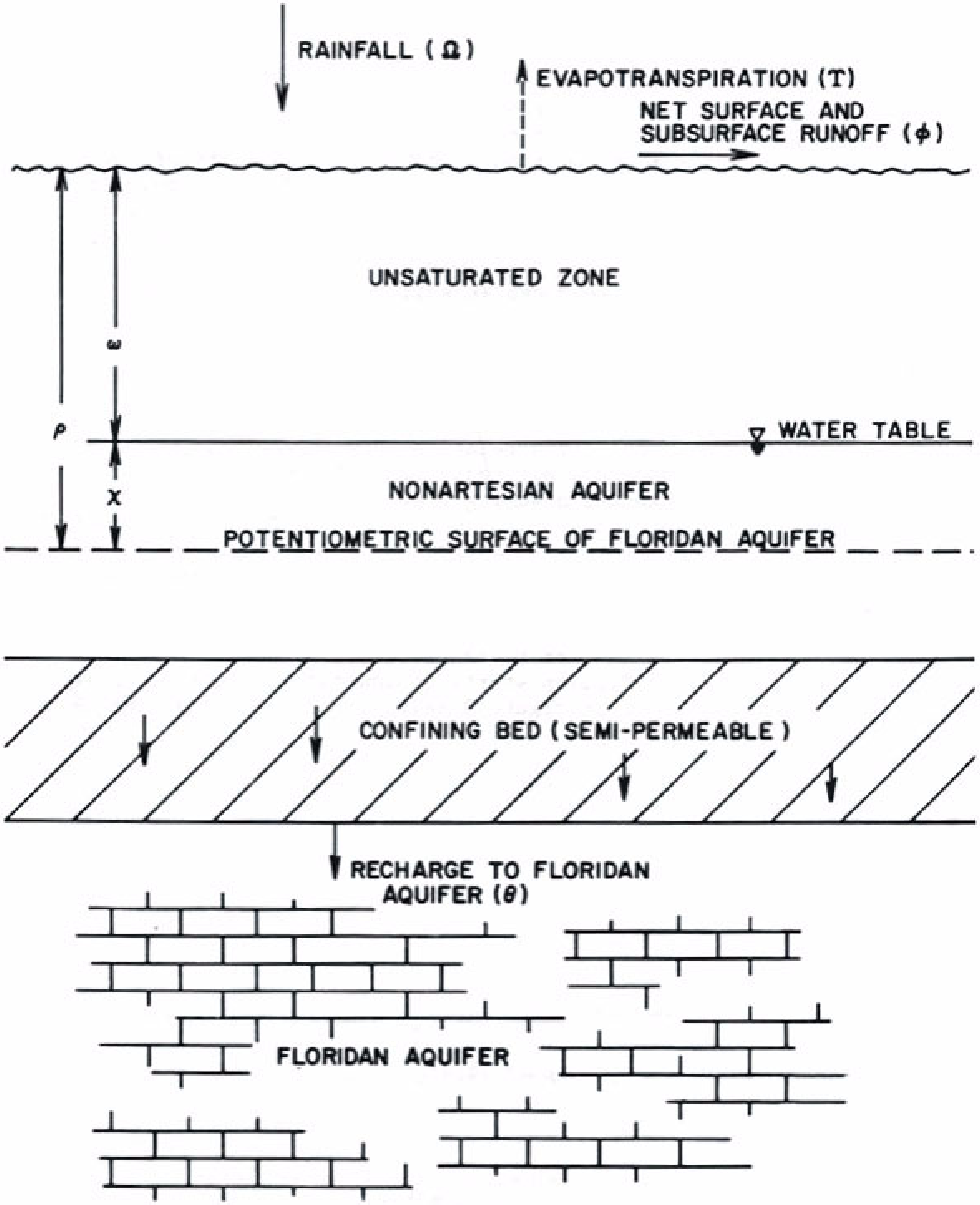


Figure 2.--Geohydrologic section showing basic elements of the hydrologic cycle in east-central Florida.

The actual evapotranspiration rate depends upon depth to water table, soil type, type of plant community, humidity, the amount of incoming energy (sunlight and wind), and the availability of water to be evapotranspired. On an areal and long-term annual basis, humidity, incoming energy, and available water can be regarded as fairly constant and uniformly distributed in east-central Florida. Different soil types and plant communities are not uniformly distributed, but for the purposes of this report, differences in soil type and plant communities are not considered a major factor in determining variability of actual evapotranspiration because depth to water table helps determine the plant community and the soil type. Therefore, depth to water table is used as the indicator of the actual rate of evapotranspiration.

It is useful to estimate a relation between depth to water table and average evapotranspiration in east-central Florida. The graph shown in figure 3 was constructed assuming that 48 in/yr is the maximum evapotranspiration rate when depth to water table is zero and that evapotranspiration asymtotically approaches a base rate, say 30 in/yr, at depths greater than 13 ft (Emery and others, 1971). Emery’s work pertains to Colorado, where the amount of evapotranspiration and its distribution in time differs considerably from that in east-central Florida. However, this author feels that the depth, as determined by Emery, that evapotranspiration starts to approach a minimum, has transfer value. The equation in figure 3 describes the shape of the curve.

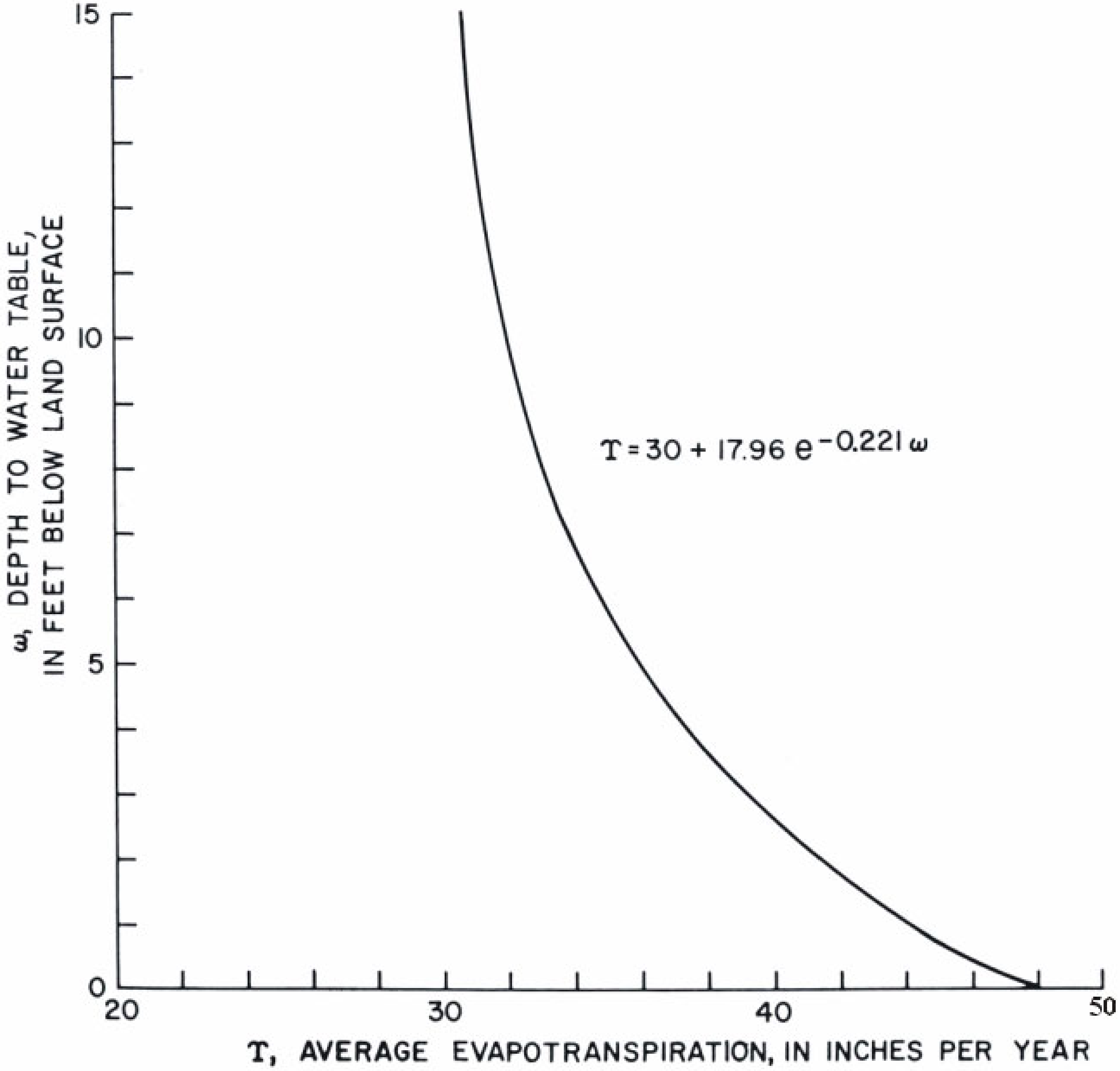


Figure 3.--Estimated relation of water-table depth to evapotranspiration in east-central Florida.

