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Relationship between precipitation, surface runoff, and shallow water-table

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ABSTRACT

RELATIONSHIP BETWEEN PRECIPITATION, SURFACE RUNOFF, AND SHALLOW WATER-TABLE

by
Manoj Patel

In this study, a model was developed to describe the relationship between precipitation, surface runoff, and shallow groundwater table in a watershed that is subjected to groundwater extraction and urbanization. Regression analysis of fourteen years (1976-1989) of time series data for precipitation, stream discharge, ground water elevation, and groundwater extraction yielded good correlation between these parameters.

Analysis of the data associated with groundwater recharge and discharge events that occurred in the watershed from 1976 to 1989 yielded a high correlation between the above cited parameters. Regression analysis utilized to predict monthly variations in groundwater elevations showed a fair correlation between precipitation, stream discharge, shallow groundwater elevation, and groundwater extraction.

The Toms River watershed was utilized because it represented a hydrogeologic framework that suited this study. It is overlain by a surficial aquifer which has been exploited heavily for water supply. Also, the region has experienced substantial urbanization during the period of study.

RELATIONSHIP BETWEEN PRECIPITATION, SURFACE RUNOFF, AND SHALLOW WATER-TABLE

by
Manoj Patel

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RELATIONSHIP BETWEEN PRECIPITATION, SURFACE RUNOFF, AND SHALLOW WATER-TABLE

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To my family

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Finally, I will never forget the love, and moral support that I have received from my wife, Kamini. Her role in achieving my goals will always be remembered.

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CHAPTER 1

INTRODUCTION

1.1 Objective

The objective of this thesis is to define a relationship between precipitation, stream discharge, and groundwater elevation in a watershed that is subjected to groundwater extraction and urbanization. The historical data for the average daily precipitation, shallow groundwater elevations for the aquifer that feeds the stream baseflow, and the stream flow for the Toms River watershed are analyzed to see how the ground water table responds to rainfall and groundwater extraction.

1.2 General Information

Groundwater is a valuable resource, the availability of which is highly dependent on various natural and artificial phenomena that occur in the environment. Natural processes such as precipitation, and evapotranspiration are primary determinants for the quantity of groundwater available for recharge, extraction and baseflow contribution. Other processes such as pumping, man made surface drainage, and land irrigation also affect the available quantity of subsurface water.

In recent years, shallow groundwater has been pumped extensively for public water supply in the Toms River watershed. The effect of increased exploitation of groundwater is evident in the declining shallow water table. The increase in land imperviousness also contributes to declining groundwater elevations because it restricts recharge.

Over the years, many researchers have made attempts to predict water level fluctuations caused by climatic and man-induced changes in a watershed. For example, the use of time series analysis in predicting the future course of the groundwater elevation by separating the natural and man induced components is the latest in hydrological research (Gehrels, J. C, 1993). Statistical analyses such as ARIMA and Transfer Models can assist in the reasonable predictions of groundwater fluctuations. These methods, however, require sophisticated computational devices and a large data set, and can not be used for rapid predictions of the changes in groundwater elevation.

It is, therefore, useful to develop simple techniques and relations that can yield reasonable estimations of groundwater levels using limited time and data. In this study, regression techniques are employed to derive simple models that can predict changes in the shallow groundwater table elevation when precipitation, stream discharge, groundwater withdrawals, and evapotranspiration data are known.

CHAPTER 2

STUDY SITE AND DATABASE DESCRIPTION

This chapter discusses the study site and its hydrologic, hydrogeologic, topographic, and climatologic features. It also discusses the availability and usability of groundwater, surface water, precipitation, and groundwater withdrawal data.

2.1 Study Site

The Toms River watershed is located in Ocean County, New Jersey. It also lies in the northern part of the physiographic province, the Coastal Plain of New Jersey (Fig. 2.1). Toms River is a major water course that drains approximately 123 mi^2 of drainage area to the Atlantic Ocean. The watershed is underlain by the Kirkwood-Cohansy aquifer, which is a main source of groundwater supply in the region.

Ocean County has experienced a high population growth in recent years, and the population is expected to increase in the future (New Jersey Department of Labor, 1984). The use of groundwater for public, private, industrial, and irrigation purposes is also increasing with population. The effects of increased ground water use are evident in the continuous, long term decline in the shallow water table in the region.

The Toms River watershed was chosen because it represented reasonable land use and hydrogeologic characteristics necessary for this study. The hydrological and hydrogeological data for the time period from 1976 to 1989 were analyzed in this study. The time period used is referred to in this thesis as the study period.

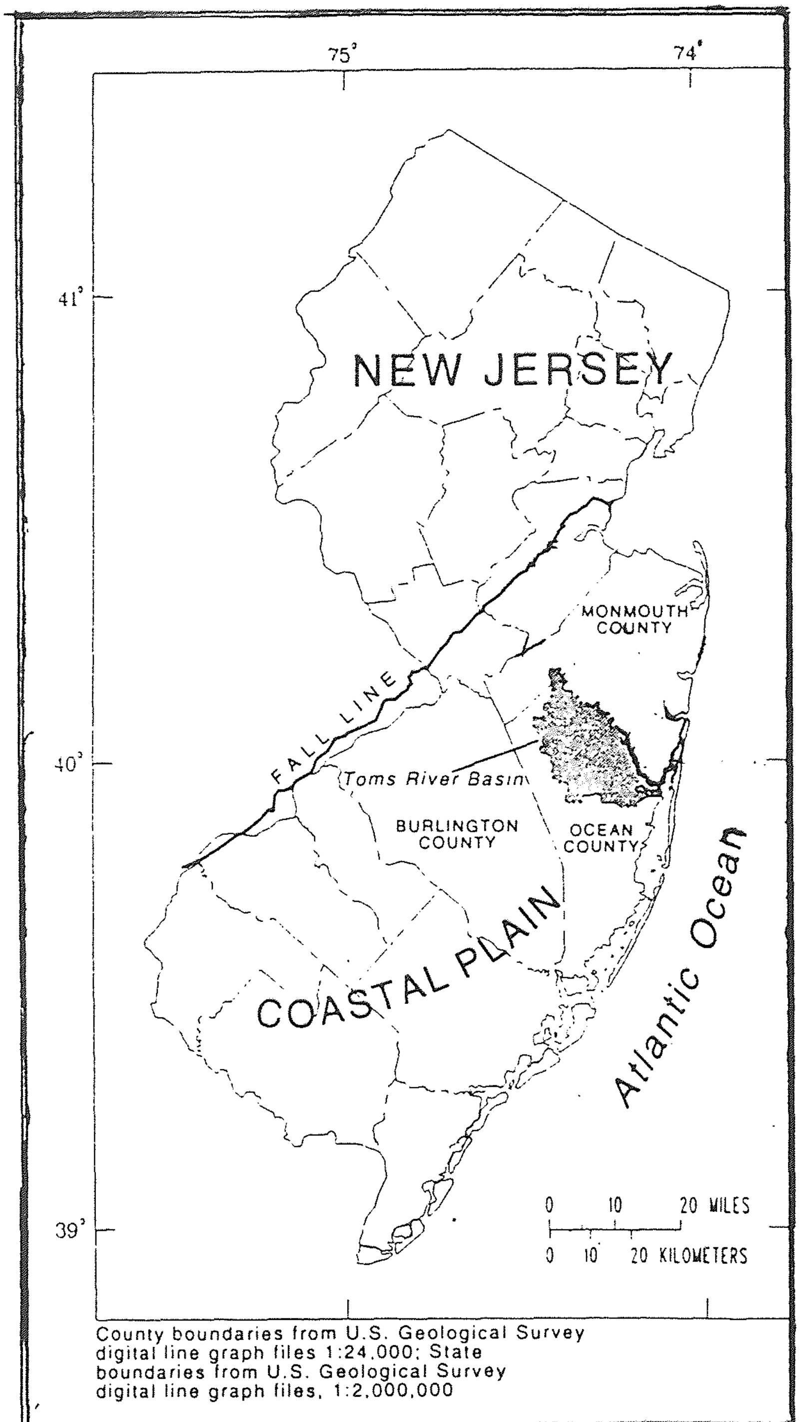


Figure 2.1 Location of Toms River Watershed in New Jersey
Area 123 square miles

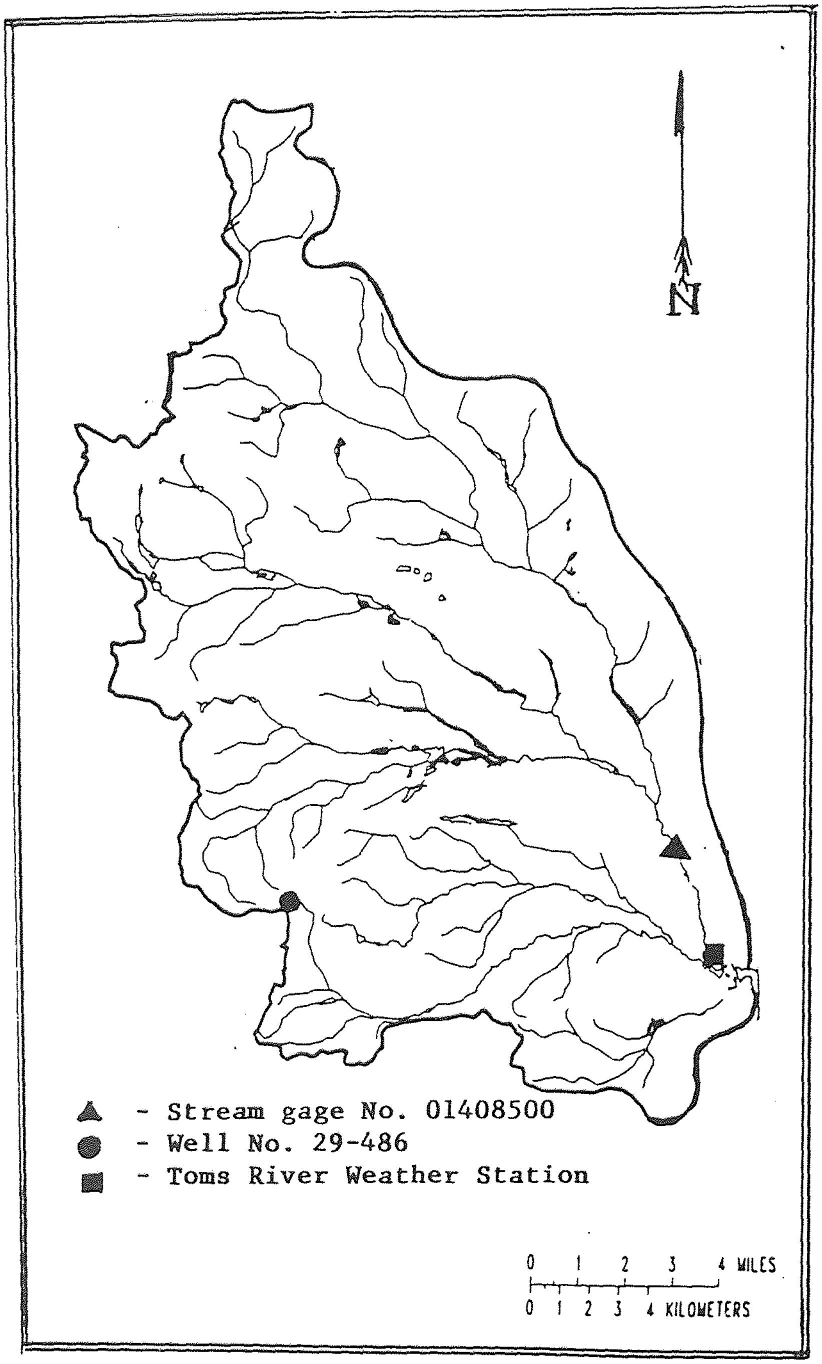
2.2 Topography

The Toms River Watershed lies in the Coastal Plain region, which is characterized by gently to moderately slopping ground (slopes ranging from 3 to 10 percents). The ground elevations in the watershed range from approximately 180 feet in the west to 50 feet in the east near the Atlantic Ocean. The western portion of the watershed has higher elevations where recharge to the shallow aquifer takes place. The groundwater discharge from the shallow aquifer occurs at topographically low areas such as rivers, and springs. Toms River is a major stream that derives its baseflow from the shallow aquifer (Fig. 2.2).

2.3 Geology and Hydrogeology

The surficial geology of the Toms River watershed is comprised of the Cohansy Sands and the Kirkwood Formation, with a major portion of the land covered by Cohansy Sands. Cohansy Sands consist of very fine to coarse grained sand, where as the Kirkwood Formation consists of fine to medium grained sands. The thickness of these formations varies from a few feet in the north-west region of the study area to approximately 150 feet near the Atlantic coast (Fig. 2.3).

Hydrogeologically, these two formations are referred to as the Kirkwood-Cohansy aquifer, and identified as hydrologic unit number 02040301 by the US Geological Survey. The hydraulic conductivity of the aquifer, determined by aquifer testing, ranges from 9.0 to 140 ft/day, which is a typical value for sand. The transmissivity (hydraulic conductivity multiplied by the aquifer thickness) of the aquifer ranges from 1900 to 25000 ft^2/day, and the storage coefficient of the aquifer is 0.024 (Watt, M.K, 1994).



