STATE OF NEW JERSEY
DEPARTMENT OF ENVIRONMENTAL PROTECTION
DIVISION OF WATER POLICY AND SUPPLY

A HYDROLOGIC ANALYSIS OF THE NEW JERSEY PINE BARRENS REGION

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Prepared in Cooperation with

United States Department of Interior

Geological Survey

A HYDROLOGIC ANALYSIS
OF THE
NEW JERSEY PINE BARRENS REGION

By

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U. S. Geological Survey

Prepared by the U. S. Geological Survey

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New Jersey Department of Environmental Protection
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STATE OF NEW JERSEY

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Water is one of the outstanding resources of the Pine Barrens region of South-Central New Jersey--a 2,250 square mile region in the **Atlantic Coastal Plain** underlain by the **Cohansey Sand.** The long-term hydrologic budget in the Pine Barrens region can be stated as P = R + ET where: P, the average annual precipitation is 45 inches; R, the average annual stream runoff is 22.5 inches; and ET, the average annual evapotranspiration is 22.5 inches.

Average annual evapotranspiration losses which total 2.41 bgd (billion gallons per day) for the Pine Barrens region can be divided into: (1) interception losses--0.63 bgd, (2) evapotranspiration for undrained depressions--0.09 bgd, and (3) evapotranspiration from soil and ground water--1.69 bgd.

Average annual stream runoff which totals 2.41 bgd for the Pine Barrens region can be divided into (1) direct runoff--0.27 bgd and (2) base runoff or ground-water runoff--2.14 bgd.

Areal variations in ground-water runoff per square mile of drainage basin are accounted for by variation in distribution of precipitation and evapotranspiration and by movement of some ground water in a regional flow system bypassing local streams and discharging into more distant, lower lying streams. The flow of water within the regional flow system in the Pine Barrens region is calculated to be 70 mgd (million gallons per day), or about 0.7 inch of water per year.

Both ground and surface waters of the Barrens area contain objectionable amounts of iron and at times color, and the pH values are in the acidic range. However, because of the low concentrations of total

dissolved solids (25-50 mg/l (milligrams per liter) treatment of the water for iron removal and pH adjustments will provide a water supply suitable for most purposes.

Development of the water resources could be achieved by locating high-yielding wells adjacent to the downstream reaches of major streams thus inducing streamflow, which is largely composed of ground-water discharge, to reenter the ground. Additional wells should be located further from the streams for use during prolonged low flow periods. Development by the use of surface reservoirs is not as suitable in the Pine Barrens region because surface reservoirs would cause inundation of large areas, would permit excessive evaporation and would create subsurface leakage toward areas of lower hydraulic head.

INTRODUCTION

Water is one of the principal resources of the Pine Barrens region of New Jersey, if indeed not its most outstanding resource. Much of the water is transpired by the native vegetation and returned to the atmosphere as water vapor. Man, too, depends upon the water resources for growing forestry products; agricultural products, such as cranberries and blueberries; and for many outdoor and recreational activities. Water is the key to man's manifold activities in the Pine Barrens. Indeed, water was the key to man's industrial and agricultural activities here during the early days of American history when iron furnaces and forges, as well as grist mills and cranberry farming, flourished along the steady-flowing Pine Barrens streams.

Importance of the water resources of the Pine Barren is underscored by the State's acquisition in 1954-55 of the Wharton Tract as a ground-water preserve. In harmony with its role as a water preserve, the 95,000 acre tract is available for use and development for recreation and forestry.

The magnitude of various important hydrologic factors operating in the Pine Barrens region of New Jersey is not well defined. Barksdale (1951, p. 36-38) in his discussion of ground water in the Pine Barrens determined the magnitude of several important hydrologic factors and suggested ways of utilizing and protecting the water resources. Tippetts and others (1955), Hely and others (1961), and Parker and others (1964) also have made contributions to the overall understanding of the region's water resources.

Water resources of the Pine Barrens are renewable because the precipitation falling upon the Pine Barrens region itself is the ultimate source of all naturally occurring potable water. No water is brought into the region from outside areas, either on the surface or underground. Hence, short of "mining water" the ultimate maximum yield is the volume of annual precipitation.

Purpose and Scope

This report discusses the hydrology of the Pine Barrens region and assigns values to many of the important hydrologic parameters. Water quality of both surface and ground water is described and its practical and hydrologic significance is shown. The report discusses concepts of water-supply development, protection, and management for the region. It is an outgrowth of a more detailed hydrologic investigation of the Wharton Tract which is part of a program of ground-water investigations authorized by the New Jersey Water Supply Act of 1958 and its companion Water Bond Act. The detailed report on the hydrology of the Wharton Tract is now in preparation.

Geography

The Pine Barrens region is located in the central part of the Atlantic Coastal Plain in New Jersey and occupies about 2,250 square miles of South-Central New Jersey. About 150 square miles are included in the Wharton Tract, and 170 square miles in other State-owned fish, game and forestry lands. Figure 1 shows the main Pine Barrens area and a number of outliers.

The landforms of the area are all of low relief and they affect the hydrologic regimen significantly. The low relief affects the overland runoff and rates of rainfall infiltration and has a direct bearing on the location of areas of dominant ground-water recharge and discharge.