DEVELOPMENT OF CONCEPTUAL MODEL

The amount of water available for recharge to the Floridan aquifer depends on the amount that percolates to the nonartesian aquifer after losses due to surface runoff, surface evaporation, and evapotranspiration from the unsaturated zone. Some of the water that percolates to the nonartesian aquifer can still discharge laterally as subsurface runoff to lakes or streams that incise the nonartesian aquifer and, if the water table is less than, say, 13 ft below land surface, some water can return to the atmosphere by evapotranspiration from the water table. The water that remains in the nonartesian aquifer after losses resulting from subsurface runoff and evapotranspiration from the water table eventually leaks downward through the confining beds and recharges the Floridan aquifer.

The basis for formulation of the conceptual model is that the excess water that runs off from paved areas under developed conditions is somehow placed in the nonartesian aquifer in the unpaved area so that the water table builds up or “mounds” under the unpaved area and thus increases the hydraulic head difference between the nonartesian and Floridan aquifers. Thus, water is driven across the confining beds and into the Floridan at an increased rate that is sufficient to make up for the reduced area of recharge resulting from paving.

Though it is assumed that recharge will occur under only the unpaved areas, it is probable that some of the water placed in the non-artesian aquifer will move laterally under the paved arias and thence move downward into the Floridan. The effect of such “run-under” in terms of the model results is to cause more water to be recharged because: (1) The water which moves under the paved area is not lost by evapotranspiration; (2) the loss' of water under the unpaved area would lower the water level and tend to reduce evapotranspiration; and, (3) the area through which recharge occurs to the Floridan is increased. Conversely, however, less water would be recharged due to the reduction in gradient across the confining bed because of lower water levels under the unpaved area. The amount and extent of such “run-under” would vary with pattern and percentage of paving, initial depth to water table, and vertical and horizontal hydraulic conductivity of the materials that comprise the nonartesian aquifer. A comprehensive evaluation of “run-under” is beyond the scope of this report.

The following are assumptions or stipulations inherent in the use of the model:

(1) All parameters are areal and temporal averages.

(2) The excess water from paved areas is evenly distributed as recharge to the nonartesian aquifer in unpaved areas and results in uniform buildup of the water table in the nonartesian aquifer.

(3) The average water table in unpaved areas will be allowed to rise no higher than within 2 ft (feet) of the average land surface.

(4) The infiltration capacity of the soil in unpaved areas does not limit the amount of water that can ultimately recharge the Floridan aquifer.

(5) No recharge to the Floridan or nonartesian aquifers occurs under paved areas.

(6) Surface runoff can be controlled (stored, and redirected if necessary).

(7) The assumed relation of depth to water table in the nonartesian aquifer to evapotranspiration in east-central Florida is valid.

(8) The effects of different patterns of paving are not considered except in one example where such calculation was made for the purpose of comparison.

(9) Any increase in surface runoff leaving the area is assumed not to be detrimental to receiving areas.

(10) The model is applicable only for land areas. Some surface and subsurface runoff from a land area may ultimately recharge the Floridan aquifer via leakage through a stream or lake bottom.

The results obtained from use of the model should not be regarded as that which definitely will occur if a certain percentage of an area is paved. Rather, the model implies that, after paving part of a Floridan aquifer recharge area, sufficient water is available to increase the net recharge rate if: (1) the rejected water from the paved area is somehow uniformly placed in the nonartesian aquifer; (2) the water table rises and is maintained no higher than within 2 ft of land surface; (3) the estimates of rainfall, runoff, evapotranspiration, depth to potentiometric surface of the Floridan aquifer, depth to water table, and leakance coefficient of confining beds are valid; and (4) the amount of increased net runoff that occurs after paving is as assumed.

The vertical and horizontal hydraulic conductivities of the fine-to-medium sands that comprise the nonartesian aquifer in the Floridan aquifer recharge areas are probably at least one order of magnitude greater than that of the clayey sands that comprise the Floridan aquifer confining beds (Chow, 1964, ch. 13, p.10). The thickness of the confining beds in the Floridan aquifer recharge areas is generally no more than three times that of the nonartesian aquifer. So, in terms of steady-state ground-water flow, the hydraulic characteristics of the nonartesian aquifer do not limit the rate of recharge to the Floridan aquifer. However, the nature of storm runoff from paved areas is such that large quantities of water are available to infiltrate the non-artesian aquifer in a relatively short period of time. Therefore, in order for the model results to be valid it must be assumed that there would be installed holding ponds, seepage galleries, or other works so the storm water from the paved areas could be placed in the nonartesian aquifer.

The model results should be corrected for the buildup of potentiometric surface of the Floridan aquifer under the unpaved area. To do that, the transmissivity of the Floridan aquifer should be known or estimated and the pattern of paving must be considered.

The annual net recharge to the Floridan aquifer (fig. 2) is given by $\theta = \Omega - T - \phi$ where θ is in in/yr; Ω is the average rainfall in in/yr; T is the average evapotranspiration (all three components as previously discussed), in in/yr; and ϕ is the net average runoff (surface and subsurface) in in/yr.

The estimated average evapotranspiration (T) is given by

$$T=30+17.96\varepsilon^{-0.221\omega}\ (\phi\iota\gamma.\ 3)$$

where T is in in/yr; e is the base of natural logarithms; and w is the average (areal and temporal) depth to the water table, in ft.

The rate of leakage or recharge (θ') through a confining bed is determined by the hydraulic head difference across the confining bed by the thickness and hydraulic conductivity of the confining bed. The average (areal and temporal) hydraulic head difference (χ) across a confining bed is given by

$$\chi=\rho-\omega$$

where χ is in ft; ρ is the average depth to the potentiometric surface of the Floridan aquifer, in ft; and ω is as previously defined.

The parameters that quantify confining bed thickness and hydraulic conductivity of the confining bed are herein combined and are referred to as the leakance coefficient (ℓ). When the net recharge (θ) is equal to the rate of leakage (θ') through a confining bed (as under unpaved conditions), the leakance coefficient is expressed as

$$\ell=\theta/\chi=\theta'/\chi$$

where ℓ is in (in/yr)/ft and θ and χ are as previously defined.

In equations that follow, the numerical subscript "$_1$" following a parameter describes a hydrologic condition preceding paving. Similarly, the subscript "$_2$" means the parameter describes a hydrologic condition after paving. A parameter having no subscript has the same value before and after paving or, by definition (see Notation and Units) it requires no qualifying subscript. Then, under unpaved conditions (fig. 4),