Base from U.S. Geological Survey
digital line graph files, 1:24,000

Figure 2.2 Toms River Basin and Locations of the stations for which hydrological data is collected

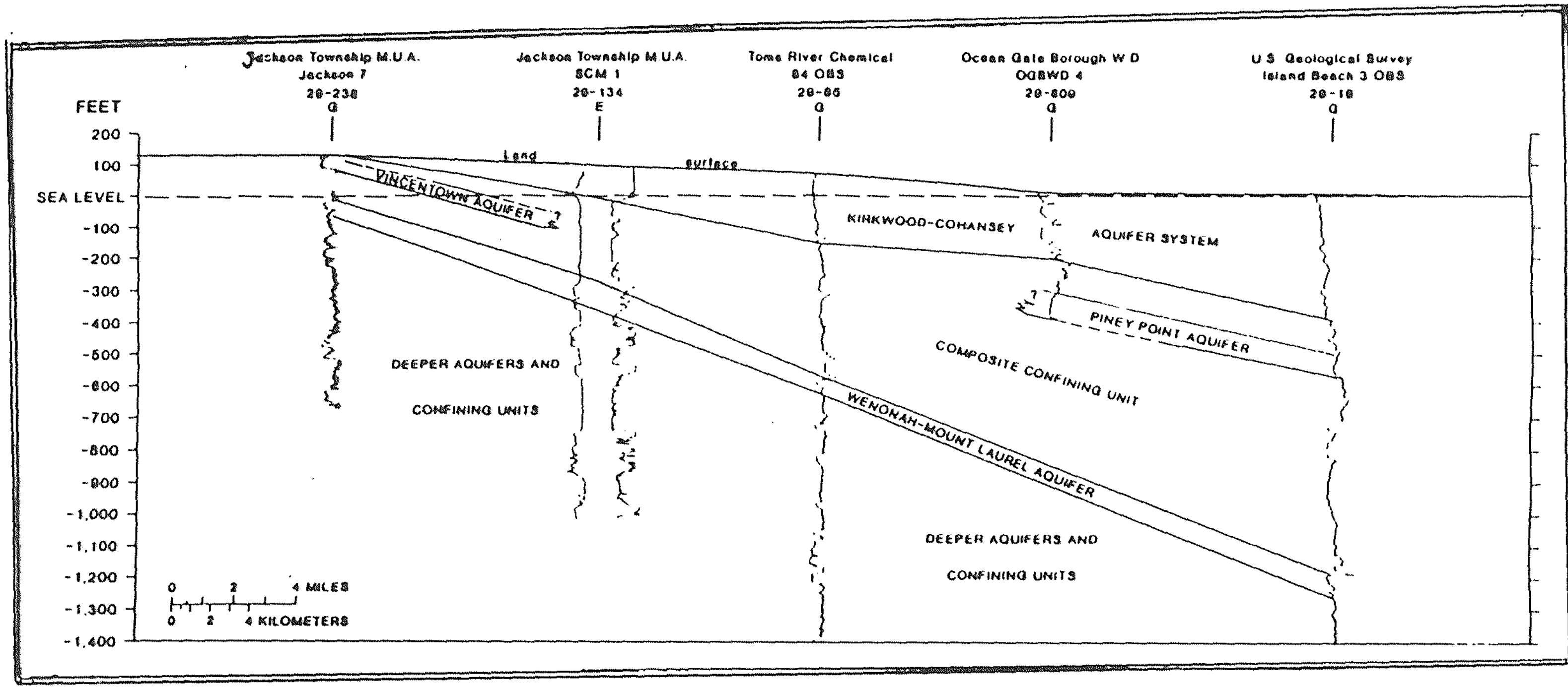


Figure 2.3 Hydrogeologic cross section across Toms River Basin based on gamma ray and electric logs (From Zapecza, 1989, pl. 3)

The direction of the ground water flow is to the south-east end of the watershed. The streams that incise the Kirkwood-Cohansy aquifer are gaining streams and are mainly sustained by groundwater (Fusillo, Thomas). The baseflow, which is essentially the contribution of groundwater to the Toms River is about 80 to 89 percent of the total annual discharge recorded at a surface water gaging station near Toms River (Watt, M.K, 1994).

2.4 Climatology

The daily precipitation during the study period (1976-1989) in the watershed ranges from a minimum of 0.00 inches to a maximum of 6.21 inches, with a mean of 0.13 inches. The values for minimum, maximum, and mean monthly precipitation during the study period were 0.32, 9.77, and 3.97 inches, respectively. During the study period, the lowest annual rainfall occurred in 1985 (35.75 inches), whereas the highest rainfall occurred in 1983 (57.28 inches).

The minimum and maximum monthly averages of air temperature recorded at the Toms River weather station during the period of 1980-89 were about 30 degree F and 75 degree F, respectively.

A significant portion of precipitation in the study area is consumed by evapotranspiration. The monthly potential evapotranspiration calculated from the temperature data of the Toms River weather station ranges from 0.00 inches in January to approximately 5.75 inches in July. These values were measured from the bar graph published in the report by Watt, M.K.

2.5 Precipitation Data

The National Oceanic and Atmospheric Administration (NOAA) maintains a long record of daily and monthly precipitation data for many locations throughout the United States. The precipitation data for the Toms River weather station (I.D. No. 288816) were obtained in a computer readable format from The National Climatic Data Center, NOAA. The historical values of monthly rainfall can also be downloaded from the on-line data and information systems operated by NOAA.

Figure 2.2 shows the location of the Toms River weather station for which the precipitation data was collected. The precipitation was assumed to be equally distributed over the study area for simplicity and because of the minor differences in the land altitude within the watershed. The amount of precipitation normally varies in a small watershed only when there is a significant difference in land elevations in the region. The daily values of precipitation for the study period (1976-1989) are reliable, with only a few missing values out of the data set of nearly 5000 values. The mean, minimum, and maximum daily, monthly, and yearly precipitation during the period from 1976 to 1989 are given in Table 2.1.

Table 2.1 Statistics of Precipitation Data from 1976 to 1989.

Data Type	Precipitation, inches		
	Minimum	Maximum	Mean
Daily	0.00	6.21	0.13
Monthly	0.32	9.77	3.97
Annual	35.75	63.76	47.87

2.6 Stream Flow Data

The United States Geological Survey maintains historical data sets of stream flows for most rivers in the United States. The mean daily values of stream discharge are kept in the files of USGS at Reston, Virginia. For the streams in New Jersey, these values are also published each year in a Water-Data Report by New Jersey Geological Survey.

For this study, the mean daily values for Toms River measured at a continuous gaging station (station I.D. No. 01408500) near Toms River, New Jersey, were obtained from the USGS Reston, Virginia. The values for the period of 1976 to 1989 are excellent except for a few values, that are fairly estimated by the USGS. The minimum, maximum, and mean daily, monthly, and yearly values of stream discharge over the study period are given in table 2.2. The Toms River gage is located on latitude 39°59'10" and longitude 74° 13'29", approximately 2.6 miles northwest of Toms River Township. The drainage area upstream of the gage is 123 mi^2 (see figure 2.2).

Table 2.2 Statistics of Stream Flow Data, Toms River from, 1976 to 1989.

Data Type	Stream Discharge in cfs		
	Minimum	Maximum	Mean
Daily	51	1800	209
Monthly	70	572	209
Annual	126	310	211

2.7 Groundwater Data

The primary source of ground water data used in this study is the United States Geological Survey (USGS). The USGS maintains and publishes groundwater elevations for many observation wells as a part of the groundwater monitoring network throughout the United States.

The daily groundwater elevations from a well drilled in the surficial aquifer of Toms River were used for this study. During the process of the data search, it was found that only three wells, NJ-WRD Well No. 29-486, 29-141, and 29-1060, had been drilled in the surficial aquifer under consideration. Of these three wells, only one well (No. 29-486) had daily values of static elevations for the time period under consideration. There are many water table wells operated by private and municipal water companies in the watershed for which quarterly values of groundwater elevations may be found in the quarterly water use reports submitted to New Jersey Department of Environmental Protection. These values, however, may not be reliable because of the lack of a common, standardized, method of taking measurements. For instance, the elevations measured without the complete recovery of the water-table after pumping are not reliable. Also, the elevations measured manually may not be consistent. In order to obtain reliable data, the measurements must be made after the complete recovery of groundwater, and automated devices must be used for consistency. The insufficiency of groundwater data had an impact on this study.

The observation well used for this study is NJ-WRD Well No. 29-486 which is located on latitude 39° 57'14" and longitude 74° 22'34", approximately 800 feet east of the Central Railroad of New Jersey tracks in Manchester Township. Hydrologically, this well is located in the upper reaches of the Toms River watershed where groundwater recharge occurs (Watt, M.K, 1994). The elevation of the ground surface near the well is 179.05 feet above mean sea level. The depth of penetration of the well is 69 feet.

The daily values for well No. 29-486 are reliable with only a few values missing. The missing values are not included in the analyses for this study. The minimum, maximum, and mean daily, monthly, and yearly values are given in table 2.3.

Table 2.3 Statistics of Groundwater Elevations from 1976 to 1989.

Data Type	Groundwater Elevation from MSL, feet		
	Minimum	Maximum	Mean
Daily	121.03	130.06	124.26
Monthly	121.08	129.99	124.33
Annual	121.52	128.49	124.15

2.8 Groundwater Extraction Data

The quantities of surface and groundwater used for various purposes in Ocean County may be obtained from the USGS. Such records are maintained since the 1960's in the Water Use Files. The data obtained for this study included monthly surface and groundwater extraction quantities for all of the Ocean County. The daily quantities of groundwater consumption in the Toms River basin were required for this study. The daily groundwater extraction values for Toms River were calculated using the following water-use ratios provided by Mr. John Nawyn, New Jersey Geological Survey, Trenton.

The ratio of the water use in Ocean County to that in Toms River basin = 2

The ratio of the surface water use to the groundwater use = 5.5

The average monthly groundwater withdrawals during the study period are given in table 2.4 below.

Table 2.4 Average Monthly Groundwater Withdrawals (million gallons) (1976 - 1989).

Month	Withdrawal	Month	Withdrawal
January	88.42	July	149.54
February	82.09	August	147.84
March	89.92	September	117.42
April	92.22	October	100.86
May	113.17	November	88.94
June	128.96	December	86.88

CHAPTER 3

INTERACTION BETWEEN PRECIPITATION, STREAM DISCHARGE, AND SHALLOW WATER TABLE

In chapter 2, the hydrology, hydrogeology, topography, and climatology of the study site were discussed and some important statistics about the data associated with the study site were presented. Also, the nature and availability of the data were discussed. This chapter presents the data in the form of charts and graphs to perform the investigations necessary for establishing relationships between precipitation, stream discharge and shallow water table elevations. Additionally, the groundwater and surface water hydrographs for the study area will be examined, and their characteristics will be discussed with regard to the theoretical aspects of hydrology and hydrogeology of a watershed.

3.1 Groundwater Hydrographs

A major portion of the rainfall that falls on a watershed becomes overland runoff and drains out of the basin through streams and channels. The water that infiltrates into the ground becomes part of the groundwater reservoir. The infiltrating water may reach the water table immediately following a rainfall event, or it may take days depending upon the thickness and hydraulic conductivity of subsurface strata. Sometimes, the water may never reach the groundwater table and remain trapped in the upper layers of the soil called the vadose zone. This occurs when rainfall intensity and duration are not great enough to push infiltrating water to the water table. Also, rainfall becomes overland runoff only when rainfall intensity exceeds the infiltration capacity of the ground surface.

Figure 3.1 shows the trend observed among the rainfall, infiltration capacity, and overland runoff (Rubin and Steinhardt, 1963). It is evident from Figure 3.1 that as the duration of rainfall increases, infiltration capacity of the ground surface decreases, and the overland flow increases.

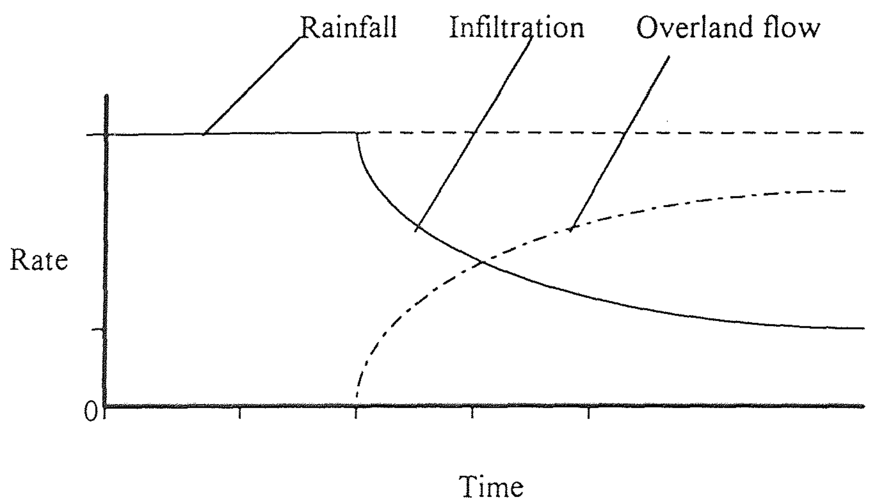


Figure 3.1 Time-dependent rates of infiltration and overland flow (modified from Freeze, 1974).

Groundwater hydrographs provide invaluable information on the response of the water table to hydrologic and other events such as groundwater withdrawals. The short term fluctuations in hydrographs are important in studying the groundwater's response to short term events such as precipitation, whereas long term fluctuations provide information on the long term events such as aquifer exploitation. Figures 3.2A and 3.2B are hydrographs of well No. 29-486 for the study period. They show the declining water table in the watershed caused by heavy groundwater withdrawal.