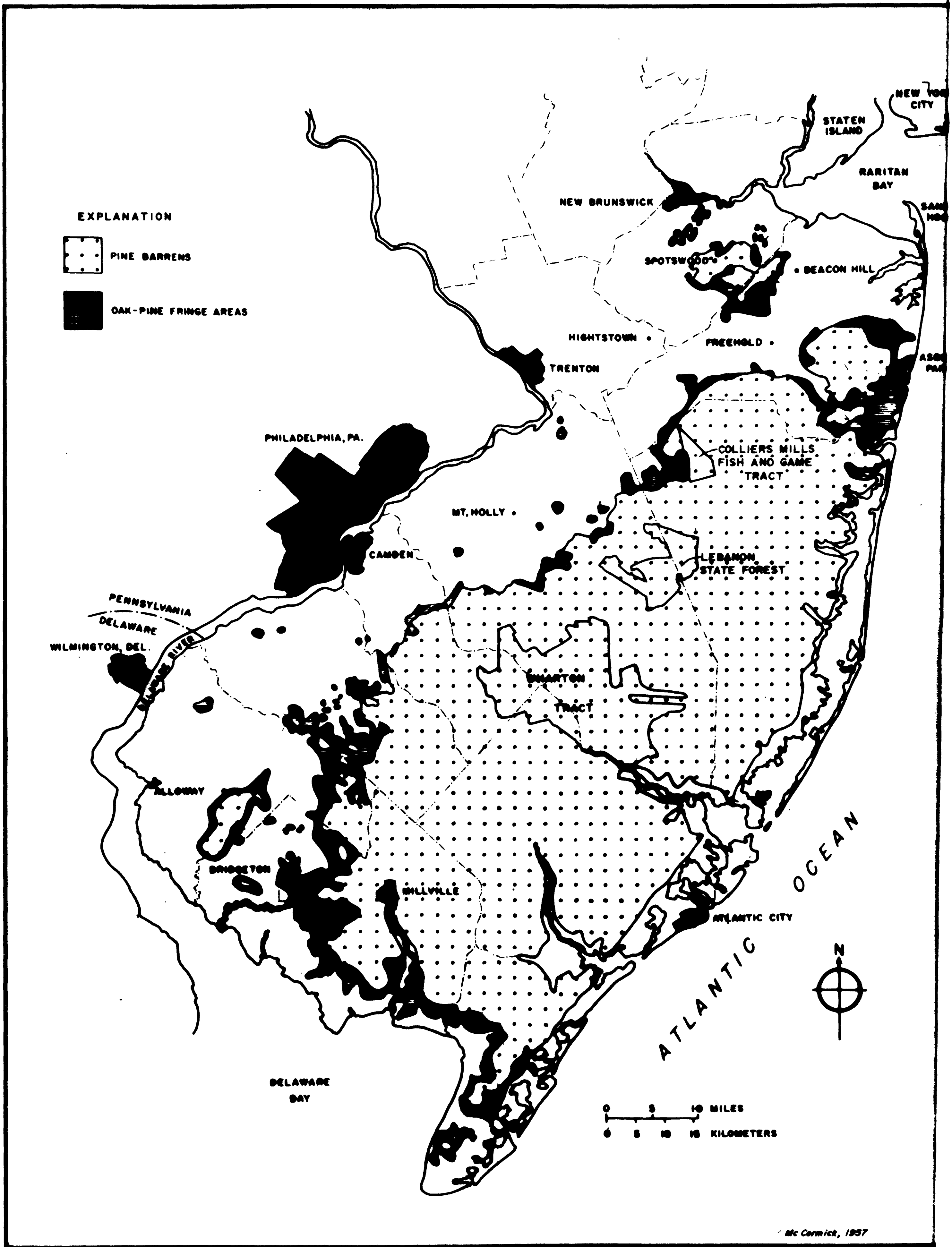

FIGURE 1-- LOCATION OF THE NEW JERSEY PINE BARRENS REGION.

The unconsolidated sedimentary formations beneath the Pine Barrens range in age from Cretaceous to Holocene and compose a sedimentary column several thousand feet thick. However, this study is concerned chiefly with the shallow and surficial sedimentary rocks--the Cohansey Sand of Miocene(?) and Pliocene(?) age and its overlying discontinuous veneer of gravel, sand, and clay of Quaternary age. These sandy materials were described in detail by Owens and Minard (1960, p. 27) and Salisbury and Knapp (1917).

The climate of the Pine Barrens region is temperate. The average annual precipitation is about 45 inches and supports abundant plant life in this predominantly forested region. Evaporation and transpiration, or the losses of water to the atmosphere from wetted surfaces or through plant processes, are relatively high.

HYDROLOGIC BUDGET FOR THE PINE BARRENS

A hydrologic budget is a statement accounting for water gains and losses for selected periods in an area. The long-term annual hydrologic budget for the Pine Barrens can be stated as follows: water input (precipitation) equals water yield (runoff) plus water loss (evapotranspiration). This then can be stated mathematically as:

$$P = R + ET,$$

where:

P = average annual precipitation, as inches depth over the area (45 inches),

R = average annual stream runoff, measured as inches depth over the area (22.5 inches), and

ET = the average annual evapotranspiration, as inches depth over the area.

In this equation, the observable seasonal and more or less cyclical changes in water storage are considered negligible because the surface- and ground-water reservoirs are considered to be filled to capacity. Disparities between volumes of annual storage from year to year are small when compared to the total flux of water passing through the system during a large number of years. Inserting the known annual quantities of water input and output into the equation and solving for the unknown ET value gives:

$$45 = 22.5 + ET$$

$$ET = 22.5 \text{ inches of average annual water loss.}$$

This is equivalent to 1.07 mgd per sq mi or a total evapotranspiration loss of 2.41 bgd for the Pine Barrens region .

Precipitation

Long-period records (1931-64) show that the average annual precipitation in Southern New Jersey is about 45 inches. This amounts to an average 2.14 mgd of water for each square mile or 4.82 bgd for the 2,250 square mile Pine Barrens region. During the period 1931-64, annual precipitation has ranged from 75 to 125 percent of this average.