$$\theta_1=\Omega-T-\phi_1, \qquad (1)$$

$$T=30+17.96e^{-0.221\omega 1}\ \text{(fig. 3)} \qquad (2)$$

$$\chi_1=\rho-\omega_{1,} \qquad (3)$$

$$\ell=\theta 1/\chi_{1,} \qquad (4)$$

$$\theta' 1=\chi_1\ell, \qquad (5)$$

$$\theta 1=\theta'_1 \text{ when } c = 0 \qquad (6)$$

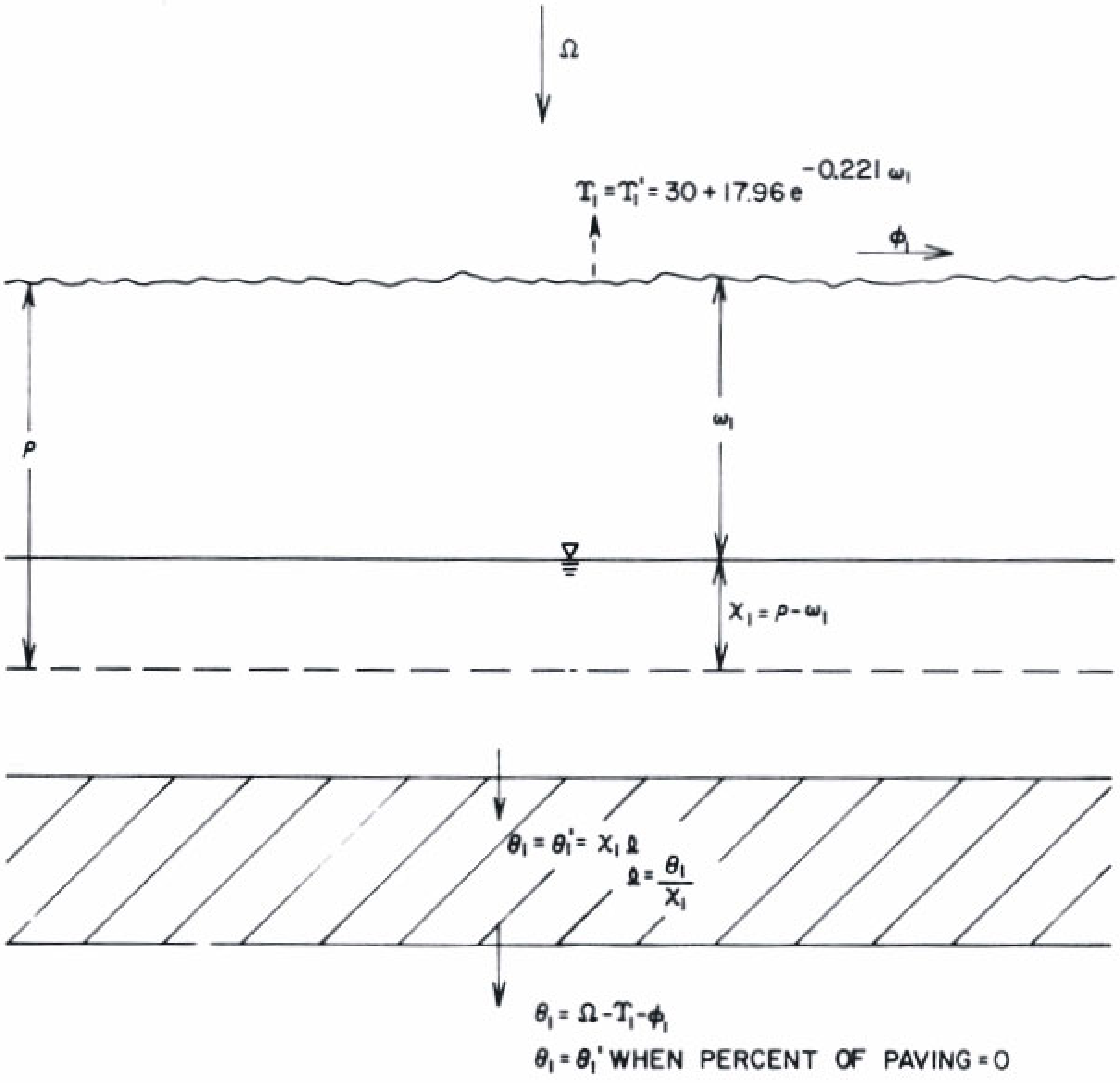


Figure 4.--Unpaved geohydrologic section showing hydrologic relations used to develop equations 1-6.

and, under partially-paved conditions (fig. 5),

$$T'_2=30+17.96e^{-0.221\omega 2,} \qquad (7)$$

$$\chi_2=\rho-\omega_{2,} \qquad (8)$$

$$\theta'_2=(\chi_{2/}\chi_1)\theta'1=\chi_2^{\ell}, \qquad (9)$$

$$\theta_2=\theta'_2(1-c)=\chi_2^{\ell}(1-c), \qquad (10)$$

and

$$\theta_2=\{\Omega-T'_2-\mu\}(1-c)+c(\Omega-\varepsilon')-\phi_1 \qquad (11)$$

where c is fractional paving expressed as a decimal fraction; p is the increase in runoff rate from the <u>unpaved</u> area, in in/yr; and all other parameters and their subscripts are as previously described. Equation is simplified and solved for c, thus obtaining

$$c=\frac{\theta_2-\Omega-T'_2+\phi_1\pm\mu}{T'_2+\mu-\varepsilon'} \qquad (12)$$

Equations 10 and 11 are equated, simplified, and solved for c, obtaining

$$c=\frac{\Omega-T'_2-\chi_2^{\ell}+\phi_1\pm\mu}{\varepsilon'-T'_2-\chi_2^{\ell}-\mu} \qquad (13)$$

Net evapotranspiration rate after paving (T_2) is the evapotranspiration rate from the unpaved area (T'_2) prorated over the entire unit area so that

$$T_2=T'_2(1-c) \qquad (14)$$

Similarly, net evaporation rate after paving is the evaporation from the paved area prorated over the entire unit area, thus

$$\varepsilon=\varepsilon'c \qquad (15)$$

If the net recharge rate after paving (82) is, for the purposes of calculation, to be a known value then the increase in runoff from the unpaved area after partial paving can be calculated by rearranging equation 11 to obtain

$$\mu=\frac{\{\Omega-T'_2-\mu\}(1-c)-\theta_2+c(\Omega-\varepsilon')-\phi_1}{(1-c)} \qquad (16)$$

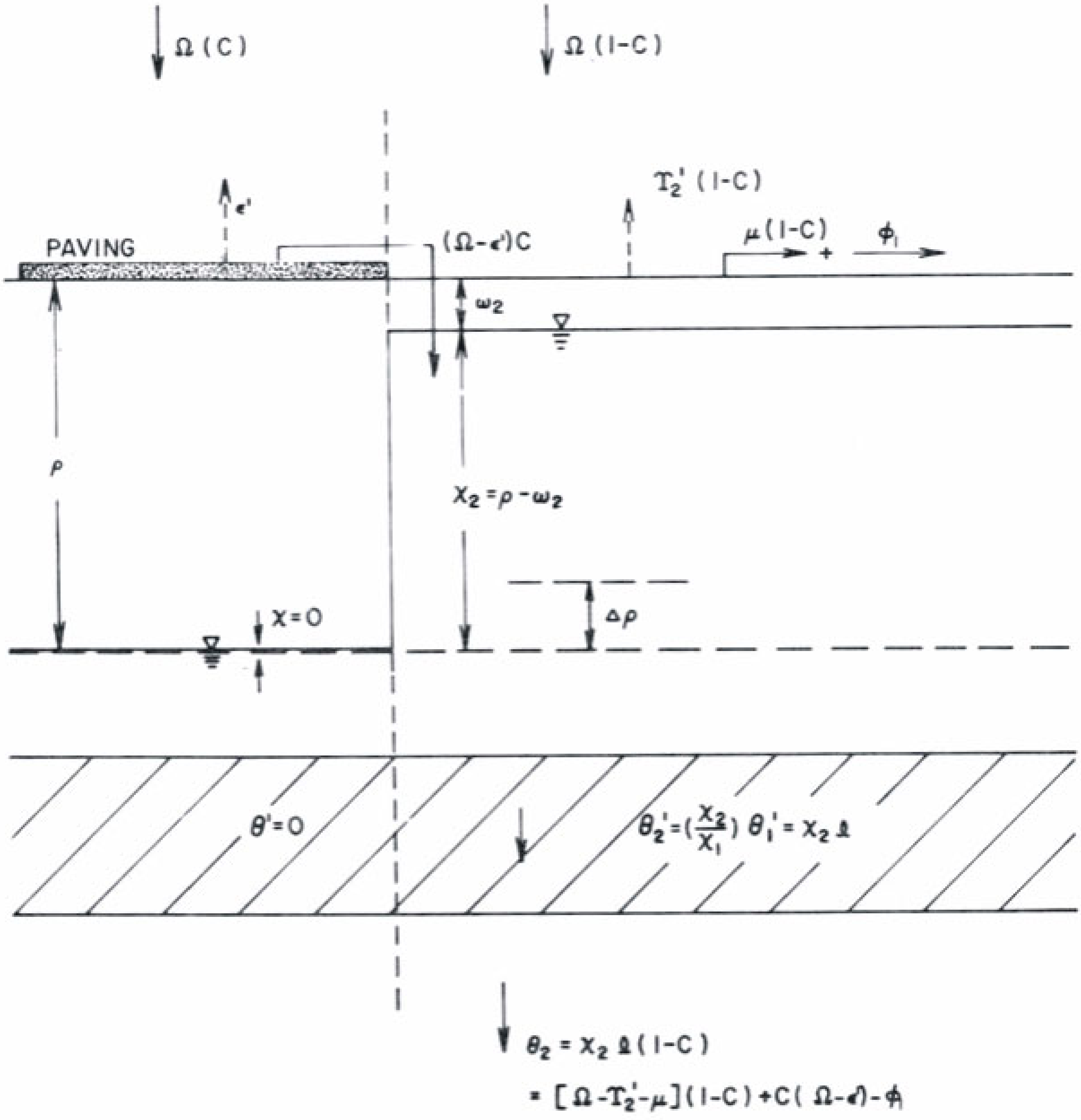


Figure 5.--Partially-paved geohydrologic section showing hydrologic relations used to develop equations 7-17.

The net runoff rate after paving (ϕ_2) is the net runoff rate before paving (ϕ_1) plus the increase in runoff rate from the unpaved area (μ) prorated over the entire unit area. Thus

$$\phi_2=\phi_1+\mu(1-c) \qquad (17)$$

The model and its applicability to a field situation is demonstrated by examples. The examples chosen are four typical geohydrologic settings, each with two conditions of allowable net runoff after paving. The two cases are: (1) zero increase in runoff rate, and (2) unrestricted increase in runoff rate.

The results of each application of the model include:

(1) c, maximum fractional paving for: Case 1, no change in runoff, maximized recharge; Case 2, no change in recharge, unrestricted runoff. It is expressed as a decimal fraction of a unit area (eq. 13),

(2) θ_2, average net recharge rate to the Floridan aquifer after paving (in/yr) (eq. 10),

(3) ϕ_2, net surface and subsurface runoff rate after paving (in/yr) (eq. 17),

(4) T_2, net evapotranspiration rate after paving (eq. 14),

(5) ε, net evaporation rate after paving (eq. 15).

Minimum geohydrologic information needed to apply the model includes:

(1) Ω, average rainfall rate (in/yr),

(2) ϕ_1, average net surface and subsurface runoff rate prior to paving (in/yr),

(3) ρ, average depth to potentiometric surface Floridan aquifer (ft),

(4) ω_1, average depth to water table prior to paving (ft),

(5) w_2, minimum allowable average depth to water table in the unpaved area after paving (ft),

(6) μ, allowable increase in surface and subsurface runoff rate from the unpaved area (in/yr).