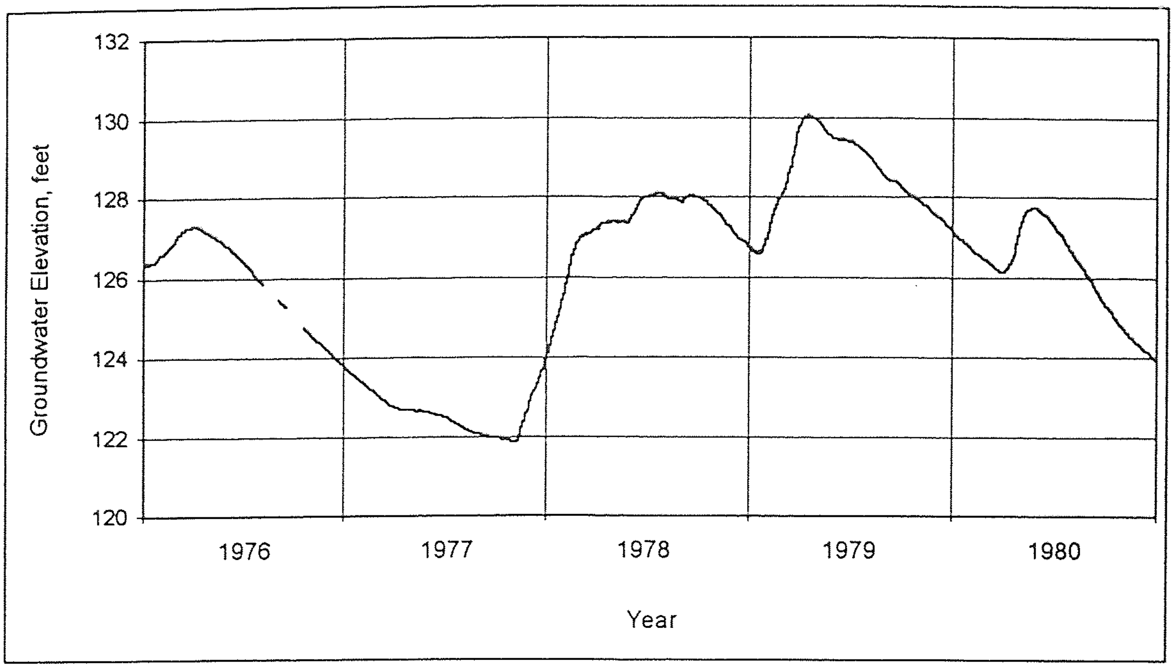


Figure 3.2A Hydrograph of Well No. 29-486 from 1976 to 1980

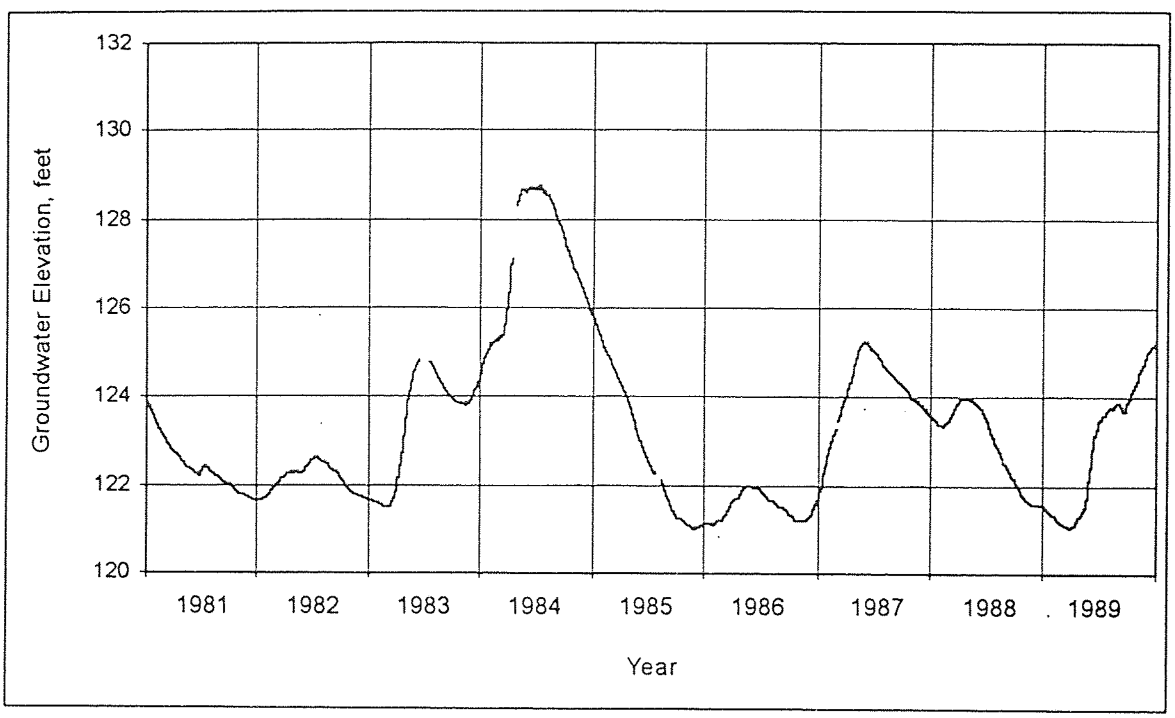


Figure 3.2B Hydrograph of Well No. 29-486 from 1981 to 1989

Figure 3.3 is a hydrograph of well No. 29-486 for year 1980. The response of the water table to an individual rainfall event is not apparent in the hydrograph, however, the series representing daily changes in water table clearly shows this effect. As plotted on the graph, the portions of the series below the X axis represent negative changes indicating declining water table, whereas the portion above the X axis represents positive changes and a rising water table. One important fact that can be drawn from the hydrograph is that a positive change, that is an increase in groundwater storage, occurs only when precipitation above a specific level falls in the watershed. French described the precipitation required for the groundwater recharge in a basin as "threshold" precipitation (French, Richard, 1994).

There are two major trends obvious from Figure 3.3 - recharge, a positive change in the water table, and discharge, a negative change in the water table. The groundwater recharge occurs in spring and fall when the soil moisture increases due to thawing of the soil and high intensity rainfall. The groundwater discharge occurs in summer months when the precipitation is too low for the basin recharge to occur. The fluctuations in the water table during low rainfall periods can be attributed to the effects such as daily groundwater pumping, when the groundwater table declines temporarily.

Later on in this study, linear regression models linking the change in groundwater elevation, precipitation, and surface runoff pertaining to recharge and discharge events will be presented. The trend of the water table in the remaining years of the study period is similar to that observed in 1980 - the recharge in spring and fall, and discharge in summer.

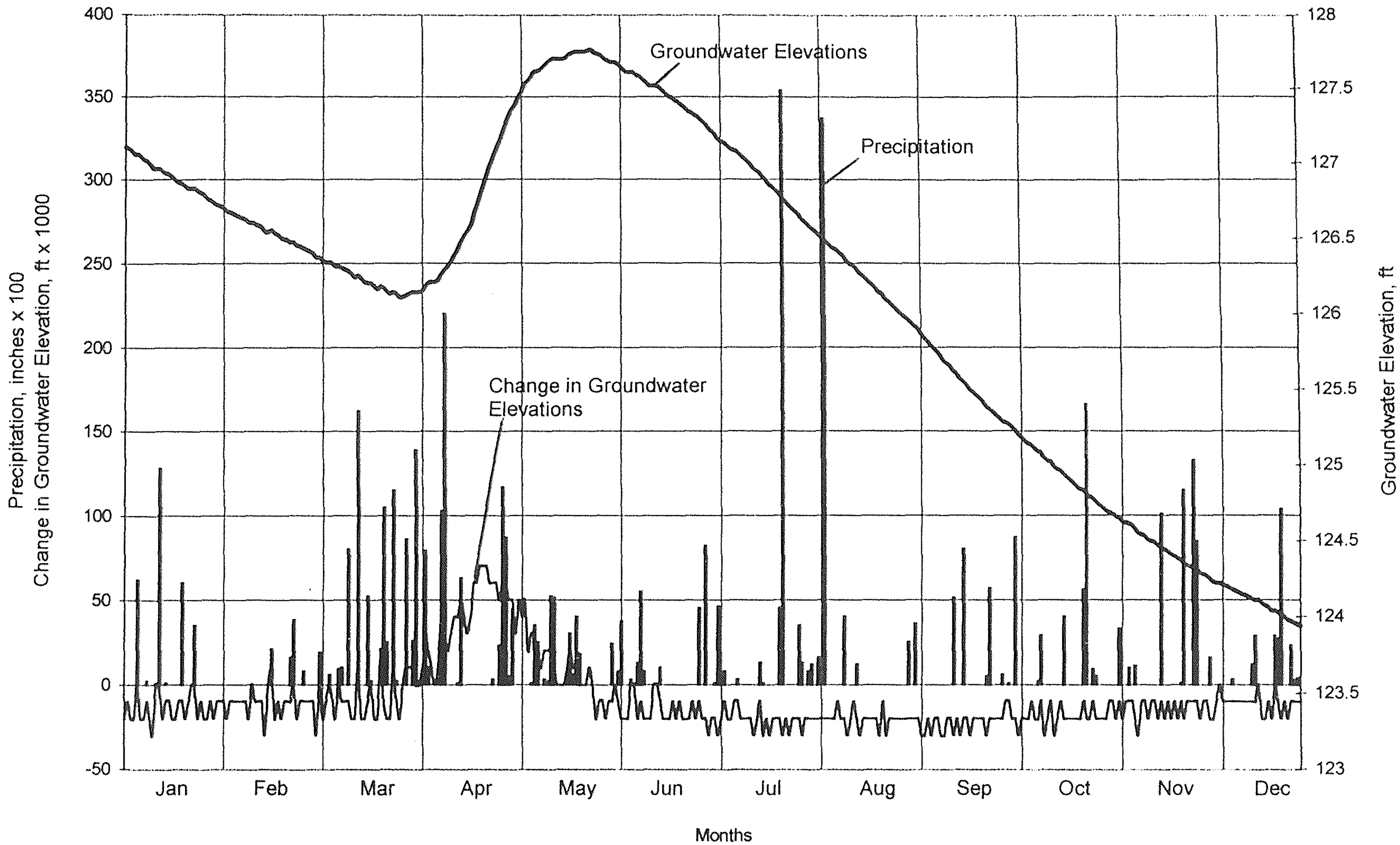


Figure 3.3 Groundwater Hydrograph, Well No. 29-486, Year 1980

A direct relationship between groundwater levels and precipitation is difficult to quantify because precipitation is a random, discrete, variable whereas groundwater elevation is a time dependent, continuous, variable. The temporal and spatial variability in groundwater level fluctuations following a precipitation event is the most important factor in quantifying this relationship, and it is difficult to determine. As mentioned previously, the time required for rainwater to get to the water table depends on the intensity and duration of precipitation, and the infiltration capacity of the soil.

An alternative approach of viewing this relationship qualitatively would be to plot a time run chart of the cumulative departure of precipitation and daily groundwater levels. Figure 3.4 is a time series plot of cumulative departure of precipitation from average daily values and groundwater elevations which shows a high correlation between the two parameters. Table 3.1 gives some values of correlation coefficients between the two parameters during the study period. The overall correlation between the two parameters was found to be very low (0.20 for 1976 to 1989), indicating the increased variability of the two parameters for longer periods. Figure 3.4 also shows the declining groundwater tables despite the increasing amounts of rainfall over the same period.

Table 3.1 Correlation between Cumulative Departure of Precipitation and Groundwater Elevations for Well No. 29-486.

Year	Correlation	Year	Correlation
1976	0.67	1983	0.70
1977	0.51	1984	0.61
1978	0.54	1985	0.92
1979	-0.08	1986	-0.38
1980	0.16	1987	-0.19
1981	0.77	1988	0.88
1982	0.13	1989	0.94

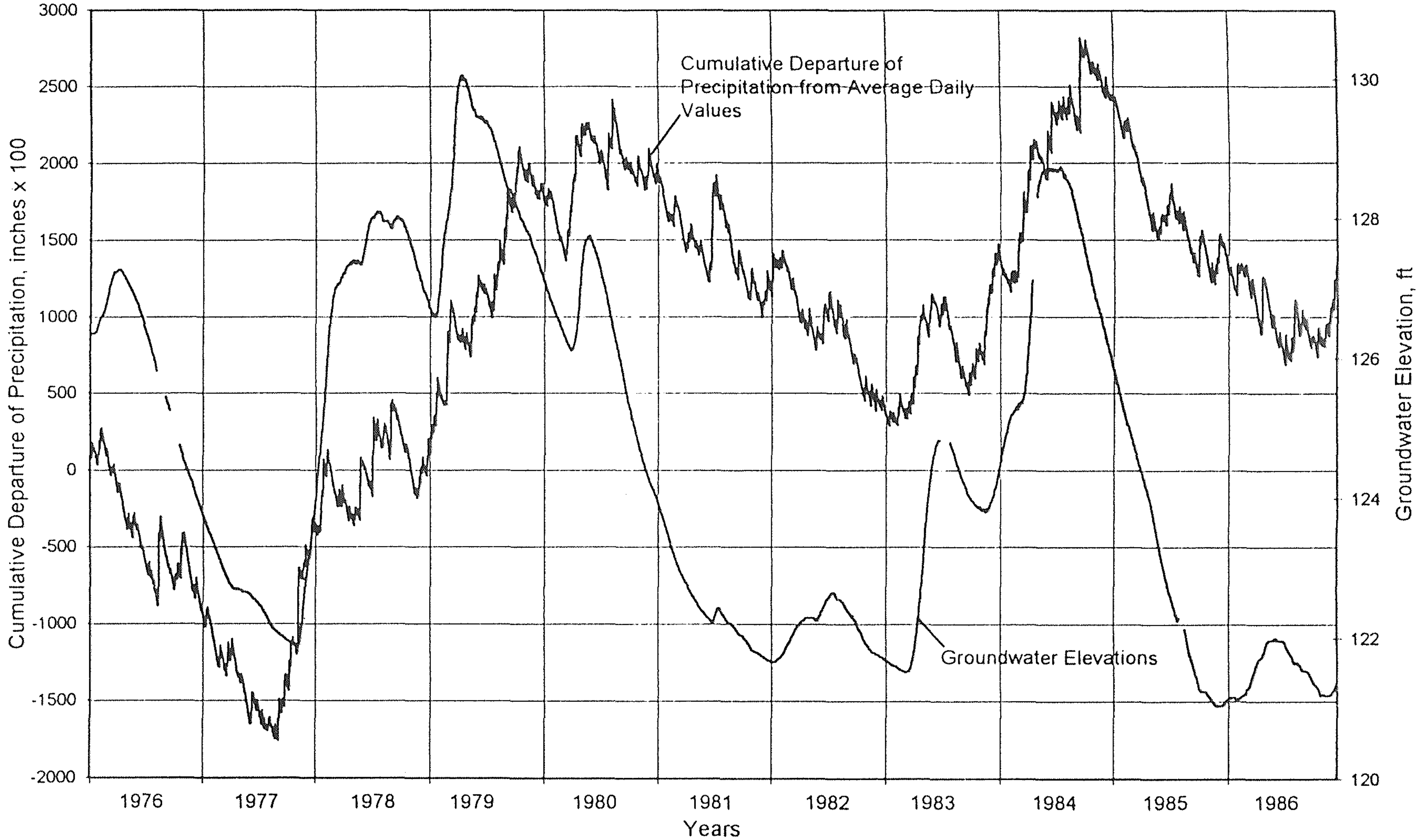


Figure 3.4 A Plot of Cumulative Departure of Precipitation and Groundwater Elevations (1976-1986)

3.1.1 Recharge Curve

As mentioned previously, the groundwater rises only when precipitation occurs above certain levels. The average slope of the recharge curve, that is, the rate at which the water table rises depends on factors such as intensity of precipitation, infiltration rate, evapotranspiration, surface water flow resulting from precipitation, and a variety of other mechanisms (Freeze and Cherry, 1979). Because of the spatial and temporal variability involved in infiltration of rain water into the ground surface, the amount of recharge can best be estimated by field measuring equipment. However, for estimating recharge at a regional level, the classical approach of using groundwater hydrographs may be satisfactory. Also, the use of field measuring equipment is not viable for regional estimation of recharge for it is difficult to locate the potential recharge areas. Also, it may be costly and time consuming to install measuring instruments at all sites. The use of a groundwater hydrograph for regional estimation of recharge is valid since it accounts for all natural and man-induced phenomena that cause basin-wide water table fluctuations

When modeling for the recharge estimation in this study, the characteristics of the hydrographs for well No. 29-486 were assumed to be representative of the basin-wide groundwater regime. The model derived from hydrographs can help us predict approximate basin-wide rise in the water table due to a rainfall of certain magnitude and duration.