When precipitation rates or amounts falling on a basin exceed the infiltration capacities of the soil, the excess water is either temporarily detained and stored at the surface to eventually infiltrate or evaporate, or it runs overland to nearby drainage ways. In the Pine Barrens, infiltration is the dominant hydrologic phenomenon. Temporary surface detention and surface-runoff are seldom important outside of swamp areas because most of the loose sandy soil, with or without a forest-litter cover, can absorb more than 2 inches of precipitation per hour. Data assembled by the author show that actually much of the region is covered with soils capable of accepting more than 6.3 inches of water per hour. Such capacities for infiltration of water are seldom exceeded by the precipitation experienced in the Pine Barrens.

Evapotranspiration

Evaporation and transpiration losses from large forested areas cannot be adequately separated because these factors are intimately interconnected to form evapotranspiration, the total vapor loss. In this report, evapotranspiration losses in the Pine Barrens region are divided into; (1) interception losses; (2) evapotranspiration from undrained depressions; and (3) evapotranspiration from soil and ground water.

Interception

The part of rainfall retained on the leaves, twigs, limbs, and trunk bark, by definition, is intercepted water. Interception generally is considered as a water-loss factor because it soon is evaporated to the atmosphere and is transported by wind out of the area. Another part of the precipitation is intercepted by and evaporated from the forest litter so that total interception loss is the sum of the tree canopy, understory vegetation, and forest litter components of interception.

The proper evaluation of interception losses under natural forest conditions is difficult. Amounts of precipitation intercepted by forest vegetation including its litter component are exceedingly variable, for these losses are dependent on such diverse and complex variables as vegetation density; age of forest stand; leaf and bark typology; litter type, depth and areal extent; intensity, amount, type, and frequency of precipitation; season of the year; relative humidity; vapor pressure gradient; temperature; wind; and sunlight. Mathematical approaches have been used to derive interception losses, but these generally require a number of assumptions used in conjunction with field measurements (Wisler and Brater, 1949, p. 142-144; Horton, 1919, p. 603-623; and Linsley and others, 1949, p. 260-268).

Studies throughout the country have shown that interception in forested areas generally accounts for about 10 to 25 percent of the perennial supply. See, for example, American Society of Civil Engineers (1956, p. 129-130), Houk (1951), p. 282-285), Horton (1923, p. 569), Kittredge (1937, p. 1011), and Butler (1957, p. 230). Many of these studies do not include interception by the forest litter. Large seasonal losses, ranging up to 37 percent, are reported by Houk (1951, p. 284).

Several studies in the Pine Barrens indicate that, on the average, probably 13 percent of the observed rainfall is intercepted (Wood, 1937, p. 251-254), and Rhodehamel and Reiners, (unpublished data). These percentages by no means represent unequivocal values for interception, for which more investigation certainly would be required. However, investigations elsewhere (U.S. Dept. Agriculture, 1955, p. 45) indicate that these values are in agreement with data from comparable forested areas. Leonard (1951, p. 1-16) found that 13 percent of the annual precipitation over northern hardwood forests was intercepted.

Total interception capacity for a particular storm generally may be expected to amount to as much as 0.5 inch of water for nonriparian forests of oak and pine, and perhaps 0.3 inch for riparian areas where litter interception is not included. Riparian areas in the Pine Barrens region are defined in this report as low swampy areas; nonriparian includes all other areas.

Although the actual presence and nature of the forest vegetation obviously is an important factor in interception losses, the manner of precipitation input also has a direct influence on total interception losses. Precipitation studies by the author for an 8-year period (1956-63) show that during at least 46 percent of the time the total weekly precipitation averaged 0.50 inch or less. Much of this water is intercepted and fails to have a measurable hydrologic effect upon the ground-water resources.

Although annual interception in the Pine Barrens oak-pine forest is reported to be 13 percent, an analysis of eight summer and fall storms in 1961 by Rhodehamel and Reiners (unpublished data) shows that interception ranged from 2 to 60 percent during these storms, the average being about 20 percent. Part of this interception was by the forest litter. Another study of individual storms (Cantlon, 1951, p. 18-26) indicates that pine stands and oak with understory vegetation may intercept as much as 28 and 23 percent respectively of the total rainfall. Interception on the forest floor by lichens and mosses has been investigated by Moul and Buell (1955, p. 155-162). Their work indicates that, on the average, well-developed moss mats have the capacity to intercept about 0.6 inch of water. The average interception by lichens is about 0.2 inch.

If about 13 percent of the average annual precipitation is lost by interception, then on the average the annual water loss by interception on each square mile of the Pine Barrens region is about 280,000 gpd (gallons per day) or about 0.63 bgd for the 2,250 square miles of Pine Barrens region.

Evapotranspiration from Undrained Depressions

Approximately 2 percent of the Pine Barrens region is covered by relatively small shallow undrained depressions that have highly impermeable clayey layers beneath them. Here precipitation is trapped and held at the surface or in the root zone where eventually all of it is evapotranspired. This undrained depression evapotranspiration loss, estimated to be 2 percent of the mean annual precipitation, is 90 mgd for the 2,250 square miles of the Pine Barrens region or an average of 40,000 gpd per square mile.

Evapotranspiration from Soil and Ground Water

The greatest single transfer of water as vapor from the Pine Barrens probably is by plant transpiration. This conclusion stems from limited data on the magnitude of total interception losses; the porous and dominantly litter-covered nature of the sandy surface that prevents large soil-evaporation losses; and the general lack of lakes and ponds that provide evaporation opportunity from their open-water surfaces. Practically all the wetlands comprising the open-drainage riparian zone are fully vegetated and this reduces land evaporation and promotes transpiration during the growing season.