Example 1

Case 1 - No Allowable increase in Runoff After Paving

The geohydrologic setting for example 1 is that of a most effective recharge area (fig. 1) where there is relatively little head difference between the water table and the potentiometric surface of the Floridan, where both the water table and potentiometric surface are relatively far below land surface, and where there is little or no surface or subsurface runoff. The objective of this example is to determine what the fractional paving could be with no allowable increase in runoff (μ=0). For the purpose of this example let

Ω = 52 in/yr,

ϕ_1 = 1 in/yr,

ρ = 40 ft, (fig. 4)

ω_1 = 35 ft,

ω_2 = 2 ft,

and

μ = 0 in/yr (fig. 5).

The beginning steps in using the conceptual model for this example consist of determining the net recharge rate and head difference between the water table and the potentiometric surface of the Floridan aquifer under unpaved conditions and determining the leakance coefficient of the confining bed.

Using equation 1 and substituting equation 2 for T_1 then

$$\theta_1 = 52-\{30+17.96e^{-0.221(35)}\}-1=21 \text{ in/yr.}$$

Equations 3 and 4 yield, respectively,

$$\chi_1 = 40-35=5 \text{ ft}$$

and

$$\ell =21/5= 4.2 \text{ (in/yr)/ft}$$

The second step is to use equations 7 and 8 to obtain, respectively, (T'_2), the rate of evapotranspiration under the unpaved area when the water table is allowed to rise within 2 ft of land surface and (χ_2) the head difference between water table and the potentiometric surf ace under the unpaved area after paving. Then, according to equation 7

$$T'_2=30+17.96e^{-0.221(2)}=41.5 \text{ in/yr},$$

and, by equation 8

$$\chi_2=40-2=38 \text{ ft}$$

Now, assuming that, (1) the excess water from the paved area can somehow be placed in the nonartesian aquifer beneath the unpaved area and cause the water table beneath the unpaved area (ω_2) to rise within 2 ft of land surface, (2) the evaporation rate from the paved area (ε') is 3 in/yr, and ( ) runoff does not increase ($\mu=0$), then equation 13 is used to calculate fractional paving:

$$c=\frac{52-41.5-38(4.2)-\ell-0}{3-41.5-38(4.2)-0} = 0.758 \text{ (75.8 percent).}$$

Equation 10 is used to obtain the net recharge rate after paving, thus

$$\theta_2=38(4.2)(1-0.758)=38.6 \text{ in/yr}$$

The net evapotranspiration rate after paving (T_2) is equal to the evapotranspiration rate from the unpaved area (T'_2) prorated over the entire unit area so that by using equation 14

$$T_2=41.5(1-0.758)=10.0 \text{ in/yr.}$$

Similarly, the net evaporation rate after paving (ε) is the evaporation rate from the paved area (ε') prorated over the entire unit area. Thus, by equation 15,

$$\varepsilon=\varepsilon'(c)=3(0.758)=2.3 \text{ in/yr.}$$

In this example (Example 1, Case 1), no increase in runoff from the unpaved area is allowed, therefore $\mu=0$. But the net runoff rate after paving is allowed to equal the net runoff rate before paving, so, by equation 17

$$\phi_2=\phi_1+\mu(1-c)=1+0(1-0.758)=1 \text{ in/yr.}$$

The results of calculations for Case 1 are summarized in table 1. Note that, the net recharge rate after paving (θ_2 = 38.6 in/yr) is 17.6 in/yr more than the net recharge before paving (θ_1). The net evapotranspiration rate after paving (T_2 = 10.0 in/yr) plus the net evaporation rate after paving (ε = 2.3 in/yr) is 17.7 in/yr less than the net evapotranspiration before paving (T_1 = 30 in/yr). Therefore, 17.7 in/yr of surplus water is available and assumed to recharge the nonartesian aquifer in the unpaved area (Note: the 0.1 in/yr discrepancy between the calculated net recharge rate and the calculated surplus water is because of rounding in the calculations). This raises the water table in the unpaved area and increases the head difference between the water table and the potentiometric surface and, thus, causes water to be driven downward, through the confining beds and into the Floridan aquifer at a rate (θ'_2 = 159.6 in/yr) which is 138.6 in/yr greater than the recharge rate before paving (θ'_1 = 21 in/yr). Prorating the recharge rate after paving (θ'_2 = 159.6 in/yr) over the entire unit area, the net recharge rate after paving is

$$\theta_2=\theta_2'1(1\text{-}c)=159.6(1\text{-}0.758)=38.6 \text{ in/yr.}$$

It should also be noted for this and other calculations that no loss is considered for the volume of water required to increase storage in the nonartesian aquifer. For a storage coefficient of 0.2, this case would require approximately 11 inches (on a unit area basis). Such losses would occur only during early times (first few years) and would not affect the computed steady-state estimates.

Table 1. --Results of calculations for Examples 1-4
(uncorrected for buildup of potentiometric surface of Floridan aquifer under unpaved area).

Example	Ω (in/yr)	ϕ_1 (in/yr)	ρ (ft)	ω_1 (ft)	T_1' (in/yr)	T_1 (in/yr)	θ_1' (in/yr)	θ_1 (in/yr)	χ_1 (in/yr)	ℓ (in/yr)	ε' (in/yr)
1 Case 1	52	1	40	35	30	30	21.0	21.0	5	4.2	3
Case 2	52	1	40	35	30	30	21.0	21.0	5	4.2	3
2 Case 1	52	1	30	20	30.2	30.2	20.8	20.8	10	2.1	3
Case 2	52	1	30	20	30.2	30.2	20.8	20.8	10	2.1	3
3 Case 1	52	10	20	8	33.1	33.1	8.9	8.9	12	0.74	3
Case 2	52	10	20	8	33.1	33.1	8.9	8.9	12	0.74	3
4 Case 1	52	10	30	3	39.3	39.3	2.7	2.7	27	0.10	3
Case 2	52	10	30	3	39.3	39.3	2.7	2.7	27	0.10	3

Table 1.--(Continued) Results of calculations for examples 1-4 (uncorrected for buildup of potentiometric surface of Floridan aquifer under unpaved area).

Example	$\underline{a}/\mu$ (in/yr)	ω_2 (ft)	T_2' (in/yr)	χ_2 (ft)	$\theta_1'=\chi_2^{\ell'}$ (in/yr)	c (in/yr)	θ_2 (in/yr)	T_2 (in/yr)	ϕ_2 (in/yr)	ε' (in/yr)
1 Case 1	0	2	41.5	38	159.6	0.758	38.6	10	1	2.3
Case 2	166	2	41.5	38	159.6	0.868	21	5.5	22.9	2.6
2 Case 1	0	2	41.5	28	58.8	0.507	29	20.5	1	1.5
Case 2	38.3	2	41.5	28	58.8	0.646	20.8	14.7	14.6	1.9
3 Case 1	0	2	41.5	18	13.3	0.247	10	31.2	10	0.7
Case 2	6.6	2	41.5	18	13.3	0.332	8.9	27.7	14.4	1.0
4 Case 1	0	2	41.5	28	2.8	0.056	2.6	39.2	10	0.2
Case 2	-0.7	2	41.5	28	2.8	0.036	2.6	40	9.3	0.1

Case 2 - Unrestricted Runoff After Paving

The objective of Example 1, Case 2 is to determine what the fractional paving could be if there were no restriction on the amount of increased runoff after paving (μ unrestricted) so long as the net recharge rate after paving (θ_2) is equal to the net recharge rate before paving (θ_1). Except for μ, values of the starting parameters (Ω, ϕ_1, ρ, ω_1, and ω_2) are the same as for Example 1, Case 1, and the values T'_1, θ_1, χ_1, ℓ, T'_2, and χ_2 derived in the first step calculations of Case 1 are identical to those of Case 2 thus

$\Omega = 52$ in/yr,

$\phi_1 = 1$ in/yr,

$\rho = 40$ ft,

$\omega_1 = 35$ ft,

$\omega_2 = 2$ ft,

$T'_1 = T_1 = 30.0$ in/yr,

$\theta_1 = 21$ in/yr,

$\chi_1 = 5$ ft

$\ell = 4.2$ (in/yr)/ft,

$T'_2 = 41.5$ in/yr,

and $\chi_2 = 38$ ft.

Because, in Case 2, θ_2 must equal θ_1, then θ_1 can be substituted for θ_2 in equation 10 and c can be solved for, thus obtaining

$$c = \frac{159.6-21}{159.6} = 0.868 \qquad \text{(86.8 percent)}$$

The increase in runoff rate from the unpaved area (p) can be calculated by using equation 16 to obtain

$$\mu = \frac{\{52-41.5\}(1-0.868)-21+0.868(52-3)-1}{(1-0.868)}$$

$$=166 \text{ in/yr.}$$

The net runoff rate after paving (ϕ_2) is equal to the net annual runoff rate before paving *(ϕ_1)* plus the increase in runoff rate prorated over the entire unit area; thus equation 17 is used to obtain

$$\phi_2=1+l66(1-0.868)=22.9 \text{ in/yr}$$

Net evapotranspiration rate after paving (T_2) is the evapotranspiration rate after paving (T'_2), prorated over the entire unit area; thus, according to equation 14

$$T_2=41.5(1-0.868)=5.5 \text{ in/yr}$$

Similarly, the net evaporation rate from the area after paving (ε) is the evaporation rate from the paved area, prorated over the entire unit area; thus equation 15 can be used to obtain

$$\varepsilon=3(0.868)=2.6 \text{ in/yr.}$$

The results of calculations for Case 2 are summarized in table 1.