3.1.2 Discharge Curve

In contrast to the recharge curve, which represents the increase in the water table level, the discharge curve represents the opposite. It is an indication of a gradual decline in groundwater reservoir storage. The discharge usually occurs in dry months when there is no significant input of rainwater into groundwater. The decline in a shallow water table is attributed to the constant losses such as evapotranspiration, groundwater withdrawals, and the discharge of the groundwater into another water body such as a stream.

In a study of the correlation of groundwater levels and precipitation on Long Island, NY, Jacob (1944) found the following relationship between time and height of the water table on a peninsula during rainless periods.

$$h = h_0 \exp(-\pi^2 \; T\,t \,/\, 4\, a^2\, S)$$

where

h_0 = the initial height of water table above sea level

h = the height of water table after a given time t

a = half the width of the peninsula

T = transmissivity of the aquifer

S = storage coefficient

The above equation considers aquifer properties such as transmissivity, storage coefficient and width. It assumes that the thickness of the aquifer is very large compared to the height of the water table above the sea level. But this equation does not consider parameters such as rainfall, groundwater withdrawals, and potential evapotranspiration, that affect the water table. Linear regression models presented in this study combine all of these parameters.

Figure 3.5 shows the discharge curve for well No. 29-486 during the year 1980. It clearly shows the effect of changing climatic conditions such as decreased precipitation, and increased evapotranspiration and withdrawal during the dry months of summer. The water table declined approximately 3.5 feet from mid June to December. The shape of the discharge components of the hydrographs during the study period are found to be similar.

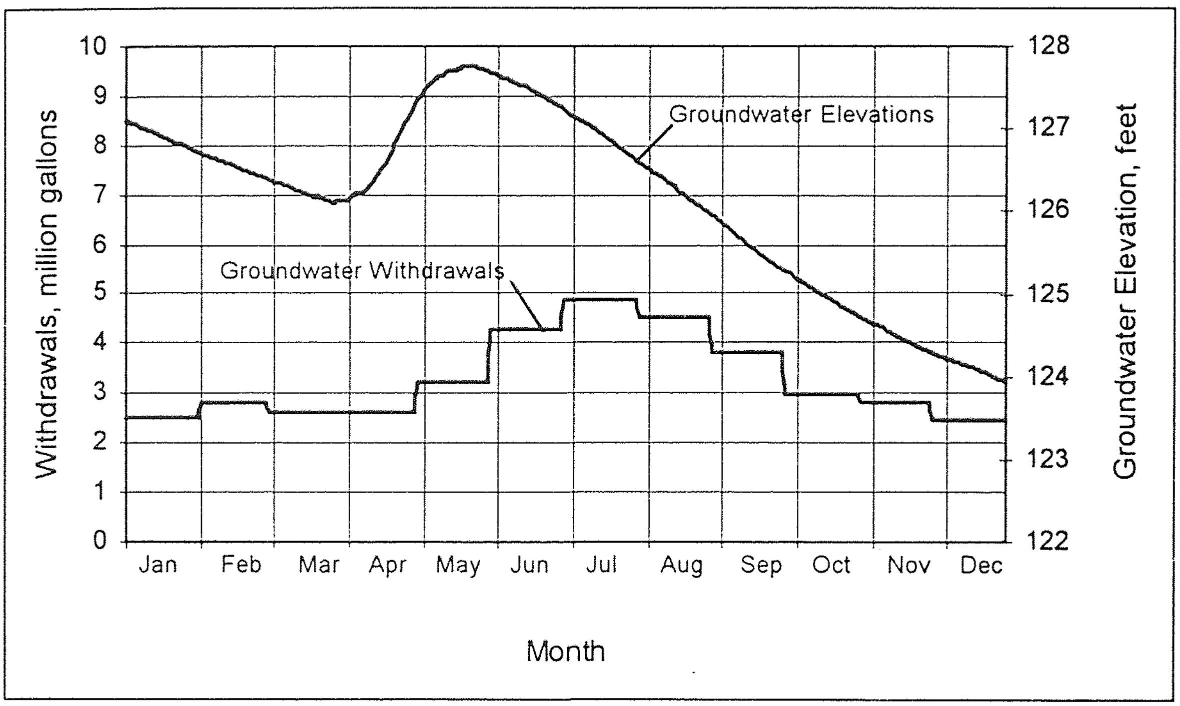


Figure 3.5 Groundwater Discharge and Withdrawals, 1980

3.2 Surface Water Hydrographs

The study of surface water hydrographs is important in assessing various surficial and subsurficial characteristics of a watershed. The effects of activities such as changing drainage patterns and increasing impervious surfaces in a watershed can be determined by studying stream hydrographs of a major stream draining the watershed. Also, subsurface features such as geology and hydrogeology of a watershed can be studied using surface water hydrographs.

Basically, a surface water hydrograph represents the watershed's response to a hydrological event. The stream discharge increases following a rainfall event and decreases when all excess rainfall water drains from the basin. The increase and decrease in stream discharge is characterized by a rising limb and a recession curve, respectively, on a surface water hydrograph. The slopes of limb and the recession curve provide information about the land characteristics of a watershed. For example, for a large watershed, the limb rises slowly because the average time for rainwater to reach the stream is larger. Also, it takes more time for excess rainwater to drain from a large basin. This is seen, on the hydrographs, by a slowly declining recession curve. Figure 3.6 is a hydrograph of discharges recorded at index gaging station no. 01408500 located on the Toms River near Toms River, NJ. It shows the changes in mean daily discharges following two successive rainfall events on the 26th and 27th March, 1978.

The changing land-use patterns can also be deduced from surface water hydrographs. For example, an increase in imperviousness due to land development reduces the response time of a basin to hydrological events, producing a steeper limb and recession curve in a hydrograph. The comparison of several annual hydrographs of a site can reveal such information.

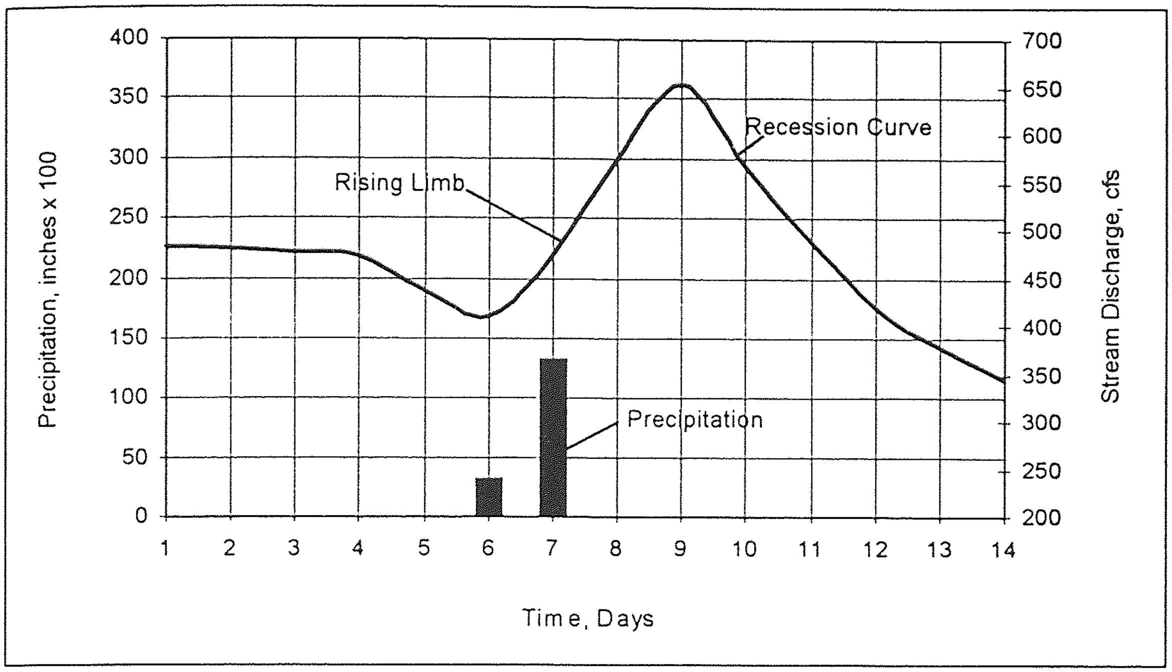


Figure 3.6 Surface water Hydrograph after the Storms on March 26 and 27, 1978

3.3 Groundwater Surface Water Interaction

After the excess rainwater drains from a basin over several days, the surface water hydrograph follows almost an identical curve path because of the discharge of groundwater into the stream. This occurs, particularly, in a gaining stream that derives its flow from shallow groundwater. The flow derived from the adjoining groundwater body such as an aquifer can be separated from a hydrograph using various graphical, and analytical techniques. Numerous computer programs are also available that can separate the baseflow from the total flow. However, none of these techniques yield accurate quantities of baseflow because of many gross assumptions regarding the time of the occurrence of the baseflow following a rainfall event. In this study, a spreadsheet was used to separate the baseflow, assuming that the direct runoff ceased in three days after the peak discharge. The basis for this assumption was an empirical relation, Days = Drainage Area $^{0.2}$, where drainage area is in square miles. The stream was assumed to be sustained by only the groundwater discharge after that period.

In the surface water hydrograph, the discharge values after the third day following the peak discharges were separated for each year. This yielded the time periods when the Toms River was presumably sustained only by the shallow groundwater. The starting points of such periods were then joined with the preceding low discharge points in order to obtain a continuous annual baseflow hydrograph. The values thus obtained were added to estimate the annual quantities of the baseflow for the Toms River. The direct runoff was calculated by subtracting the baseflow from the total discharge values. The method adopted was similar to the manual methods of estimating baseflow except that a spreadsheet was used to achieve consistency in the estimation. Figure 3.7 shows the surface water and baseflow hydrographs for year 1980. The values of the baseflow, the direct flow, and the total flow in the Toms River during the study period are tabulated in Table 3.2. Figure 3.8 is a bar chart showing the variations in the baseflow contribution to the Toms River for the study period.

Table 3.2 Baseflow Contribution to the Toms River , in cfs (1976 - 1989).

Year	Total Flow	Baseflow	Direct Flow
1976	63939	58493	5446
1977	77768	66627	11141
1978	106426	93112	13314
1979	113509	97379	16130
1980	67466	61273	6193
1981	46314	41380	4934
1982	60986	53732	7254
1983	92815	80722	12093
1984	106864	92458	14405
1985	49719	45200	4519
1986	66067	57993	8075
1987	79931	70862	9069
1988	54295	49745	4550
1989	86013	75995	10018

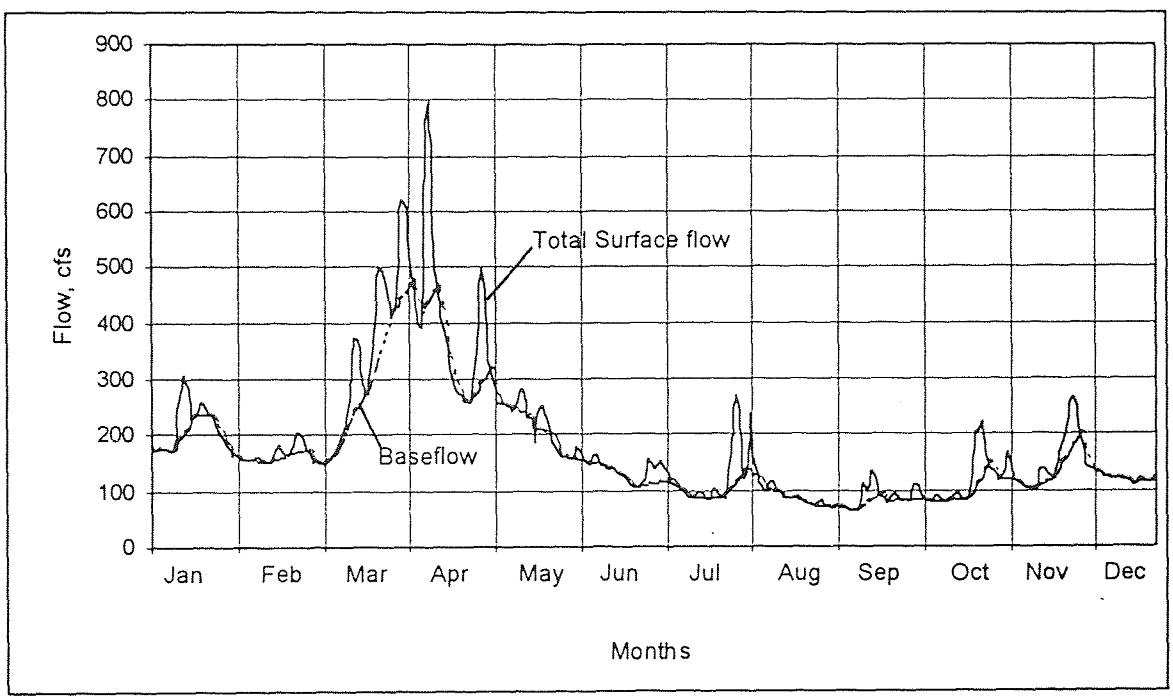


Figure 3.7 Baseflow Hydrograph, 1980

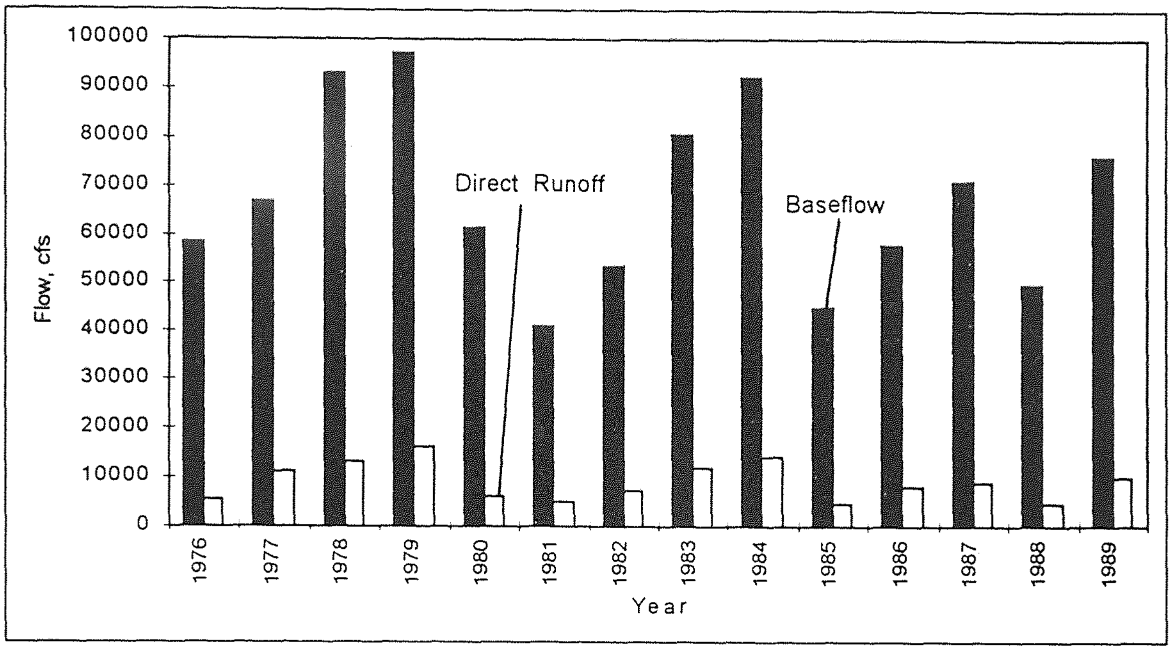


Figure 3.8 Variation in Baseflow (1976-1989)

The study of a baseflow curve can provide a great insight into the nature of the groundwater regime (Freeze and Cherry, 1979). Numerous studies have been carried out to quantify the relation between surface water and groundwater based on the characteristics of the baseflow curve. Singh (1969) has produced sets of theoretical baseflow curves based on analytical solution to the boundary value problem of free surface flow to a stream in an unconfined aquifer under Dupuit-Forchheimer assumptions.