When average annual interception losses of 280,000 gpd per square mile and evapotranspiration losses of 40,000 gpd per square mile from precipitation trapped in undrained depressions are subtracted from the 1.07 mgd per square mile overall evapotranspiration loss, there remains about 750,000 gpd per square mile of evapotranspiration resulting from (1) soil and open-water evaporation occurring in the open-drainage system, and (2) actual plant transpiration losses taking place from the soil column and main ground-water body circulating in the Pine Barrens. Because the soil is sandy and open-textured, and because the water table usually lies deeper than 2 feet below the surface, direct evaporation losses from the main ground-water body are relatively small (Buckingham, 1907; Houk, 1951, p. 292, 295; Remson, 1962, p. D23; Davis and DeWiest, 1966, p. 19).

Thus plant transpiration, on the average, most likely accounts for practically all of the remaining losses of 0.75 mgd per square mile. The combined interception and undrained-depression loss of 6.8 inches when subtracted from the 22.5 inches of total long-term evapotranspiration losses provides 15.7 inches of water loss from soil moisture and ground water. Because the direct evaporation loss from the water table is comparatively small, the 15.7 inches of water loss appears to be a valid approximation of actual transpiration for the New Jersey Pine Barrens. The value is in good agreement with humid-region values (American Society of Civil Engineers, 1957, p. 135) and the work by Wilm (1948, p. 258-262) who reports that annual transpiration from a hardwood forest with dense shrub understory in Western North Carolina was 19 inches. There the annual precipitation is about 62 inches instead of 45 inches experienced in Southern New Jersey and this may, in part, account for the larger transpiration value observed by Wilm.

As computed from the long-term hydrologic budget, total evapotranspiration in the Pine Barrens equals about 50 percent of the annual precipitation. This value is 20 percent less than the national average of about 70 percent as computed from the data of Leopold and Langbein (1960, p. 31).

Water Yield

Water yield or natural runoff is conveniently divided into two parts: (1) direct runoff, which reaches stream channels by overland flow soon after rain or snowmelt; and (2) base runoff, dominantly groundwater runoff, which has been discharged into a stream channel.

Precipitation falling directly on riparian lands creates direct runoff. Considerable riparian land exists, and constitutes about 15 percent of the area of several of the major drainage basins in the Pine Barrens region. Precipitation falling directly on these high water-table areas during the non-growing season cannot infiltrate simply because these wetlands already are saturated. Accordingly, riparian areas permit significant amounts of surface runoff during the non-growing season. During this runoff process, a small quantity of the surface water is lost by evapotranspiration.

Most direct runoff from riparian areas in the Pine Barrens region occurs from December through April. During these five months, the Pine Barrens region normally receives about 17.25 inches of precipitation. Because evapotranspiration losses are very small during this period, most of the precipitation on the riparian area becomes direct runoff. As the riparian area occupies about 15 percent of the region, direct runoff is approximately 2.5 inches or, on the average, about 120,000 gpd per square mile or 0.27 bgd for the 2,250 square miles of the Pine Barrens region.

Thus, an estimate of 20 inches for annual ground-water runoff can be arrived at by subtracting the computed 2.5 inches of annual direct runoff from the 22.5 inches of measured average annual runoff. This dominating form of runoff is equal to a yield of about 950,000 gpd per square mile or 2.14 bgd for the 2,250 square miles of the Pine Barrens region. The amount of this runoff that may be developed for use is discussed in the section of this report entitled "Water resources development of the Pine Barrens region."

As Pine Barrens streams carry only about 6 percent (2.5 inches) of the average annual precipitation as direct runoff, disastrous floods are uncommon events. Storm runoff is most prevalent during December through April, and notable floods are most likely to occur during early spring months. Ground-water discharge, which constitutes on the average 89 percent (20 inches) of the total annual discharge, gives the streams a remarkably uniform flow. This uniformity of flow is well shown by the analyses of water-supply characteristics of selected Southern New Jersey streams (Hardison and Martin, 1963; and Miller, E. G., 1966).

Large floods occur infrequently. A size flood that would be expected to occur on the average about once in every 50 years probably will be no larger than three or four times the size of the annual flood (Region A and C, Thomas, 1964, p. 12-16) except in the southern fifth of the state where a storm having a probable recurrence interval of about 50 years may be about five times the size of the annual flood (Region D, Thomas, 1964, p. 13).

Variations in Water Yield

Water yields as determined from stream-gaging measurements are not uniform throughout the Pine Barrens region. This is demonstrated by long-term streamflow records which show variations of several inches of annual runoff above and below the average of 22.5 inches. Annual runoff ranges from 14 inches in McDonalds Branch, an upland stream of 2.32 square miles drainage area, to 33 inches in the Mullica River near Batsto, which has a drainage area of 46.1 square miles. Some of these variations are accounted for by variation of precipitation distribution and evapotranspiration. Much of the variation in water yield is probably the result of some ground water bypassing some local streams and discharging into more distant, lower lying streams. Figure 2 shows an idealized flow pattern in the Pine Barrens region. Some recharge enters a shallow local flow system in the Cohansey Sand and the underlying upper sediments of the Kirkwood Formation and discharges to more distant streams at lower altitudes.

Most recharge to the deeper regional flow system is probably from precipitation on the upland areas that occupy roughly 25 percent of the Pine Barrens region. Discharge from this deep regional flow system appears to be to streams largely in the peripheral area of the region. Discharge to the streams in the peripheral area is controlled on the south and east by an increase in silt and clay content in the Cohansey Sand and the upper part of the Kirkwood sediments which forces ground water to the surface. On the north and west the water is forced to the surface by the thinning, to a feather edge, of the Cohansey Sand.

The quantity of water in the regional flow system in the Cohansey Sand and Kirkwood Formation which recharges in the upland areas and discharges in the peripheral areas is not presently known. The magnitude of that part of it that flows in the Cohansey Sand, however, can be estimated by use of the simplified variation of the Darcy equation:

$$Q = TIL$$

where:

Q = the flow of ground water, in gallons per day (gpd), into the peripheral area.