Examples 2, 3 and 4

For Example 2, the geohydrologic setting is that of a recharge area (fig. 1) similar to that of Example 1 and having the same runoff rate (ϕ_1) and net recharge rate (θ_1) but with less depth to potentiometric surface of the Floridan (ρ), less depth to water table (ω_1), but about the same evapotranspiration rate (T_1), and with twice the head difference between the water table and the potentiometric surface (χ_1) (table 1). The method of application of the equations of the conceptual model for Example 2 is identical to that for Example 1 and the results are shown in table 1.

The fractional paving (c) calculated for Case 1 (no increase in runoff) and Case 2 (net recharge held constant, runoff allowed to vary) of example 2 are, respectively, 67 percent and 74 percent of that for Case 1 and Case 2 of Example 1. The calculated leakance coefficient (ℓ) is only half that determined in Example 1 thus the head difference (χ_2) between the water table and the potentiometric surface in Example 2 would have to be twice as large as in Example 1 to drive water across the confining bed at a rate (θ'_2) equivalent to that in Example 1. But in Example 2, the water table (ω_1) at the start is 15 ft closer to land surface than in Example 1 so, there is not enough room for the water table to rise enough to create twice the head difference between the water table and the potentiometric surface under the unpaved area (χ_2). This means the percentage of unpaved area under which recharge occurs must be larger in Example 2 than in Example 1 in order to recharge the same amount of water.

For Example 3, the geohydrologic setting is that of a moderately effective recharge area (fig. 1)--somewhat similar to that of Examples 1 and 2 but with more runoff (ϕ_1), shallower water table (ω_1), shallower Floridan aquifer potentiometric surface (ρ), slightly more head difference between the water table and the potentiometric surface (χ_1), and slightly less than half the net recharge rate (θ_1) (table 1).

The method of applying the equations of the conceptual model for Example 3 is identical to that for Examples 1 and 2; and the results are shown in table 1.

The fractional paving (c) calculated for Case 1 (no increase in runoff rate) and Case 2 (net recharge rate held constant, runoff rate allowed to vary) of Example 3 are, respectively, 33 percent and 38 percent of that for Case 1 and Case 2 of Example 1, and 49 percent and 51 percent of that calculated for Case 1 and Case 2 of Example 2.

For Example 4, the geohydrologic setting is that of a poor recharge area (fig. 1). The depth to the potentiometric surface (ρ) of the Floridan aquifer is the same as in Example 2 (most effective recharge area) and the runoff rate (ϕ) is the same as that in Example 3 (moderately effective recharge area), but, in comparison with any of the three previous examples, the depth to water table (ω_1) is less and the head difference (χ_1) between the water table and the potentiometric surface is greater (table 1). The method of applying the conceptual model for Example 4 is the same as for Examples 1-3, and the results are shown in table 1. Note that the calculated fractional paving (c) for Cases 1 and 2 is only 0.056 and 0.036 (5.6 percent and 3.6 percent)--very small in comparison with previous examples.

Correction for Buildup of Potentiometric Surface of Floridan Aquifer

In sample calculations thus far, the potentiometric surface of the Floridan aquifer is assumed to remain unaffected by increases in net recharge. This, of course, is unrealistic; therefore, the following text discusses a method of correcting conceptual model calculations to allow for buildup of the potentiometric surface of the Floridan.

The buildup of the potentiometric surface of the Floridan aquifer resulting from increased recharge depends on: (1) the rate of increased recharge, (2) the areas over which the increased recharge rate occurs (1-c), (3) the pattern of distribution of increased recharge, and (4) the transmissivity (the quantity of water that is transmitted through a unit width of aquifer per unit time under a unit hydraulic gradient) of the Floridan.

Many different patterns of paving are possible; potentiometric surface buildup solutions for all types of paving patterns are beyond the scope of this report. A solution for any particular pattern of paving is, however, obtainable by electronic digital computer using the U.S. Geological Survey finite-difference model for aquifer simulation (Trescott and others, 1976). The paving pattern assumed in using the model to obtain the curves of figure 6 is shown in that figure. Use of the computer model is explained in a later section of this report.

Figure 6 shows the assumed buildup of the Floridan aquifer potentiometric surface ($\Delta\rho_{\propto}$) as a function of fractional paving (c) and rate of increased recharge ($\chi_{3^{\ell}}$) using an assumed Floridan aquifer transmissivity (T_a) of 100,000 ft^2/d, and a paving pattern as shown in the figure. Figure a 7 gives the value of a by which the assumed potentiometric buildup ($\Delta\rho$) must be divided to obtain the estimated potentiometric buildup ($\Delta\rho_{\propto}$) corrected for actual transmissivity of the Floridan aquifer.

The method of correcting the conceptual model results for buildup of potentiometric level in the Floridan aquifer is demonstrated by correcting the results of Example 1, Case 1 (table 1). A first estimate is made of the increase in head difference between the water table and Floridan aquifer after paving by using

$$\chi_3=\chi_2-\Delta\rho_{\propto}-\chi_2$$

so that

$$\chi_3=38-0-5=33 \text{ ft.}$$

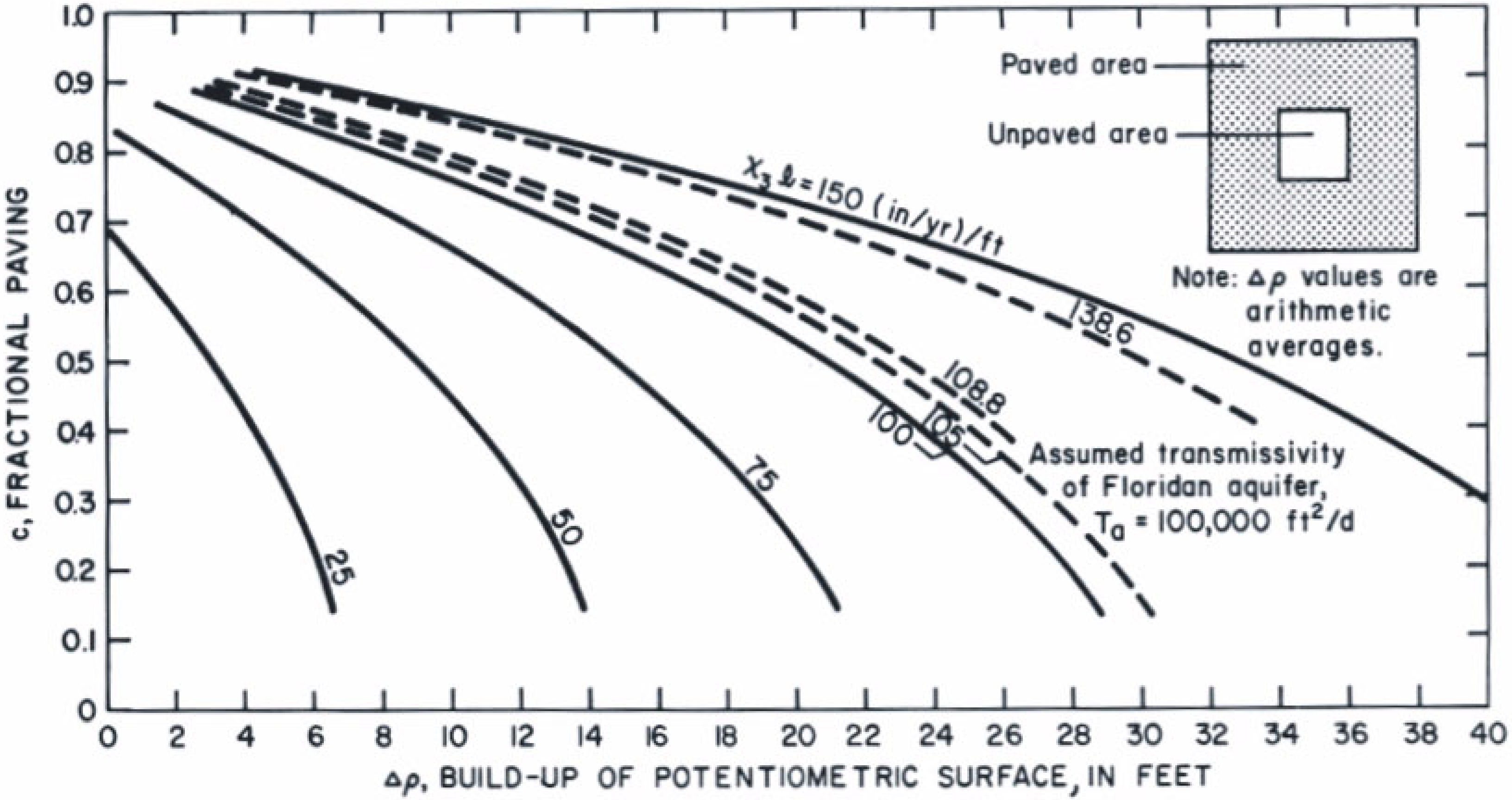


Figure 6.--Buildup of potentiometric surface (Δφ) as a function off fractional paving (c) and increase in recharge rate (x3ϑ) where initial recharge rate (θ1) is 21 in/yr.