There is also an alternative way of assessing the stream flow variability and groundwater contribution within a watershed. The flow-duration curve ratios, Q_{20}/Q_{80}, that is, the discharge equaled or exceeded 20 percent of the time divided by the discharge equaled or exceeded 80 percent of the time, can help perform a quick evaluation of groundwater contribution to a stream (Hordon, Robert M.). The higher the ratio, the greater the variability and the lesser the opportunity for groundwater storage. Table 3.4 lists such ratios for Toms River during the study period. The ratios indicate that the groundwater contribution of Kirkwood-Cohansy aquifer to Toms River is substantial during the study period.

Table 3.3 Flow Duration Curve Ratios for Toms River (1976 - 1989).

Year	Q_{20}/ Q_{80}	Year	Q_{20}/ Q_{80}	Year	Q_{20}/ Q_{80}
1976	2.48	1981	2.12	1986	2.42
1977	2.79	1982	1.83	1987	2.02
1978	2.17	1983	2.6	1988	2.86
1979	1.92	1984	2.35	1989	1.27
1980	2.57	1985	1.99	1976-1989	2.24

3.4 Precipitation

Studying precipitation data such as annual rainfall, and the duration and intensity of the rainfall, is the most important process in groundwater evaluation because rainfall is the primary source of groundwater. A groundwater study first must consider how much rainwater is available and how much of it becomes groundwater. When plotted along with the well and stream hydrographs, precipitation data provides a good understanding of the mechanism that link rainfall, surface water and groundwater. On a time scale, precipitation is the first event followed by a rise in the groundwater and stream hydrographs. As described in the earlier paragraphs, the time lag between the occurrence of a rainfall and the rise in groundwater and surface water hydrographs may very depending on the intensity and duration of precipitation, infiltration rate, temperature, basin size, and land use.

Figure 3.9 is a combined plot of precipitation, groundwater and surface water for 1980, which shows seasonal variations in precipitation and its effects on groundwater level and surface water flow. As is seen from the plot, the prolonged precipitation during the spring causes a rise in groundwater level. This is the period when the moisture content of soil is higher than its moisture retention capacity. Interestingly enough, groundwater did not rise in response to the two major rainfall events that occurred in July and August, suggesting that the moisture retention capacity of subsurface soil was not exceeded during that period. In a study by Richard French, it was found that there is a threshold value of precipitation that causes groundwater recharge (Richard, French).

Also, it is apparent from Figure 3.9 that the surface water flow during prolonged rainfall is much higher, and the groundwater contribution to the stream is minimum. In contrast, the storms of shorter duration during the summer generate small surface flows, and groundwater contribution during that period is larger.

Due to the randomness in its occurrence, precipitation can not be directly correlated with a rise in groundwater. Jacob(1944, p565) analyzed daily precipitation data as cumulative departure from normal daily precipitation and compared with groundwater elevations for the same time period. A similar approach was taken in this study to relate precipitation and groundwater elevations, the plots for which are shown in Figure 3.4. Despite the similar trend, a low correlation coefficient was found for the entire study period. The correlation was high when each year was analyzed separately, the results of which are given in Table 3.1.

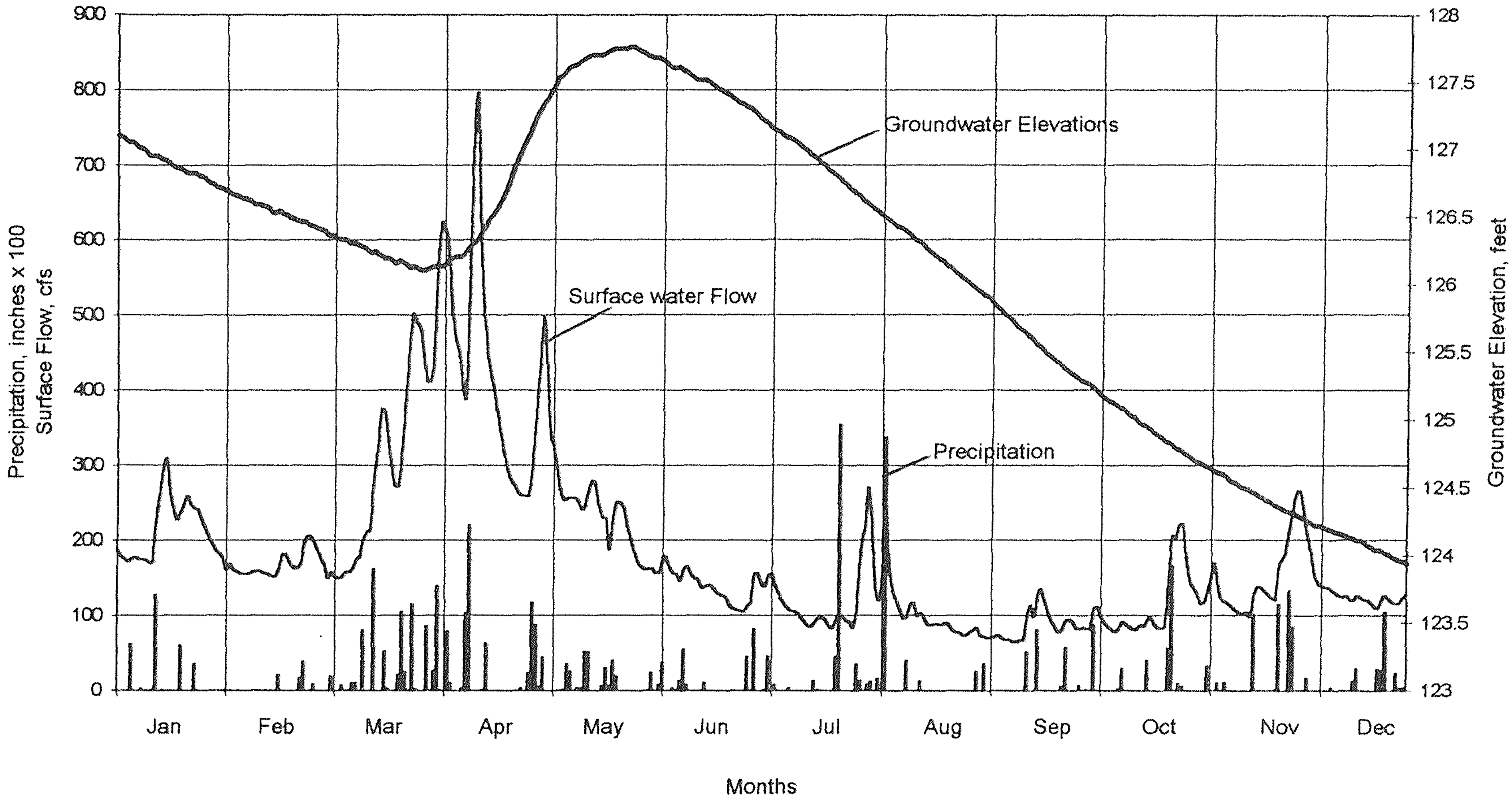


Figure 3.9 A Combined Plot of Precipitation, Groundwater, and Surface Flow, Year 1980

CHAPTER 4

DATA ANALYSIS

This chapter presents various analyses performed in order to develop linear regression models that can reasonably predict the relationship between precipitation, shallow groundwater level, and surface water discharge. The results of the analyses are compared with the actual values used to predict the models. The actual data used in each analysis are given in Appendix A. Appendix B summarizes the results of regression analyses performed in the study.

4.1 Approach to the Analysis

In order to establish a relationship between precipitation, groundwater levels, and stream flows, the hydrologic and climatologic data for the Toms River basin were used. The precipitation data used in this study included normal daily values recorded at the Toms River weather station during the period from 1976 to 1989. The groundwater elevation data included daily mean values of static water levels recorded at well No. 29-486 from 1976 to 1989, which were the best available set of values. The stream discharge data used included daily mean flows in the Toms River recorded during the study period at an index gaging station near Toms River, NJ.

Since all the data used in this study belonged to one watershed, factors such as soil properties and topographical characteristics remained invariant and were not considered in the analysis. Furthermore, the groundwater elevation was considered a response variable, whereas precipitation, stream flow, groundwater withdrawals, and potential evapotranspiration were independent variables. The constants of the regression analyses were assumed to represent the factors that were unknown or could not be determined and, therefore, used in regression. The significance of the variables included in regression models is shown by lower P-values in the summary statistics given in Appendix B.

4.2 Regression Analysis of the Data for the Entire Study Period

In the beginning of the analysis, a stepwise regression was performed on the raw data for the entire study period (1976-1989) with groundwater elevation as dependent variable and precipitation, groundwater withdrawals, and stream flow as independent variables in order to see how they correlate with each other. The correlation coefficient found was insignificant (R-square = 0.277). It was thought that one of the reasons for the poor correlation could be the time lag in the response of groundwater to precipitation. The groundwater elevation data were then shifted backwards for five, and seven days but no significant positive changes were observed in correlation.

It was observed, from the groundwater hydrographs for well no. 29-486, that the groundwater elevation curve was lagging a few weeks behind precipitation. Following this observation, several trial, stepwise, regressions were run on the data after shifting the groundwater elevation data backwards for one, two, three, and so on, up to sixteen weeks. Interestingly, the correlation improved by 0.02 in each trial. The maximum multiple R-square value was found when the groundwater elevation data were shifted for twelve weeks. After this, no significant improvement was observed in the R-square values. In order to optimize the correlation coefficient, a regression was performed with groundwater elevations (shifted twelve weeks) as a dependent variable and the daily precipitation , the natural log of one month moving average of the surface water data, the potential evapotranspiration data, and the withdrawal data, as independent variables. The natural log values of the surface water data were used in the analysis in order to improve R-square value by reducing variability in the surface water data. The following model was derived with the multiple R-square value of 0.49. The comparison of the observed and predicted values is shown in Figures 4A and 4B.

$$\mathbf{GE12 = 107.46 + 3.44\ Ln\ (SW30) + 0.804\ PEV - 0.504\ GX + 0.002\ PCP} \qquad \mathbf{(4.1)}$$

GE12 = Groundwater elevation after twelve weeks from a given day, feet

Ln (SW30) = Natural log of the one month moving averages of surface water flows, cfs

PEV = Average daily potential evapotranspiration, inches x 10

GX = Average daily groundwater withdrawals, million gallons

PCP = Average daily precipitation, inches x 100

Multiple R-square = 0.490

Standard error of prediction = 1.71

4.3 Analysis of the Monthly Data

As an alternative, stepwise regression was performed on the monthly averages of groundwater elevation, stream flow, monthly total groundwater withdrawals, evapotranspiration, and cumulative departure of precipitation from average monthly precipitation. The following linear regression model was derived with a fair correlation.

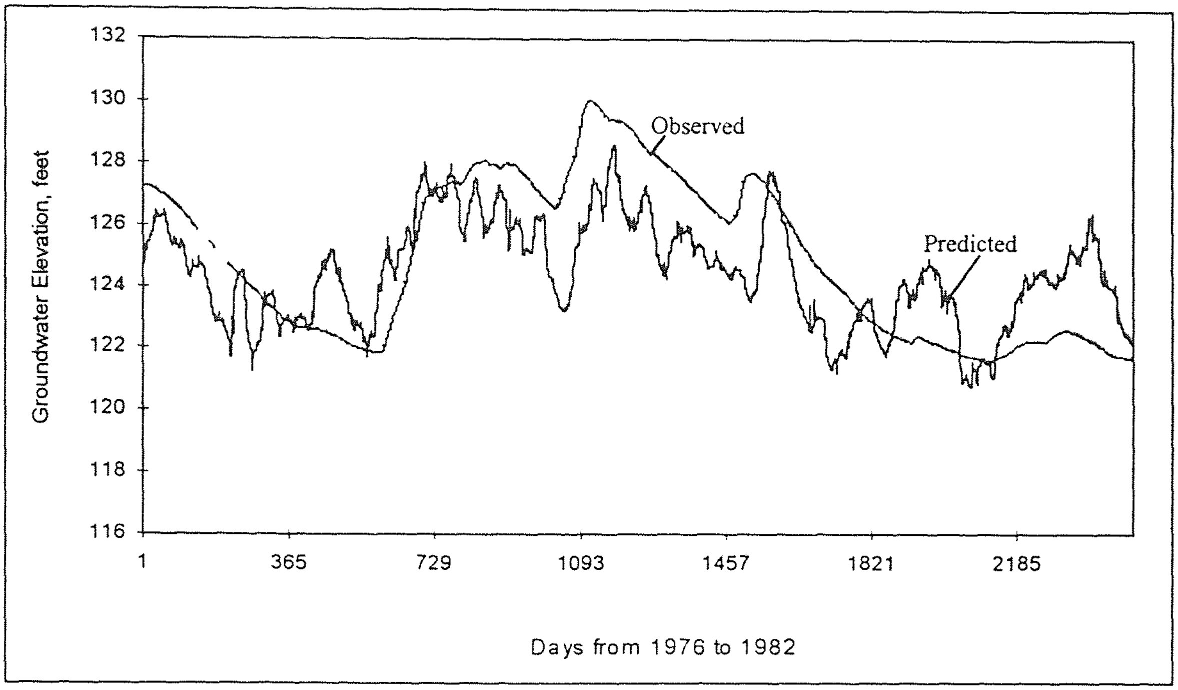


Figure 4A Comparison of Observed and Predicted Values of Groundwater Elevations (shifted 12 weeks)