T = the coefficient of transmissibility for the aquifer, expressed as the flow of water transmitted through a strip of the aquifer 1 foot wide, measured at right angles to the direction of flow, under a hydraulic gradient of 1 foot per foot.

I = the hydraulic gradient expressed in feet per mile, and

L = the length (circumference) of the peripheral area, in miles, along which regional flow is taking place.

The coefficient of transmissibility (T) of the Cohansey Sand in the peripheral area is conservatively estimated to be 56,000 gpd per foot. This is based on an average thickness of saturated aquifer of 75 feet and a permeability of 750 gpd per square foot. This conservative permeability value is based upon a pumping test conducted in the Wharton Tract and described by Lang and Rhodehamel (1963). An average hydraulic gradient (I) toward the peripheral area of the Pine Barrens is estimated from stream gradients and regional water-table contours to be about 5 feet per mile. Extension of a smooth line around the periphery of the Pine Barrens gives a length (L) of about 250 miles.

The flow of water (Q) in the deep regional flow system in the Cohansey Sand discharging to streams the peripheral area of the Pine Barrens region is of the magnitude of 70 mgd. This is equivalent to 0.7 inches of water per year from the entire Pine Barrens region, or 2.8 inches of water per year from the upland areas occupying 25 percent of the total Pine Barrens region.

Summary of Hydrologic Budget

The association between the various major hydrologic factors in the Pine Barrens is complex. In the generalized annual hydrologic budget in Table 1, the various important hydrologic factors and their measured or estimated values are summarized.

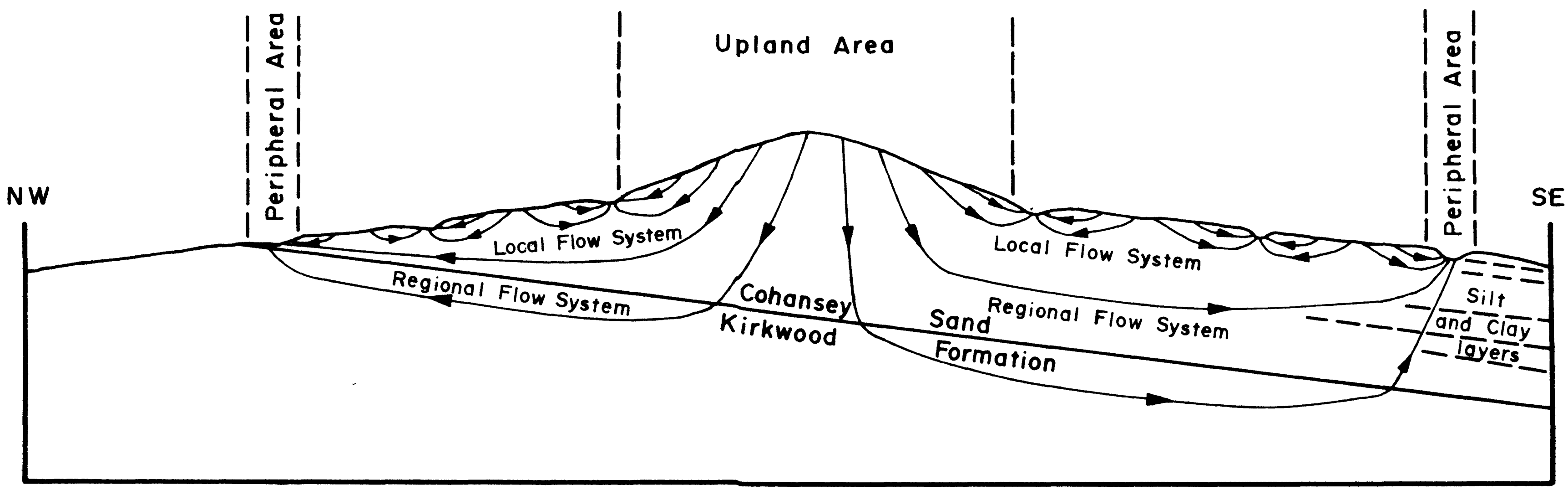

FIGURE 2-- IDEALIZED SECTION SHOWING GROUND WATER FLOW PATTERN IN THE PINE BARRENS REGION.

Table 1.--Annual hydrologic budget for the New Jersey Pine Barrens Region 1931-64

Water Input - Water Loss = Water Yield

		Inches of Water	Millions of gallons of water per day per square mile	Billions of gallons of water per day for 2,250 square miles
Water input	Precipitation	45	2.14	4.82
Water loss	Interception	5.9	0.28	0.63
	Evapotranspiration from undrained depressions	0.9	.04	.09
	Evapotranspiration from soil and ground water	15.7	.75	1.69
	Total water loss	22.5	1.07	2.41
Water yield	Direct runoff	2.5	.12	.27
	Ground-water runoff	20.0	.95	2.14
	Total water yield	22.5	1.07	2.41

WATER QUALITY

Pine Barrens water comes from precipitation which percolates through forest litter and enters a porous ground-water reservoir that is remarkably inert to chemical solution. The ground water of the Pine Barrens region has some objectionable physical and chemical characteristics but generally is suitable after treatment for a variety of man's uses. Also the ground water is relatively uniform in temperature; most of it approximates Southern New Jersey's mean annual air temperature of about 12°C (54°F). The ground water is low in dissolved solids, generally ranging from 25-50 mg/l. Total hardness of water (almost entirely noncarbonate hardness) is generally less than 40 mg/l. Because of the low dissolved solids, the ground water is only moderately buffered against large changes in its acidity or alkalinity (pH). Table 2 summarizes the observed concentration ranges for principal inorganic constituents in Pine Barrens region water. The table presents the range of values for both ground and surface water.

Although dissolved-solids content of Pine Barrens ground water is low, the water has the objectionable qualities of low pH (acidic), high dissolved iron, and at times undesirable color. The pH values range from 4.2 to 7.3 but most often are less than 6.0. Because the water is acidic it is corrosive and it readily dissolves iron from (a) organic compounds in the decaying forest litter and to a lesser extent, (b) minerals in the soils and underlying sediments.