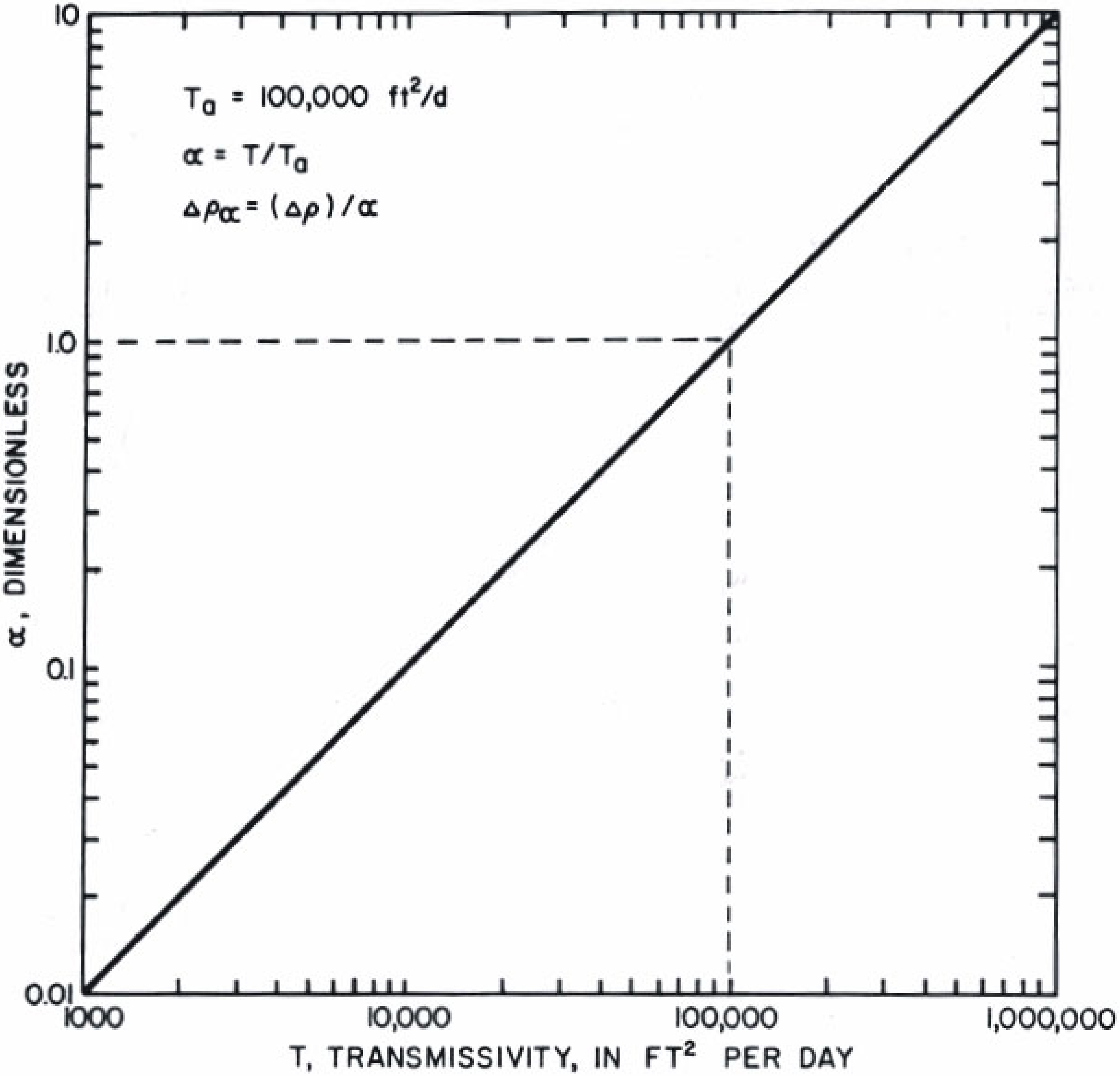


Figure 7.--Values of α (ratio of T to T_a) as a function of T

Then, a first estimate of χ_3^{ℓ} is made to obtain

$$\chi_3^{\ell}\ 33(4.2)=138.6\text{(in/yr)/ft.}$$

Referring to figure 6 and using the fractional paving (c) calculated in Example 1, Case 1 (table 1), c=0.758 and χ_3^{ℓ}=138.6 (in/yr)/ft, a first estimate of $\Delta\rho$ is obtained so that $\Delta\rho$=l6 ft. Now, if the actual transmissivity at this particular site is, say, 200,000 ft^2/d, then, from figure 7, $\propto$=2. Using

$$\Delta\rho_{\propto}=(\Delta\rho)/\propto, \qquad (19)$$

$$\Delta\rho_{\propto}=16/2=8.0\text{ ft.}$$

This is a first estimate of buildup of the potentiometric surface of the Floridan aquifer under the unpaved area, assuming c=0.758. However, because the potentiometric surface of the Floridan aquifer tends to build up under the unpaved area, the original value of c=0.758 is no longer valid because the equations of the conceptual model, and the parameters used in Example 1, Case 1, assumed the depth to the potentiometric surface would remain the same after paving. Hence, a new value of c is calculated, using the equations of the conceptual model but, in equation 13, χ_2 is replaced by $\chi_2-\Delta\rho_{\propto}$.

Then, using equation 13

$$c=\frac{52-41.5-\{(38-8)(4.2)\}-1-0.708}{3-41.5-((38-8)(4.2)\}-0}$$

A new value of χ_3 is calculated using equation 18, thus

$$\chi_3=38-8-5-25\text{ ft.}$$

A new value of χ_3^{ℓ} is also obtained;

$$\chi_3^{\ell}=25(4.2)=105\text{ (in/yr)/ft.}$$

Again referring to figures 6 and 7, and using the new values for c and χ_3^{ℓ}, new values for $\Delta\rho$ and $\Delta\rho_{\propto}$ are obtained. Hence, a new value for $\chi_2-\Delta\rho_{\propto}$ is obtained and, by using equation 13, a new value of c is calculated. This iterative process is repeated until the value of c does not appreciably change from that obtained in the previous Iteration. At this point the model results are assumed to be corrected for buildup of the potentiometric surface of the Floridan aquifer under the unpaved area. The results of correcting Example 1, Case 1 are listed in table 2.

Table 2. --Final results for Example 1, Case 1 showing correction for buildup of potentiometric surface of the Floridan aquifer under the unpaved area.

Iteration	c	$\chi_2 - \Delta\rho_\propto$ (ft)	$\chi_3 = \chi_2 - \Delta\rho_\propto - \chi_1$ (ft)	χ_3^ℓ (in/yr)/ft	$\Delta\rho$ (ft)	$\propto$	$\Delta\rho_\propto$ (ft)
First	0.758	38	33	138.6	0		0
Second	0.708	30	25	105.0	16	2.0	8.0
Third	0.715	30.9	25.9	108.8	14.2	2.0	7.1
Final	0.716	31	-	-	14.0	2.0	7.0

Computer Model Used to Correct Buildup of Potentiometric Surface of Floridan Aquifer

The computer model used in this report (Trescott and others, 1976) uses a digital computer program that calculates the head response of a confined or unconfined aquifer to simulated stresses (in this case, recharge) imposed on the aquifer. The geohydrologic conditions simulated here are those of an infinite, homogeneous, and isotropic confined aquifer bounded above and below by impermeable confining beds (fig. 8).

A grid of 60 rows and 60 columns is superimposed on the area to be modeled, dividing it into 3,600 finite-difference nodes (fig. 9). Each node simulates an area 1,000 ft square. Each node has assigned values for aquifer transmissivity, confining bed hydraulic conductivity, initial potentiometric head, storage coefficient, and pumping. Each of these parameters is input in the form of a matrix of 3,600 values, one for each node in the finite-difference grid.

The computer program uses the input parameters and an iterative, alternating-direction implicit procedure to solve two-dimensional ground-water flow equations for head values at each node. The head values calculated at each node are printed out by row and column and correspond to the finite-difference grid. A suite of head values is printed out at the end of each simulated pumping period, or, for the model simulated here, when steady-state (equilibrium) conditions are reached.

The transmissivity matrix has, with the exception of the outermost nodes, a value of 100,000 ft^2/d at each node. The outermost nodes have a transmissivity of 0 ft^2/d for reasons that relate to the model's computational process. The matrix of hydraulic conductivity of the confining bed has a value of 0 ft/d at each node to simulate an impermeable confining bed.

The initial potentiometric head matrix is arbitrarily set to zero at each node. The purpose in using the computer model is to determine the change in potentiometric head at each recharging node resulting from: (1) increased recharge at nodes that correspond to the unpaved area and (2) decreased recharge at nodes that correspond to the paved area. Therefore, the value of initial potentiometric head is irrelevant.

The water-table head matrix is set to an arbitrary value of zero because in this model, no water can leak through the confining beds, therefore, the head difference between the nonartesian aquifer and the artesian aquifer does not affect the model computations.