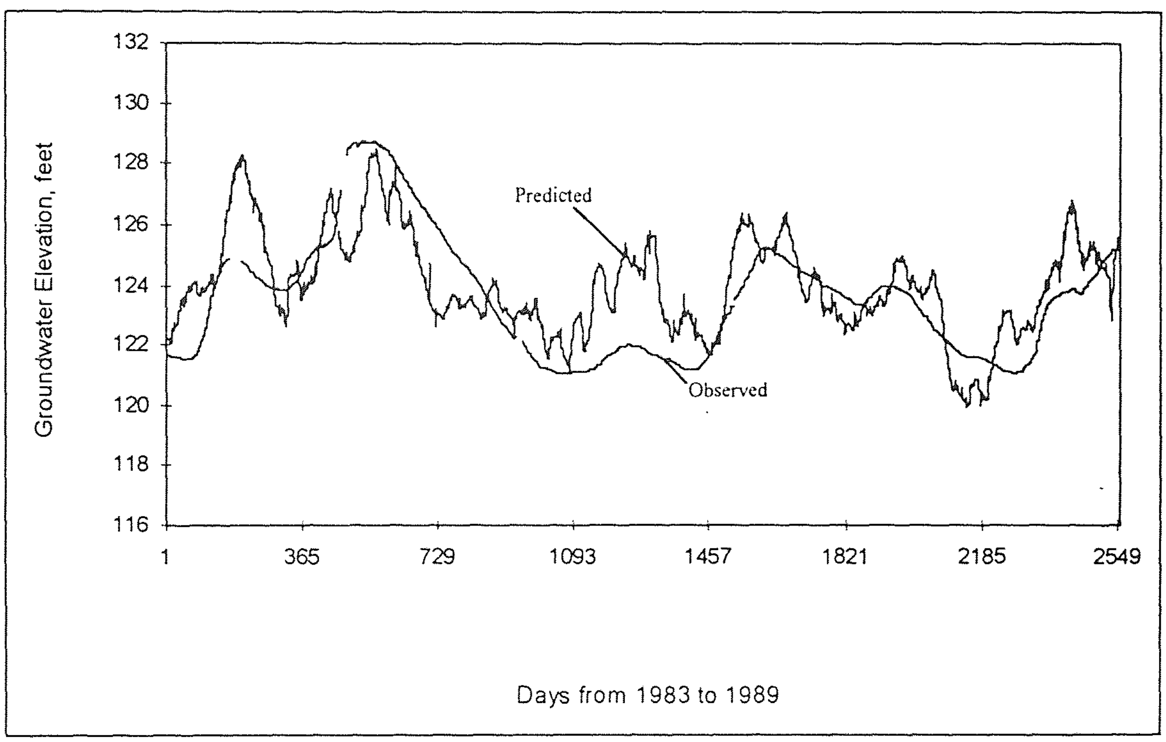


Figure 4B Comparison of Observed and Predicted Values of Groundwater Elevation (shifted 12 weeks)

GE = 120.92 + 0.008 SW + 0.05 GX - 0.264 PEV - 0.044 MN + 0.001 DPCP **(4.2)**

where

GE = Groundwater elevation above mean sea level, in feet

DPCP = Cumulative departure of precipitation from monthly average, in inches x 100

SW = Monthly average stream discharge, in cfs

GX = Monthly groundwater extraction in million gallons

PEV = Monthly potential evapotranspiration, in inches

MN = Number of months since January 1976.

Multiple R- square = 0.568

Standard error of estimation = 1.16

The comparison of the observed and predicted values of groundwater elevations is given in Table 4.1. Figure 4.1 is a graphical representation of the observed and predicted values. The data used in the analysis are given in Table A-1 in Appendix A.

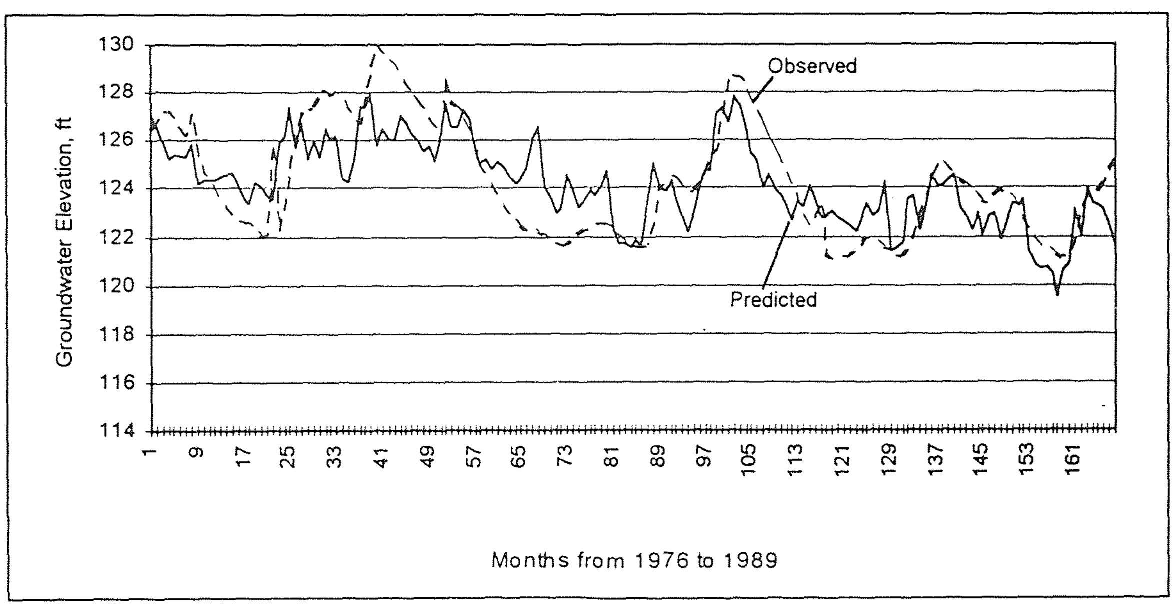


Figure 4.1 Comparison of Observed and Predicted Values of Groundwater Elevation

Table 4.1 Comparison of the Observed and Predicted Values of groundwater Elevations

	Month	Observed	Predicted	Difference
1976	**1**	126.4	127.06	-0.66
	2	126.74	126.56	0.18
	3	127.18	125.89	1.29
	4	127.21	125.26	1.95
	5	126.95	125.39	1.56
	6	126.6	125.40	1.20
	7	126.15	125.29	0.86
	8	127.12	125.87	1.25
	9	125.35	124.22	1.13
	10	124.66	124.37	0.29
	11	124.38	124.34	0.04
	12	123.98	124.39	-0.41
1977	**13**	123.57	124.54	-0.97
	14	123.23	124.62	-1.39
	15	122.9	124.63	-1.73
	16	122.7	124.13	-1.43
	17	122.66	123.58	-0.92
	18	122.56	123.40	-0.84
	19	122.39	124.23	-1.84
	20	122.15	124.08	-1.93
	21	122.02	123.70	-1.68
	22	125.88	123.57	2.31
	23	122.2	125.98	-3.78
	24	123.36	126.15	-2.79
1978	**25**	124.75	127.40	-2.65
	26	126.37	125.74	0.63
	27	127.09	126.73	0.36
	28	127.33	125.20	2.13
	29	127.38	125.99	1.39
	30	127.79	125.29	2.50
	31	128.07	126.48	1.59
	32	127.95	126.10	1.85
	33	127.99	126.21	1.78
	34	127.84	124.42	3.42
	35	127.4	124.27	3.13
	36	126.94	125.18	1.76

Table 4.1 (continued)

	Month	Observed	Predicted	Difference
1979	**37**	126.69	127.49	-0.80
	38	127.63	127.35	0.28
	39	128.9	127.93	0.97
	40	129.99	125.81	4.18
	41	129.67	126.51	3.16
	42	129.43	126.12	3.31
	43	129.24	126.01	3.23
	44	128.77	127.03	1.74
	45	128.37	126.85	1.52
	46	128.05	126.32	1.73
	47	127.74	126.13	1.61
	48	127.34	125.54	1.80
1980	**49**	126.9	125.79	1.11
	50	126.55	125.18	1.37
	51	126.23	126.37	-0.14
	52	128.58	127.60	0.98
	53	127.65	126.60	1.05
	54	127.49	126.60	0.89
	55	126.94	127.27	-0.33
	56	126.29	126.89	-0.60
	57	125.62	125.53	0.09
	58	125	125.07	-0.07
	59	124.49	125.23	-0.74
	60	124.11	124.82	-0.71
1981	**61**	123.71	125.13	-1.42
	62	123.26	124.92	-1.66
	63	122.91	124.50	-1.59
	64	122.65	124.19	-1.54
	65	122.43	124.44	-2.01
	66	122.27	124.83	-2.56
	67	122.37	126.05	-3.68
	68	122.23	126.58	-4.35
	69	122.08	124.12	-2.04
	70	121.92	123.65	-1.73
	71	121.79	122.98	-1.19
	72	121.7	123.12	-1.42

Table 4.1 (continued)

	Month	Observed	Predicted	Difference
1982	**73**	121.68	124.60	-2.92
	74	121.85	123.95	-2.10
	75	122.1	123.21	-1.11
	76	122.26	123.57	-1.31
	77	122.27	123.92	-1.65
	78	122.45	123.71	-1.26
	79	122.61	124.09	-1.48
	80	122.49	124.74	-2.25
	81	122.29	122.24	0.05
	82	122.03	121.75	0.28
	83	121.82	121.69	0.13
	84	121.73	121.58	0.15
1983	**85**	121.63	121.87	-0.24
	86	121.55	121.63	-0.08
	87	121.61	123.52	-1.91
	88	122.51	125.09	-2.58
	89	124.07	124.01	0.06
	90	124.2	123.90	0.30
	91	124.33	124.34	-0.01
	92	124.47	123.63	0.84
	93	124.1	122.88	1.22
	94	123.9	122.18	1.72
	95	123.85	123.11	0.74
	96	124.17	124.15	0.02
1984	**97**	124.84	124.85	-0.01
	98	125.25	124.74	0.51
	99	125.54	127.10	-1.56
	100	127.06	127.40	-0.34
	101	128.61	126.70	1.91
	102	128.7	127.83	0.87
	103	128.67	127.45	1.22
	104	128.18	126.42	1.76
	105	127.69	125.45	2.24
	106	127.2	125.21	1.99
	107	126.65	124.06	2.59
	108	126.12	124.56	1.56

Table 4.1 (continued)

	Month	Observed	Predicted	Difference
1985	**109**	125.55	123.94	1.61
	110	125.03	123.72	1.31
	111	124.58	123.25	1.33
	112	124.1	122.71	1.39
	113	123.47	123.49	-0.02
	114	122.82	123.24	-0.42
	115	122.38	124.14	-1.76
	116	122.89	123.45	-0.56
	117	123.41	122.74	0.67
	118	121.23	122.84	-1.61
	119	121.08	123.04	-1.96
	120	121.08	122.78	-1.70
1986	**121**	121.15	122.61	-1.46
	122	121.19	122.42	-1.23
	123	121.44	122.22	-0.78
	124	121.74	122.89	-1.15
	125	121.97	123.36	-1.39
	126	121.96	122.80	-0.84
	127	121.77	123.08	-1.31
	128	121.6	124.29	-2.69
	129	121.47	121.40	0.07
	130	121.26	121.55	-0.29
	131	121.2	121.81	-0.61
	132	121.44	123.51	-2.07
1987	**133**	122.15	123.70	-1.55
	134	122.99	122.32	0.67
	135	123.67	123.27	0.40
	136	124.37	124.59	-0.22
	137	125.1	124.10	1.00
	138	125.15	124.15	1.00
	139	124.9	124.34	0.56
	140	124.59	124.57	0.02
	141	124.37	123.25	1.12
	142	124.15	122.91	1.24
	143	123.9	122.30	1.60
	144	123.69	123.00	0.69

Table 4.1 (continued)

	Month	Observed	Predicted	Difference
1988	**145**	123.45	122.04	1.41
	146	123.39	122.85	0.54
	147	123.73	122.98	0.75
	148	123.97	121.89	2.08
	149	123.9	122.68	1.22
	150	123.65	123.42	0.23
	151	123.14	123.33	-0.19
	152	122.64	123.58	-0.94
	153	122.23	121.38	0.85
	154	121.87	120.86	1.01
	155	121.62	120.65	0.97
	156	121.57	120.79	0.78
1989	**157**	121.43	120.42	1.01
	158	121.22	119.52	1.70
	159	121.1	120.62	0.48
	160	121.21	120.89	0.32
	161	121.77	123.14	-1.37
	162	123.11	122.03	1.08
	163	123.62	124.03	-0.41
	164	123.81	123.43	0.38
	165	123.78	123.35	0.43
	166	124.19	123.16	1.03
	167	124.72	122.46	2.26
	168	125.14	121.64	3.50

4.4 Analysis of the Recharge and Discharge Events

During the course of this study, it was realized that a better relationship between the change in groundwater level, precipitation, surface water flow, evapotranspiration, and groundwater withdrawal could exist when groundwater recharge is occurring. In order to quantify the relationship between the above mentioned variables, a regression analysis was performed on the data associated with sixteen annual recharge events that occurred from

1976 to 1989. The results of the analysis came out as expected. The following linear regression equation for predicting rise in groundwater level during recharge was obtained.