Iron concentrations generally range from 1 mg/l to 11 mg/l although concentrations as high as 49 mg/l have been reported. The latter, as well as a color greater than 10 units, is generally a result of man's activities such as farming, manufacturing, and waste disposal.

Table 2.--Minimum and maximum concentrations of chemical constituents and physicochemical properties of Pine Barrens region water. (Concentrations are reported in milligrams per liter (mg/l); other properties are reported in units shown in the left column.[1])

	SURFACE WATER			GROUND WATER		
	Min.	Max.	More Common Extreme Value[3]	Min.	Max.	More Common Extreme Value[3]
Period of Collection	circa 1920-1925 to 1967			circa 1951 to 1967		
Silica (SiO_2)	0.14	17.00		1.10	42.00[2]	10.0
Aluminum (Al)	.0	.6		.00	10[2]	1.8
Iron (Fe)	.00	7.1		.00	49[2]	.5 - 11.0
Manganese (Mn)	.00	.77		.00	2	
Calcium (Ca)	.0	26		.0	90[2]	10
Magnesium (Mg)	.0	7.8		.0	18[2]	4.4
Sodium (Na)	.4	28		.9	26[2]	5.7
Potassium (K)	.0	7		.0	6.2[2]	4
Lithium (Li)	--	trace		--	.4	
Bicarbonate (HCO_3)	.0	72[2]	10	.0	146[2]	10
Carbonate (CO_3)	--	.0		--	.0	--
Sulfate (SO_4)	.8	85		.0	45[2]	15
Chloride (Cl)	.0	60[2]	8	1.8	34[2]	7
Fluoride (F)	.0	1		.0	4[2]	.3
Nitrate (NO_3)	.0	8.9		.0	37[2]	7
Phosphate (PO_4)	.00	.51		--	.0	
Boron (B)	trace	.10		.00	.14	
Carbon dioxide (CO_2)	.00	.02		2.2	25	
Dissolved solids Calculated	--	--		--	--	
Residue on evaporation at 180°C	17	195[2]	50	13	135[2]	35
Hardness as $CaCO_3$	2	78[2]	25	.0	70[2]	13
Noncarbonate hardness as $CaCO_3$	.0	71[2]	15	.0	52[2]	18
Alkalinity as $CaCO_3$	--	--		--	--	
Total acidity as H^{+1}	.1	.4		.0	.6	
Specific conductance (micromhos at 25°C)	24	364[2]	90	15	315[2]	45
pH	3.8	8.0[2]	7	4.2	7.3[2]	5.8
Color	.0	450[2]	3 - 100	1	1,300[2]	10
Temperature (°C)	0	30[2]	24	9	21[2]	14
Dissolved oxygen (D.O.)	4.2	10.3		--	--	
Suspended sediment (in tons/day/mi^2)	.001	.24		--	--	

[1] Table based upon about 7,000-10,000 separate quality of water determinations.

[2] These values are considered to be atypical for the region, and are thought to be influenced by man's activities such as farming, waste disposal, and manufacturing.

[3] Values in these columns are interpreted as being more indicative of the upper and where a range is given of lower and upper values existing in the natural environments.

Bog iron deposits, common to the area, are the result of aeration of ground-water seepage to surface depressions and the resulting precipitation of iron from the water solution.

Surface water of the area is composed of ground-water discharge most of the time and hence is similar in chemical quality. However, aeration results in precipitation of the iron from solution as ferric hydroxide and consequently lower iron concentrations in the streamflow are more common than in the ground water.

During the growing season and during times of storm runoff iron hydroxide is flushed from soils and streambeds. The resulting streamflow contains considerable amounts of iron in suspension either as ferric hydroxide or complexed with organic exudates from plants such as tannin. When this occurs, the surface flow has a high color content which at times exceeds 400 units.

Temperature of surface water during the summer may reach 21°C (70°F). In the winter the influx of ground-water discharge to the streams with temperatures of about 12°C (54°F) usually prevents freezing from bank to bank, even when air temperatures are substantially below freezing.

Aeration with resultant removal of CO_2 and iron precipitation plus addition of small amounts of alkali for pH control will provide a water supply of excellent quality suitable for agriculture, domestic, and most industrial uses.

AVAILABILITY OF WATER SUPPLY

Safe withdrawal of water from the Pine Barrens over an extended period cannot exceed the average annual water discharge of 22.5 inches. However, water stored in the ground-water reservoir can be extracted, at least temporarily, at greater rates. Tapping the Pine Barrens ground-water reservoir at rates greater than the 20 inches of ground-water runoff creates additional reservoir storage that can be replenished in part during major periods of ground-water recharge throughout the winter months. If, for example, ground-water storage was created adjacent to or beneath the riparian zone, some or all of the 2.5 inches of direct runoff would be captured. If withdrawal of greater than 20 inches per year is maintained and the created additional storage is continuously replenished by winter recharge, the additional water actually is made available by either reducing soil and ground-water evapotranspiration or by reducing direct runoff as described above. Extraction of water beyond these additional amounts provided by reductions of evapotranspiration and direct runoff will initiate a program of water mining: a program wherein continuous annual water withdrawals exceed the annual replenishment and systematic ground-water decline occurs. Such a water-mining program will result in extraction of stored water from the ground-water reservoir--water which has accumulated over the extensive period of years needed to fill the reservoir to its present capacity. Water-resources management that permits the mining of water in humid regions seldom has been justified in view of the large volume of water available for human needs. However, maximum and near-maximum water utilization may justify tapping the reserve of water in the reservoir during periods of drought in order to satisfy peak water demands.