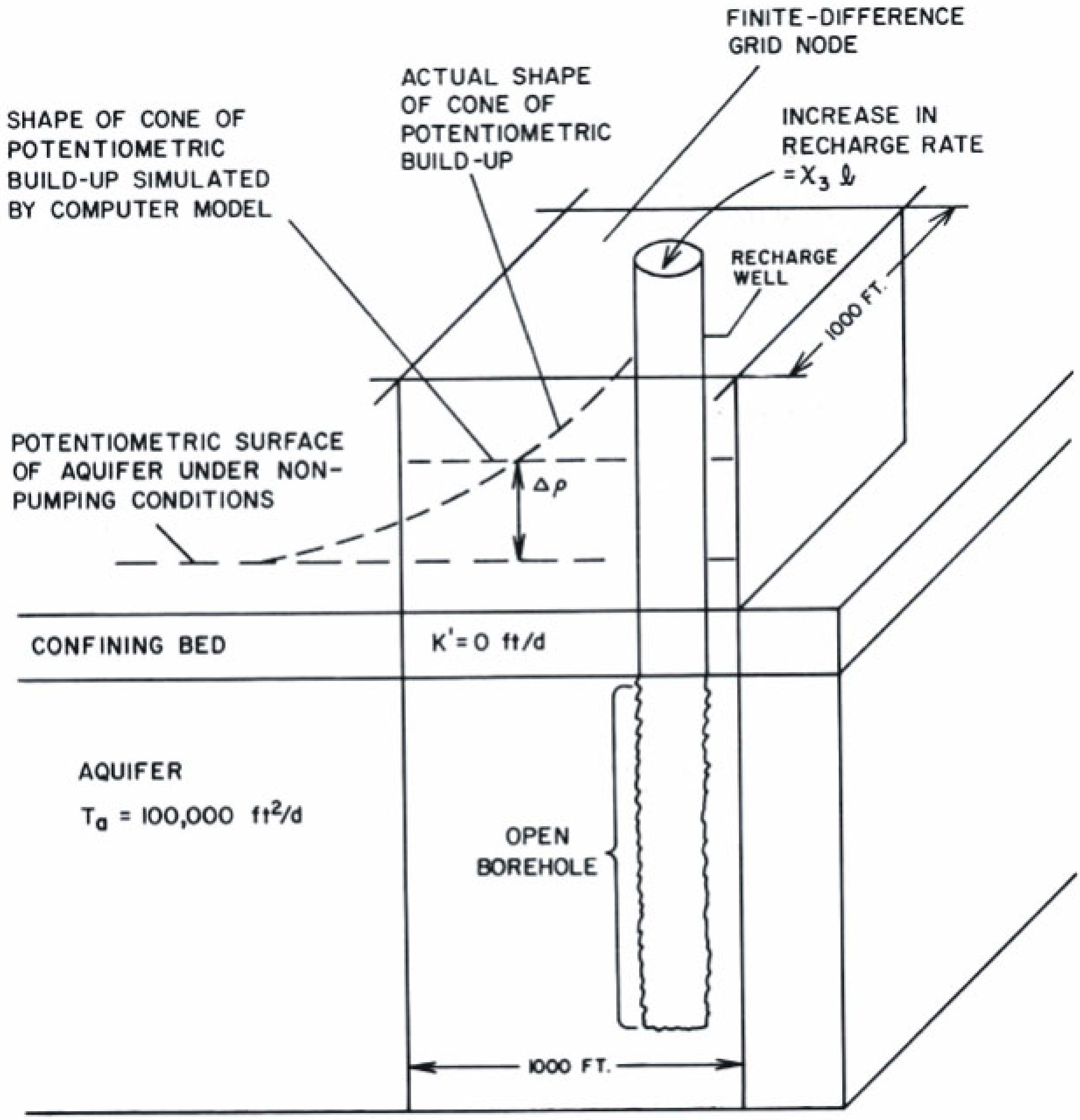


Figure 8.--Geohydrologic conditions simulated by computer model for a recharging node.

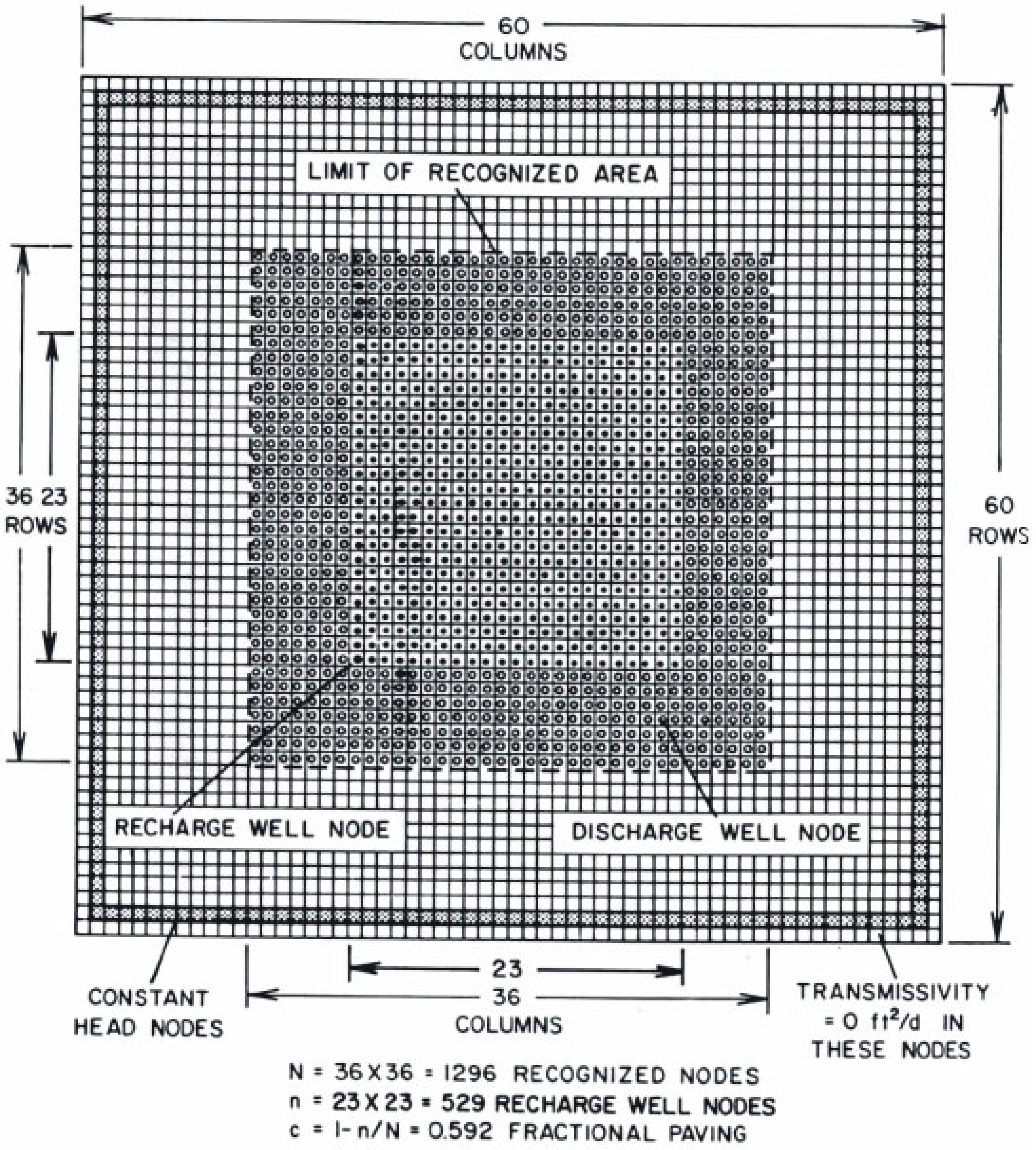


Figure 9.--Layout of finite-difference grid of computer model with recharging well nodes in "close-packed" configuration.

With the exception of the next-to-outermost nodes, the storage coefficient matrix has a value of zero at each node because the computer model is to simulate steady-state conditions. For the next-to-outermost nodes the storage coefficient is set to -1. The model treats these as constant-head nodes (fig. 9) that act, collectively, as four line sinks that, for computational purposes, remove water from the edges the simulated aquifer system.

The matrix that simulates changed recharge rates on a node-by-node basis is actually a matrix of recharging and discharging wells. The wells in unpaved nodes recharge at a rate equal to the increase in recharge rate after paving. The wells in paved nodes discharge at a rate equal (but of opposite sign) to the recharge rate prior to paving.

The wells are presumed to be located at the centers of their respective nodes (fig. 8), the computer model treats each well's recharge or discharge water as if the water enters or leaves the aquifer uniformly over the entire area of each node where a recharge or discharge well is located. This causes the model to compute a discrete average value of head change at each node (fig. 8) as if the head change occurred uniformly over the node area. Because the aquifer is presumed to be homogeneous and isotropic, it makes no difference, in terms of the model's computational process, whether the water is presumed to enter or leave the aquifer by leaking vertically into a node, or radially as it would by way of an actual recharging or discharging fully penetrating well.

During the computer model run, the computed head change within every node of the model is due to the cumulative head change caused by the nodes that have recharging or discharging wells. Thus, the head buildup in a recharge well node is the sum of the head buildup within the node resulting from its recharge well plus the cumulative head buildup due to all the other nodes that have recharge wells minus the cumulative head decline due to the nodes that have discharge wells.