DGW = 0.019 TPCP + 0.048 AVSW - 0.016 PEV - 15.55 **(4.3)**

DGW = Change in groundwater elevation, in feet

TPCP = Total precipitation over a recharge period, in inches x 100

AVSW = Average surface water flow resulted from precipitation, in cfs

PEV = Potential evapotranspiration over a recharge period, in inches x 1000

Multiple R square = 0.926

Standard error of estimation = 4.59

A numerical comparison of the observed and predicted values is given in Table 4.2, and a graphical representation is shown in Figure 4.2

Table 4.2 Comparison of the Observed and Predicted Changes in Groundwater Elevations During Recharge

Event No.	Observed	Predicted	Difference
1	0.89	1.22	-0.33
2	5.1	4.33	0.77
3	0.68	0.95	-0.27
4	3.36	3.50	-0.14
5	1.64	2.43	-0.79
6	0.2	-0.14	0.34
7	0.61	0.51	0.10
8	0.4	0.19	0.21
9	3.31	3.04	0.27
10	1.16	1.39	-0.23
11	3.15	3.37	-0.22
12	0.84	1.21	-0.37
13	4.07	4.72	-0.65
14	0.54	0.23	0.31
15	2.68	2.02	0.66
16	1.47	1.75	-0.28

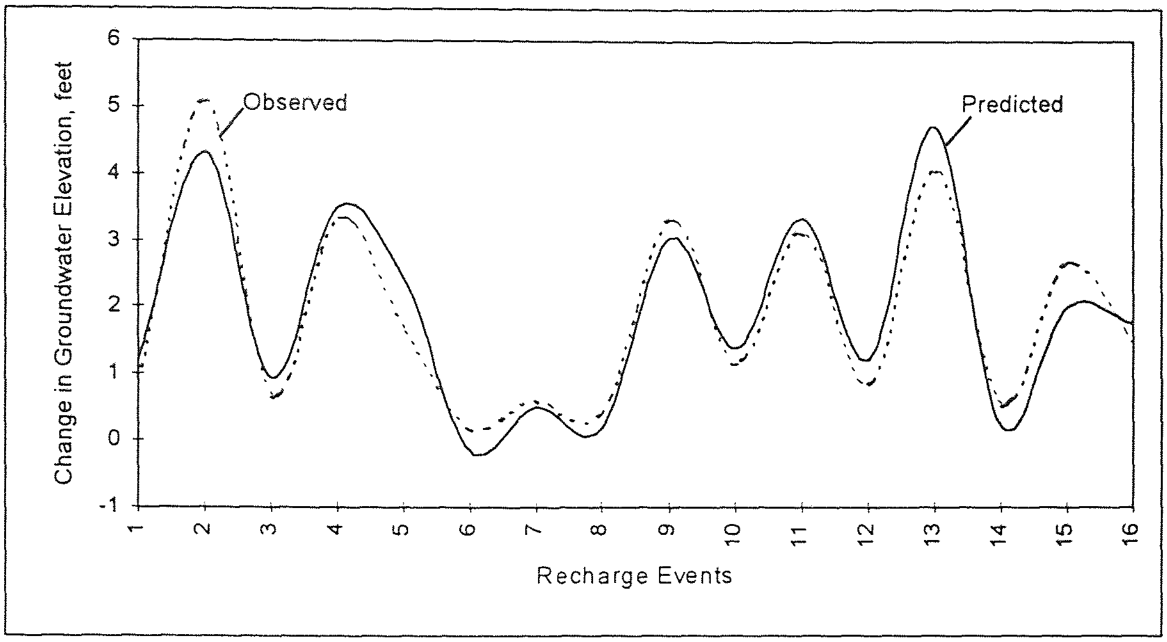


Figure 4.2 Observed and Predicted values of the Change in Groundwater Elevation During Recharge Period

Equation 4.3 can be employed to determine the amount of recharge that would occur in a watershed if the amounts of rainfall, average stream discharge, and potential evapotranspiration are substituted.

A similar analysis was performed on the data associated with fourteen annual discharge events that occurred during the study period. The discharge period is characterized by low precipitation and stream flow, and high evapotranspiration and groundwater withdrawals. Interestingly enough, the results of stepwise regression using only the best independent variables did not include precipitation and evapotranspiration as predictors, suggesting that their importance in computing the decline in groundwater elevation is insignificant.

The following simple linear regression model was obtained that can predict the decline in groundwater elevation over a period of low or no precipitation.

$$DGW = 0.006\ GX + 0.006\ AVSW - 1.59 \quad (4.3)$$

DGW = Decline in groundwater elevation over a period, in feet

GX = Groundwater withdrawals over a period, in million gallons

AVSW = Average surface runoff, in cfs

Multiple R-square = 0.903

Standard error of estimation = 0.37

The comparison of the observed and predicted values is given in Table 4.3. Figure 4.3 is a graphical representation of the observed and predicted values. The data used in the regression analysis are given in Table A-3 in Appendix A.

Table 4.3 Comparison of the Observed and Predicted Values of Changes in Groundwater Elevations During Discharge Events

Event No.	Observed	Predicted	Difference
1	1.05	1.03	0.02
2	1.25	0.86	0.39
3	0.53	1.01	-0.48
4	0.96	1.27	-0.31
5	1.25	1.37	-0.12
6	0.96	0.89	0.07
7	3.82	3.90	-0.08
8	1.68	2.20	-0.52
9	0.6	1.50	-0.90
10	2.72	3.01	-0.29
11	3.55	3.69	-0.14
12	0.87	0.50	0.37
13	0.37	0.50	-0.12
14	1.29	1.80	-0.51

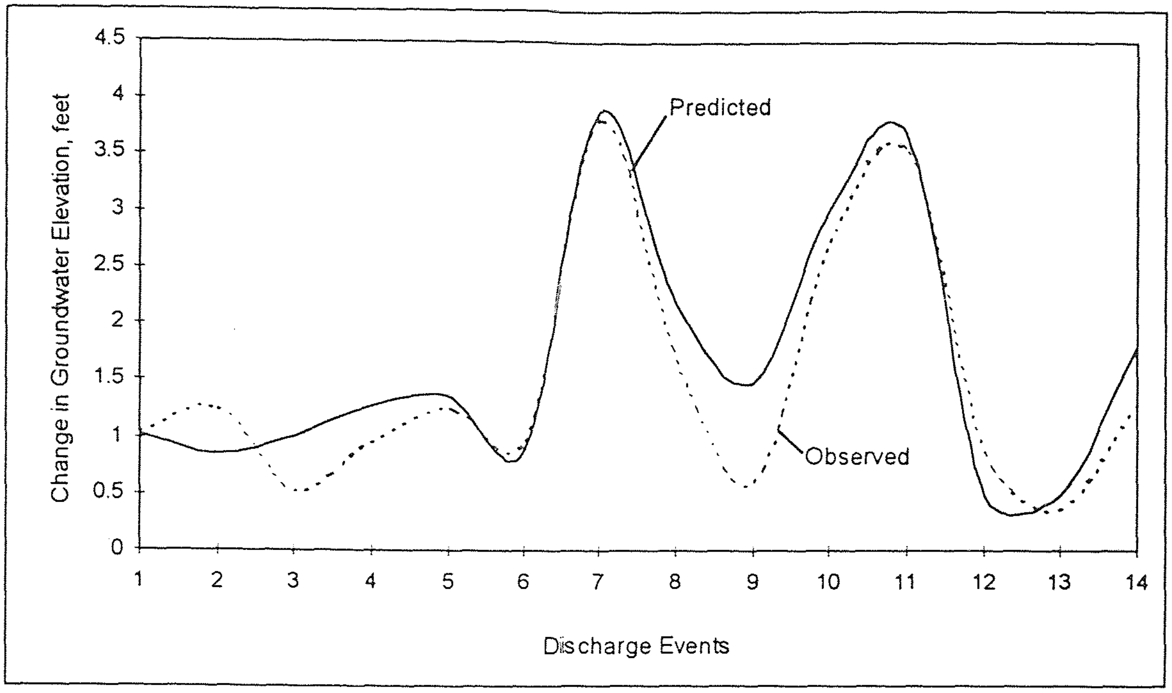


Figure 4.3 Observed and Predicted Values of Change in Groundwater Elevation During Recharge Period

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 General

The objective of this study was to define a relationship between the three hydrological parameters - precipitation, groundwater elevation, and stream discharge, in a watershed underlain by a shallow aquifer which is subjected to heavy groundwater pumping. Statistical analyses of fourteen years (from 1976 to 1989) of hydrologic data pertaining to these parameters showed a fair to high correlation. The summary and conclusions of the analyses are presented in the following paragraphs.

5.2 Analysis of the Time Series Data for the Entire Study Period

Stepwise regression analysis of the time series data considering shallow groundwater elevations (shifted backwards twelve weeks) as the response variable, and daily precipitation, the natural log of thirty days moving averages of stream flows, and the average daily values of groundwater extraction and evapotranspiration, as independent variables, showed a fair correlation between these parameters. The coefficient of determination, R-square, turned out to be 0.49, which is a significant number by all means for such hydrological studies. The standard error of prediction was 1.71.

The time lag in the rise of groundwater following a rainfall event was taken into account by shifting the groundwater elevation data backwards by twelve weeks. The R-square value improved by 0.02 for each shift until the twelfth week. After that, the R-square value declined gradually. Also, the use of the natural log of thirty days moving averages of the stream flows in the regression reduced variability of the data set yielding a better correlation.

5.3 Analysis of the Monthly Data

The correlation was slightly improved during the regression analysis of the monthly averages of shallow groundwater elevation, stream discharge, groundwater withdrawal, potential evapotranspiration, and the cumulative departure of precipitation from the monthly averages. The R-square value obtained in the analysis was 0.568, with the standard error of prediction of 1.16.

5.4 Analysis of the Recharge and Discharge Events

Stepwise regression performed on the recharge and discharge events that occurred during the study period yielded very high correlation between the change in groundwater elevation, precipitation, stream discharge, and potential evapotranspiration. The groundwater withdrawals were found be insignificant in predicting the groundwater elevation changes during the recharge periods. This may be due to a poor partial correlation of groundwater withdrawals with the changes in groundwater elevation compare to other parameters during the recharge period. For the recharge events, the coefficient of determination, R-square, was 0.926, with the standard error of prediction of 4.59.

During the discharge periods, precipitation and evapotranspiration were not critical in predicting groundwater elevation changes. The R-square value was found to be 0.903, with the standard error of prediction of 0.37.

5.5 Conclusions

The results of this study indicate that the relationship between the shallow groundwater elevation, precipitation, and stream discharge could be described by simple, linear statistical models. These models can be used for the rapid and reliable estimation of groundwater elevation when the amounts of precipitation, stream discharges, groundwater withdrawals, and evapotranspiration are known. The predicted values reflect the basin-wide, natural and man-induced, hydrologic phenomena that affect the shallow groundwater table.

The models described in this study are based on the hydrological data pertaining to a single basin (the Toms River Basin), and are independent of the factors such as size, shape, topography, and land-use characteristics. However, they must be modified to account for the changes in hydrogelogic characteristics because the time lag in the rise of the groundwater table may be different for different basins. The modification indices can be developed by comparing similar studies in the watersheds with different hydrogeologic characteristics.

Also, the type and availability of hydrologic data may have impact on the reliability of the models in this study. If the daily values of shallow groundwater elevation were available for more well sites and for larger time period, the reliability of the models could have been improved considerably. It seems that a comprehensive, basin-wide or greater hydrologic data monitoring network is essential in understanding and quantifying the relationship between precipitation, shallow groundwater elevation, and stream discharge.

As mentioned in the above paragraph, the models described in this study are based on the limited, but best available hydrologic data, and may leave room for refinements.

APPENDIX A

DATA USED IN REGRESSION ANALYSES

Table A-1 Data Used in the Regression Analysis on Monthly Values

GE	SW	GX	MN	DPCP	PEV
126.4	326.1	67.447	0	155.65	0
126.74	316.79	61.543	1	83.9	0.05
127.18	238.74	68.398	2	-127.74	0.55
127.21	179.17	76.484	3	-359.5	1.6
126.95	178.94	89.472	4	-363.63	3.4
126.6	109.3	114.191	5	-612.68	4.8
126.15	94.23	123.491	6	-793.04	5.7
127.12	167.87	114.643	7	-547.37	4.8
125.35	80.6	94.346	8	-786.66	3.5
124.66	138.97	72.426	9	-415.43	1.8
124.38	128.63	76.13	10	-765.45	0.8
123.98	134.77	76.84	11	-942.95	0.1
123.57	141.84	81.339	12	-1054.3	0
123.23	162.54	83.086	13	-1166.05	0.05
122.9	217.42	79.272	14	-1233.69	0.55
122.7	186.57	83.112	15	-1357.45	1.6
122.66	118.94	98.59	16	-1617.58	3.4
122.56	96.8	105.21	17	-1537.63	4.8
122.39	94.03	131.549	18	-1718.99	5.7
122.15	205.45	108.031	19	-1779.32	4.8
122.02	210.93	85.796	20	-1389.61	3.5
125.88	228.35	68.377	21	-1197.38	1.8
122.2	465.33	62.918	22	-630.4	0.8
123.36	434.13	63.48	23	-381.9	0.1
124.75	505.74	70.082	24	-10.25	0
126.37	319.07	70.195	25	-133	0.05
127.09	418.75	78.512	26	-178.64	0.55
127.33	282.43	79.697	27	-349.4	1.6
127.38	354.23	87.42	28	-7.53	3.4
127.79	231.37	104.485	29	-166.58	4.8
128.07	257.1	124.671	30	93.06	5.7
127.95	218.32	114.025	31	362.73	4.8
127.99	301.57	100.421	32	183.44	3.5
127.84	154.1	84.215	33	-19.33	1.8
127.4	153.5	78.726	34	-103.35	0.8

Table A-1 (continued)

GE	SW	GX	MN	DPCP	PEV
126.94	297.1	67.547	35	70.15	0.1
126.69	504.77	77.91	36	216.8	0
127.63	431.82	80.96	37	573.05	0.05
128.9	524.39	81.79	38	539.41	0.55
129.99	303.53	80.941	39	557.65	1.6
129.67	331.06	95.713	40	815.52	3.4
129.43	261.17	107.251	41	819.47	4.8
129.24	168.1	125.077	42	842.11	5.7
128.77	259.26	119.94	43	1196.78	4.8
128.37	270.47	103.798	44	1437.49	3.5
128.05	243.74	86.816	45	1567.72	1.8
127.74	232.2	81.173	46	1529.7	0.8
127.34	205.23	72.585	47	1444.2	0.1
126.9	214.61	77.607	48	1383.85	0
126.55	168.9	78.716	49	1140.1	0.05
126.23	293.74	80.233	50	1432.46	0.55
128.58	438.13	78.802	51	1901.7	1.6
127.65	254.61	99.923	52	1828.57	3.4
127.49	141.27	127.764	53	1763.52	4.8
126.94	114.77	150.336	54	1796.16	5.7
126.29	115.58	140.31	55	1721.83	4.8
125.62	85.53	113.888	56	1623.54	3.5
125	110.52	91.815	57	1662.77	1.8
124.49	141.43	84.026	58	1741.75	0.8
124.11	138.13	76.303	59	1600.25	0.1
123.71	103.58	94.369	60	1298.9	0
123.26	172	78.18	61	1411.15	0.05
122.91	150.37	82.744	62	1110.51	0.55
122.65	182.27	77.845	63	1115.75	1.6
122.43	175.03	97.014	64	987.62	3.4
122.27	133.9	109.701	65	1482.57	4.8
122.37	103.81	147.222	66	1346.21	5.7
122.23	73.42	165.68	67	998.88	4.8
122.08	82.47	110.51	68	930.59	3.5
121.92	90.19	91.955	69	922.82	1.8
121.79	106.27	76.974	70	650.8	0.8
121.7	158.58	66.125	71	774.3	0.1
121.68	192.9	86.854	72	957.95	0
121.85	206.82	74.485	73	876.2	0.05
122.1	167.68	74.784	74	609.56	0.55