Accordingly, the amount of water stored in the reservoir and the reservoir's ability to transmit water to pumping wells must be estimated. The volume of the ground water in storage is the volume of the Cohansey Sand multiplied by its average porosity. The lack of accurate knowledge of the irregular shape of the wedge of Cohansey Sand and its variations in composition and texture, does not permit more than a rough estimate of the amount of water held in storage. The volume of the Cohansey Sand can be estimated from its approximate dimensions. The formation underlies about 2,250 square miles and ranges in thickness from a thin sand lens to about 250 feet; the average thickness is about 100 feet. Porosity determinations from widely separated locations and depths average about 38 percent. It then follows that the volume of water held in storage in the reservoir is equivalent to a lake 2,250 square miles in area, averaging about 38 feet deep, and holding about 17.7 trillion gallons of water.

Not all the 17.7 trillion gallons of this water is recoverable from the porous ground-water reservoir because some of it adheres to the surfaces of the granular materials. This adherence of water against the pull of gravity is called specific retention or field capacity (Smith, 1967, p. 545) and it is reported as a percent of the rock volume. Many factors influence specific retention, and the magnitude of values obtained for the Cohansey Sand vary markedly ranging from less than 1 percent to more than 17 percent. The average for these water-bearing sediments appears to be about 15 percent of their total volume.

The water which is freely drained from the pore spaces by gravity is called specific yield or gravity yield. This is the water that can be extracted from these sediments for man's use. Specific yield, like porosity and specific retention, is reported as a percent of the sediment volume. Specific retention plus specific yield equals the total porosity. Hence, the average specific yield, established by a wide range of test data, is 38 percent minus 15 percent or about 23 percent. Thus the total usable water held in storage in the Cohansey Sand in the Pine Barrens is believed to be about 10.8 trillion gallons or about 108 billion gallons per foot of head decline throughout the ground-water reservoir.

At present, the large ground-water reservoir in the Pine Barrens remains virtually untapped. Many aquifer tests show that the Cohansey Sand can be expected to transmit large quantities of water to wells. Generally, the coefficient of permeability, P, is found to be large--typically ranging from 750 to 1,000 gpd per ft^2 (Rhodehamel and Lang manuscript in preparation). The coefficient of permeability when multiplied by the saturated thickness of the aquifer, in feet, provides a measure of the coefficient of transmissibility, T, in gpd per ft. Multiplying the range of permeability coefficients by 100 feet of saturated thickness provides a range of coefficients of transmissibility from 75,000 to 100,000 gpd per ft. However, much larger values of transmissibility have been reported at several localities.

Many wells constructed at different localities demonstrate the practical value of extracting ground water by properly constructed wells. Pumping tests show that modern large-diameter wells (12 or more inches), fitted with large-capacity electric turbine pumps, can continuously and efficiently yield 500 to 1,000 gpm of water. A well pumping at a rate of about 700 gpm will produce 1,000,000 gpd--enough water for many moderate-sized industries.

WATER RESOURCES DEVELOPMENT OF THE PINE BARRENS REGION

The Pine Barrens water reserve is ideally located to support the growth of nearby Southern New Jersey communities (Barksdale, 1951) as well as those along the industrialized reaches of the Delaware River to the west and the resort communities along the New Jersey Coast (Tippetts and others, 1955, p. V1-V13). Remoteness from areas of water need is an advantage when viewed with respect to water-supply protection; in many parts of New Jersey the two desirable features, nearness and maximum protection, are seldom obtainable together.

Water resources of the Pine Barrens region can be developed by surface-water utilization, ground-water utilization, or a combination of both. Because the water supply of this region is essentially an unused resource, an excellent opportunity is afforded planners and water-supply managers to scientifically and systematically develop the resource to its optimum.

Development of the ground-water reservoir could proceed by the drilling of large-yielding wells (500-1,000 gpm) that tap the ground-water reservoir in such a way as to induce some of the 20 inches of annual ground-water discharge to surface streams to reenter the ground. The induced water would be captured within the cones of influence produced by the pumping wells, from where it would be discharged into a suitable water-transmission system. The proposed system of wells, with individual wells spaced perhaps 1,000 feet apart could be located adjacent to the downstream reaches of major streams at locations above tidal influences (to prevent salt-water encroachment). The streams will serve as natural collecting channels, funneling surplus ground water close to the wells. The drawdown effects on ground-water levels created by any of the pumping wells would spread out under the adjacent stream, and the reduced hydrostatic head (pressure) thus created beneath the stream will permit water to reenter the ground through the permeable stream bed and reach the wells. This induced river recharge method has been found to be feasible in the Wharton Tract in Atlantic and Burlington Counties, New Jersey, and has been used successfully elsewhere (Rorabaugh, 1948).

Although it is technically possible to construct enough large-capacity wells to induce infiltration of all or most of the streamflow and intercept it by nearby wells, it is necessary to leave an assured amount of surface-water flow. According to George R. Shanklin (written communication), Director and Chief Engineer of the New Jersey Division of Water Policy and Supply, "it is not the State of New Jersey water allocation and management policy to induce infiltration of all the streamflow and intercept it by nearby wells as to adversely affect low streamflows and the natural environmental conditions of the area." Such a policy is sound from technological, political, and esthetic viewpoints.

Selected limits of assured minimum streamflow could be established as the average of the minimum mean discharge for 1, 7, 14, and 30 consecutive days, respectively, each year. The amount of water available for pumpage by induced-recharge wells then would be the difference between the mean flow of the stream and the selected limit. These values of available water for the four limiting conditions are given in the table below.

Computations of the average of the minimum mean discharges for the various number of consecutive days indicated in the table are derived from the areally weighted average for 10 streams draining 738 square miles of the Pine Barrens Region. The low-flow periods for the individual streams were compiled in the manner described by Miller and McCall (1961 p. 1-3), and Stanley Laskowski (oral communication). Values given are presented on the basis of a one-time use of water and are therefore minimal values of the available water as water treatment and reuse will increase the available supply.