The average head buildup in nodes that have recharge wells is a function of the number of nodes that have recharging and discharging wells, the spacing of the recharge and discharge well nodes, the recharge or discharge rate of the wells, and the aquifer transmissivity.

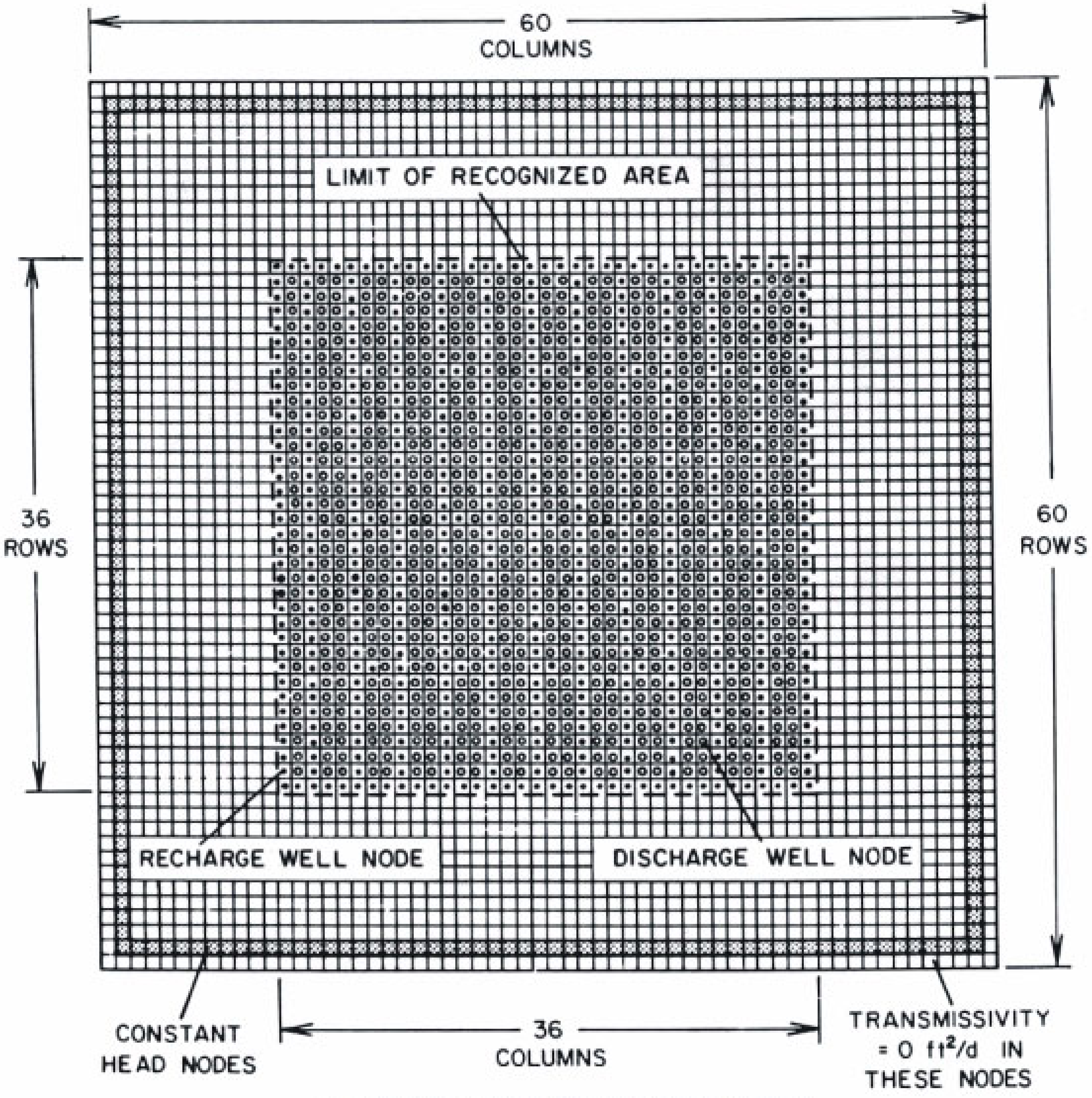
The outer boundary of the "paved" node area serves to define the "recognized" part of the aquifer where changed recharge rates occur and is used to calculate the value of c from

$$c=1-n/N \tag{20}$$

where n is the number of nodes that have recharging wells, and N is the number of nodes (in this report N = 1296) in the portion of the aquifer that is to be dealt with, or “recognized” (fig. 9). The computer model matrix is made larger than the recognized area to reduce the effects of the constant-head boundaries on the model results.

The number of recharge and discharge wells can be varied in order to simulate the effects of different percentages of paving on the buildup of potentiometric head in the Floridan aquifer. The distribution of the recharge and discharge wells within the model’s recognized area can be varied in order to simulate different patterns of recharge.

The pattern of recharge simulated to construct the curves of figure 6 is that of a rectangular area within the rectangular-shaped recognized area. This pattern is “close-packed”; each node in the recharging area contains a recharging well and every node within the recognized area (exclusive of the recharge nodes) contains a discharging well. This distribution pattern of recharging wells causes the model to calculate an average head buildup of 67 ft in the recharging nodes whereas the same number of recharging wells dispersed throughout the recognized area in “semi-strip” fashion would give a head buildup of only 4.2 ft (fig. 10 and table 3).



$N = 36 \times 36 = 1296$ RECOGNIZED NODES

$n = 529$ RECHARGE WELL NODES

$c = 1 - n/N = 0.592$ FRACTIONAL PAVING

Figure 10.--Layout of finite-difference grid of computer model with recharging well nodes in "semi-strip" configuration.

Table 3. --Results of correcting Floridan aquifer potentiometric head buildup in unpaved area for two different patterns of paving.

	Paving Pattern	
Computer model parameters	Close-packed	Semi-strip
N, total nodes in recognized area	1,296	1,296
n, number of recharge well nodes	529	529
c, Fractional paving (1-n/N) (dimensionless)	0.592	0.592
Recharge rate (in/yr)	69	69
Transmissivity (ft^2/d)	100,000	100,000
Hydraulic conductivity of confining bed (ft/d)	0	0
Storage coefficient (dimensionless)	0	0
Starting water table head (ft)	0	0
Starting potentiometric head in Floridan aquifer (ft)	0	0
average buildup of Floridan aquifer potentiometric head in recharge well nodes (ft)	6.7	4.2

SUMMARY

The conceptual model developed in this report is considered applicable to Floridan aquifer recharge areas in east-central Florida. Its purposes are to show approximate mathematical interrelations of rainfall, runoff, evapotranspiration, depth to water table, depth to potentiometric surface of the Floridan aquifer, percentage paving, and recharge to the Floridan aquifer and to develop perspective regarding approximate amounts of water available for recharge to the Floridan aquifer before and after paving.

The model implies that after paving a significant fraction of an area, sufficient water is available to increase the net recharge rate if (1) the rejected water from the paved area is uniformly placed in the nonartesian aquifer, (2) the water table rises and is maintained no higher than within 2 ft of land surface, (3) the estimates of rainfall, runoff, evapotranspiration, depth to potentiometric surface of the Floridan aquifer, and depth to water table are as estimated, and (4) no net increase in runoff rate occurs after paving. Model results should be corrected for the buildup of potentiometric surface of the Floridan aquifer under the unpaved area and, to do this, the transmissivity of the Floridan should be known and the pattern of paving must be considered.

It is important to note that the calculated net recharge rates after paving are conservative because of the model constraint which stipulates that no recharge occurs under the paved areas. In fact, though, some of the surplus water that is placed in the nonartesian aquifer will seep back under the paved areas. This will increase the cross-sectional area through which recharge to the Floridan aquifer will occur and will also reduce evapotranspiration. Thus, the actual Floridan aquifer recharge rate will be greater than calculated. However, the water that seeps under the paved areas lowers the water level under the unpaved area and thus reduces the recharge rate there. The rate at which water in the nonartesian aquifer will seep under the paved area depends on the pattern and percentage of paving, water table gradient, and the horizontal and vertical hydraulic conductivity of the materials that comprise the nonartesian aquifer. The actual pattern of paving will greatly influence the effect that under-paving recharge will have on the net recharge rate. For example, the amount of under-paving recharge in an area paved in strips will be greater than that which would occur if the area were paved as shown in figure 6.

The results obtained from use of the conceptual model should not be applied literally nor used as the basis for engineering design because of the severely limiting assumptions and stipulations. For instance, in Example 1, Case 1, the model results indicate that if 75.8 percent of the area is paved, net recharge rate can be increased from 21.0 in/yr to 38.7 in/yr (table 1). It does not follow that this will automatically occur just because 75.8 percent of that particular area is paved.

Although the geohydrologic settings used in the calculations for the example are somewhat typical of those in the four types of recharge areas (fig. 1), the results of the conceptual model applied in the examples cannot be used in “broad-brush” fashion to generalize or categorize the fractional paving that can occur in a given type of recharge area. Examples 1 and 2 illustrate that although the geohydrologic settings in both examples are typical of those found in “most effective” recharge areas in east-central Florida (fig. 1), the conceptual model results are quite different (table 1). Therefore, the conceptual model should be applied only on a site-by-site basis.

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