Table A-1 (continued)

GE	SW	GX	MN	DPCP	PEV
122.26	214.43	79.739	75	668.8	1.6
122.27	198.58	102.256	76	537.67	3.4
122.45	238.9	94.891	77	792.62	4.8
122.61	169.84	120.822	78	704.26	5.7
122.49	127.45	140.641	79	510.93	4.8
122.29	93.83	94.015	80	316.64	3.5
122.03	102.26	77.555	81	176.87	1.8
121.82	131.75	67.928	82	138.85	0.8
121.73	165.08	60.633	83	-17.65	0.1
121.63	164.42	67.775	84	-56	0
121.55	185.03	60.199	85	-22.75	0.05
121.61	363.04	68.71	86	188.61	0.55
122.51	512.87	73.545	87	636.85	1.6
124.07	329.63	90.082	88	721.72	3.4
124.2	236.39	110.675	89	738.67	4.8
124.33	139.01	146.24	90	459.31	5.7
124.47	126.99	133.554	91	287.98	4.8
124.1	176.88	105.536	92	235.69	3.5
123.9	163.4	83.098	93	364.92	1.8
123.85	267.55	72.358	94	781.9	0.8
124.17	394.12	66.072	95	984.4	0.1
124.84	269.53	103.885	96	803.05	0
125.25	285.62	94.618	97	1081.3	0.05
125.54	495.9	103.875	98	1475.66	0.55
127.06	572.92	101.489	99	1603.9	1.6
128.61	357.95	129.372	100	1743.77	3.4
128.7	378.52	156.036	101	1786.72	4.8
128.67	330.2	160.88	102	1837.36	5.7
128.18	189.13	160.323	103	1769.03	4.8
127.69	138.91	133.829	104	2228.74	3.5
127.2	151.81	120.436	105	2146.97	1.8
126.65	157.03	95.435	106	1987.95	0.8
126.12	170.79	101.766	107	1919.45	0.1
125.55	142.06	99.445	108	1667.1	0
125.03	197.68	88.195	109	1622.35	0.05
124.58	143.52	96.102	110	1360.71	0.55
124.1	120.26	100.937	111	1085.95	1.6
123.47	131.1	124.391	112	1125.82	3.4
122.82	129.5	123.357	113	1358.77	4.8
122.38	83.45	158.677	114	1140.41	5.7

Table A-1 (continued)

GE	SW	GX	MN	DPCP	PEV
122.89	101.95	142.945	115	898.08	4.8
123.41	95.16	122.082	116	979.79	3.5
121.23	119.81	116.636	117	757.02	1.8
121.08	171.83	103.536	118	969	0.8
121.08	201.91	94.862	119	768.5	0.1
121.15	194.42	92.337	120	799.15	0
121.19	245.5	82.035	121	768.4	0.05
121.44	206.24	92.944	122	517.76	0.55
121.74	290.15	96.288	123	664	1.6
121.97	156.65	142.804	124	395.87	3.4
121.96	101.51	152.871	125	193.82	4.8
121.77	136.26	150.842	126	577.46	5.7
121.6	119.08	176.913	127	430.13	4.8
121.47	95.1	119.181	128	319.84	3.5
121.26	102.32	113.435	129	287.07	1.8
121.2	200	93.609	130	539.05	0.8
121.44	333.81	97.859	131	820.55	0.1
122.15	343.84	94.384	132	1113.2	0
122.99	241.86	90.179	133	818.45	0.05
123.67	274.68	109.402	134	726.81	0.55
124.37	385.8	121.035	135	893.05	1.6
125.1	234.81	147.03	136	831.92	3.4
125.15	167.93	169.192	137	717.87	4.8
124.9	186.29	176.078	138	705.51	5.7
124.59	158.9	180.89	139	716.18	4.8
124.37	137.57	154.411	140	591.89	3.5
124.15	140.29	138.98	141	593.12	1.8
123.9	166.6	120.321	142	492.1	0.8
123.69	184.23	130.623	143	396.6	0.1
123.45	199.74	109.265	144	398.25	0
123.39	277.62	111.426	145	527.5	0.05
123.73	217.45	129.356	146	417.86	0.55
123.97	172.07	123.531	147	306.1	1.6
123.9	200.97	142.796	148	417.97	3.4
123.65	113.9	184.311	149	194.92	4.8
123.14	77.29	198.882	150	-44.44	5.7
122.64	70.19	202.285	151	-103.77	4.8
122.23	71.27	155.728	152	-282.06	3.5
121.87	87.45	133.709	153	-240.83	1.8
121.62	152.67	111.727	154	-87.85	0.8

Table A-1 (continued)

GE	SW	GX	MN	DPCP	PEV
121.57	136.06	120.137	155	-378.35	0.1
121.43	135.58	115.239	156	-486.7	0
121.22	159.75	95.391	157	-523.45	0.05
121.1	197.77	112.698	158	-418.09	0.55
121.21	215.97	117.63	159	-220.85	1.6
121.77	379.13	137.482	160	247.02	3.4
123.11	228.87	145.561	161	355.97	4.8
123.62	264.13	179.21	162	672.61	5.7
123.81	218.45	169.629	163	718.28	4.8
123.78	277.03	150.342	164	835.99	3.5
124.19	304.87	132.558	165	905.22	1.8
124.72	262.1	120.348	166	937.2	0.8
125.14	179.16	121.526	167	581.7	0.1

Table A-2 Data Used in the Regression Analysis on Recharge Events

YEAR	DGW	TPCP	AVSW	PEV
1976	0.89	680	298.4	40.6
1977	5.1	1936	435.2	82.4
1978	0.68	1174	296.2	663.6
1979	3.36	1362	486.1	48.1
1980	1.64	1278	366.7	203
1981	0.2	491	150.6	157.7
1982	0.61	636	179.9	51.3
1982	0.4	725	221.5	406.7
1983	3.31	1929	384.5	591.6
1983	1.16	676	323.3	11.6
1984	3.15	1250	558.5	185.5
1986	0.84	1016	244.2	242.4
1987	4.07	2697	302.41	317.9
1988	0.54	395	215.2	42.3
1989	2.68	2705	268.37	1587.6
1989	1.47	1164	298.4	255.2

Table A-3 Data Used in the Regression Analysis on Discharge Events

YEAR	PCP	AVSW	DGW	GX	PEV
1977	1005	179	1.05	257.1	3.15
1978	1013	204.3	1.25	203.6	14.73
1979	796	329.5	0.53	103.1	4.1
1979	1476	222.9	0.96	254.3	10.53
1979	1375	214.4	1.25	278.1	3.96
1980	863	204.9	0.96	208.2	1.79
1980	2624	122.4	3.82	793.1	21.93
1981	1461	150.9	1.68	480.1	8.93
1981	964	79.74	0.6	434.5	12.87
1984	2097	161.48	2.72	604.5	10.62
1985	1792	135.3	3.55	744.6	15.51
1985	513	98.12	0.87	250.9	7.17
1987	500	158.1	0.37	189.4	5.58
1988	520	80.12	1.29	485.5	12.72

Table A-4 Monthly Average Groundwater Withdrawals from Kirkwood-Cohansy Aquifer for the Toms River Watershed (from Water Use file, USGS, Trenton), in million gallons

YEAR	JAN	FEB	MAR	APR	MAY	JUN
1976	67.4469	61.5431	68.3975	76.4841	89.472	114.191
1977	81.33923	83.0858	79.272	83.1119	98.5902	105.21
1978	70.08239	70.195	78.5121	79.6968	87.4204	104.485
1979	77.90985	80.9599	81.7895	80.9411	95.7131	107.251
1980	77.60708	78.7158	80.2328	78.8025	99.9235	127.764
1981	94.36946	78.1804	82.7437	77.8455	97.0144	109.701
1982	86.85438	74.4853	74.7836	79.7393	102.256	94.8906
1983	67.77467	60.199	68.7102	73.5455	90.0821	110.675
1984	103.8845	94.6175	103.875	101.489	129.372	156.036
1985	99.44544	88.1946	96.1016	100.937	124.391	123.357
1986	92.33708	82.0354	92.9445	96.2875	142.804	152.871
1987	94.38386	90.1792	109.402	121.035	147.03	169.192
1988	109.2648	111.426	129.356	123.531	142.796	184.311
1989	115.2392	95.3906	112.698	117.63	137.482	145.561

Table A-4 (continued)

YEAR	JAN	FEB	MAR	APR	MAY	JUN
1976	123.4908	114.643	94.3459	72.4261	76.1299	76.84
1977	131.5488	108.031	85.7962	68.3771	62.9179	63.4796
1978	124.6711	114.025	100.421	84.2152	78.7258	67.5475
1979	125.0774	119.94	103.798	86.8158	81.1735	72.585
1980	150.3359	140.31	113.888	91.8149	84.0257	76.3029
1981	147.2217	165.68	110.51	91.9554	76.9743	66.125
1982	120.8218	140.641	94.0148	77.5552	67.928	60.6334
1983	146.2398	133.554	105.536	83.0975	72.3582	66.0721
1984	160.8798	160.323	133.829	120.436	95.4353	101.766
1985	158.6769	142.945	122.082	116.636	103.536	94.8621
1986	150.8425	176.913	119.181	113.435	93.6092	97.8592
1987	176.0785	180.89	154.411	138.98	120.321	130.623
1988	198.8824	202.285	155.728	133.709	111.727	120.137
1989	179.2104	169.629	150.342	132.558	120.348	121.526

Table A-5 Monthly Average Potential Evapotranspiration in the Toms River basin (measured from a chart, Watt, M. K.), in inches

MONTH	PEV	MONTH	PEV
Jan	0.00	Jul	5.69
Feb	0.06	Aug	4.75
Mar	0.56	Sep	3.5
Apr	1.62	Oct	1.81
May	3.88	Nov	0.75
Jun	4.75	Dec	0.06

APPENDIX B

SUMMARY OF REGRESSION ANALYSES

Table B-1 Summary of Regression Analysis on the Time Series Data for Entire Study Period

MODEL GE12 = CONSTANT+PEV+LNSW30+GX+PCP

Dep. Var: GE12 N: 4904 Multiple R: 0.702 Squared Multiple R: 0.493
Adjusted Squared Multiple R: .492 Standard Error Of Estimate: 1.708

Variable	Coefficient	Std Error	Std Coef	Tolerance	T	P(2 Tail)
Constant	107.464	0.313	0.000	.	343.730	0.000
Pev	0.804	0.054	0.219	0.484	14.986	0.000
Lnsw30	3.436	0.053	0.674	0.944	64.308	0.000
Gx	-0.504	0.035	-0.214	0.477	-14.553	0.000
Pcp	0.002	0.001	0.033	0.998	3.245	0.001

Analysis of Variance:

Source	Sum-Of-Squares	Df	Mean-Square	F-Ratio	P
Regression	13884.797	4	3471.199	1189.220	0.000
Residual	14299.630	4899	2.919		

Table B-2 Summary of Regression Analysis Performed on the Monthly Data

MODEL GE = CONSTANT+SW+GX+PEV+MN+DPCP

Dep Var: GE N: 168 Multiple R: 0.754 Squared Multiple R: 0.568
Adjusted Squared Multiple R: .555 Standard Error Of Estimate: 1.593

Variable	Coefficient	Std Error	Std Coef	Tolerance	T	P(2 Tail)
Constant	120.924	0.679	0.000	.	178.154	0.000
Sw	0.008	0.001	0.347	0.870	6.268	0.000
Gx	0.050	0.009	0.663	0.181	5.454	0.000
Pev	-0.264	0.119	-0.221	0.269	-2.222	0.028
Mn	-0.044	0.004	-0.896	0.355	-10.337	0.000
Dpcp	0.001	0.000	0.410	0.892	7.505	0.000

Table B-2 (continued)

Analysis of Variance:

Source	Sum-Of-Squares	Df	Mean-Square	F-Ratio	P
Regression	540.468	5	108.094	42.575	0.000
Residual	411.299	162	2.539		

Table B-3 Summary of Regression Analysis Performed on the Data for the Recharge Events

MODEL DGW = CONSTANT+TPCP+AVSW+GX+PEV

Dep Var: DGW N: 16 Multiple R: 0.962 Squared Multiple R: 0.926
Adjusted Squared Multiple R: .908 Standard Error Of Estimate: 4.592

Variable	Coefficient	Std Error	Std Coef	Tolerance	T	P(2 Tail)
Constant	-15.551	3.791	0.000	.	-4.102	0.001
Tpcp	0.019	0.002	0.918	0.433	7.706	0.000
Avsw	0.048	0.013	0.347	0.694	3.692	0.003
Pev	-0.016	0.004	-0.404	0.491	-3.617	0.004

Analysis of Variance:

Source	Sum-Of-Squares	Df	Mean-Square	F-Ratio	P
Regression	3178.970	3	1059.657	50.259	0.000
Residual	253.007	12	21.084		

Table B-4 Summary of the Regression Analysis Performed on the Data for the Discharge Events

MODEL DGW = CONSTANT+AVSW+GX+PEV+PCP

Dep Var: DGW N: 14 Multiple R: 0.950 Squared Multiple R: 0.903
Adjusted Squared Multiple R: .885 Standard Error Of Estimate: 0.370

Variable	Coefficient	Std Error	Std Coef	Tolerance	T	P(2 Tail)
Constant	-1.590	0.484	0.000	.	-3.286	0.007
Avsw	0.006	0.002	0.357	0.673	3.108	0.010
Gx	0.006	0.001	1.108	0.673	9.655	0.000

Table B-4 (continued)

Analysis of Variance:

Source	Sum-Of-Squares	Df	Mean-Square	F-Ratio	P
Regression	13.976	2	6.988	50.947	0.000
Residual	1.509	11	0.137		

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