Number of consecutive days	A Average of the minimum mean discharge for designated number of days (in/yr) or (mgd/mi²)	B Mean flow (in/yr) or (mgd/mi²)	Water available for pumpage from induced-river-recharge wells. (B minus A in specified units). Inches depth per year from region	Million gallons per day per sq mi	Billion gallons per day for the 2250 sq mi region
1-day	6.6 or 0.32	22.5 or 1.07	15.9	0.75	1.70
7-day	8.0 or 0.38	22.5 or 1.07	14.5	0.69	1.55
14-day	8.7 or 0.41	22.5 or 1.07	13.8	0.66	1.48
30-day	9.7 or 0.46	22.5 or 1.07	12.8	0.61	1.37

In a stream basin properly managed for water-yield purposes the observed streamflow should not fall below a prescribed rate as a result of man's actions. To insure this, an auxiliary system of wells located at some distance from the stream could be used to withdraw the necessary water from ground-water storage during the critical periods. Such auxiliary wells normally would be used in the event of well-breakdowns and for critical periods of drought. Withdrawal of ground water from beneath the riparian zone along the streams would create subsurface storage which would retain some, or perhaps most, of the 2.5 inches of average annual direct runoff.

Surface-reservoir development in the flat-shallow drainage ways of the region generally would tend to waste water, partly because the unfavorably large ratio of reservoir-surface area to usable reservoir storage would permit excessive evaporation losses. Surface-reservoir waters in this terrain would cover large areas to rather shallow depths. Annual evaporation may be expected to range from 29 to 34 inches over the reservoir (Hely and others, 1951; Kohler and others, 1959, Pl. 2; and Carter, 1958, p. 261). Such losses would exceed 0.5 billion gallons of water per year per sq mi of water surface. Water-treatment requirements for bacteria, colloidal-sized iron ligands, and other common pollutants from surface water developed for multiple use purposes may increase the cost of development and daily operation. Furthermore, the porous sediments underlying the surface reservoirs would permit additional loss to subsurface leakage at many locations.

The State of New Jersey over the past decades has acquired tracts of Pine Barrens land such as the Wharton Tract, the Colliers Mills Fish and Game Tract, and the Lebanon State Forest, along with the adjoining game lands. Using "Green Acres" public funds, the State has acquired Pine Barrens acreage for open-space purposes. Approximately 15 percent of the region and contiguous land is now State owned. Regardless of the primary reasons for acquiring the land, State-owned lands in the Pine Barrens are amenable to ground-water supply development without undue restrictions or limitations on the use for which the lands were originally acquired. In maintaining the lands as forest or recreational areas, the State obtains beneficial use of these lands while protecting the ground-water aquifers from pollution and surface contamination and preserving such aquifers for development when required.

Such protection is important as Pine Barrens water resources are particularly sensitive to various forms of pollution and contamination common to municipalities, industry, and modern agriculture. Part of this sensitivity is due to the shallow water-table conditions that permit a rather direct connection between the surface and the ground water. But just as important is the inability of the permeable and chemical-resistant aquifer materials to quickly and effectively filter out or immobilize wastes by oxidation, sorption, biochemical, and ion exchange actions. As a result of these factors, contaminants and pollutants readily can enter and move long distances in the ground-water reservoir.

Protection of the surface water resources outside of State-owned lands against contamination and pollution assumes major importance with any development by induced river-recharge methods discussed previously. Contamination and other wastes introduced in the stream from areas outside the State-owned water reserves can move downstream and be introduced into the water supply through pumping of wells adjacent to the stream. Accordingly, as a key to both maximum development and optimum management of the Pine Barrens region water reserve, which includes both surface and ground water, the possibilities for chemical and organic wastes contamination, according to Shanklin (written communication), "must be held to a minimum consistent with laws pertaining to the private use of property by sound control over residential, industrial, and other land use development and by strict enforcement of such regulations." To do this, even though there is enlightened industrial and agricultural management, it would appear best, according to Barksdale (1951), to limit industrial growth to peripheral areas. This should be accomplished, according to Shanklin (written communication), "by amending current water laws in New Jersey to authorize the sale of water or water rights by owners of lands located within critical areas for use on peripheral areas without the necessity of incorporating as a water supply utility." Such peripheral areas are those lying outside of and downstream from the water-supply collection areas of the Pine Barrens streams.

CONCLUSIONS

The Pine Barrens water reserve is ideally located to support the growth of nearby Southern New Jersey communities, industrialized areas along the Delaware River, and the resort communities along the New Jersey Coast. Pine Barrens water when treated for iron removal and pH adjustments is suitable for potable public supply and many industrial purposes.

Development of the water resources of the Pine Barrens region could proceed by the drilling of large-yielding wells (500-1,000 gpm) that tap the ground-water reservoir adjacent to the downstream reaches of major streams at locations above tidal influence. The drawdown of ground-water levels created by pumping wells would permit water to enter the ground through the permeable stream beds and reach the wells. Although it is possible to construct enough wells to induce infiltration of all the streamflow which averages 22.5 inches annually, and intercept it by nearby wells, this is contrary to the water allocation and management policy of the State of New Jersey. An auxiliary system of wells located at some distance from the stream would be needed to withdraw ground water from storage during periods when pumping from wells adjacent to the stream would cause streamflow to fall below accepted minimum rates. The amount of water available for development can be increased substantially by water treatment and reuse.

Protection of the water resources of the Pine Barrens region against contamination and pollution are of major importance. Contaminants and pollutants can readily enter and move long distances in the ground water reservoir. Spreading of surface contaminants and pollutants to the ground water reservoir would be further increased by the induced river recharge method of water resources development.

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