HYDROLOGY OF SPRING

by

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Abstract

The springflow models which are hitherto available are based on the assumption of lumped recharge in the recharge zone of a spring.But in reality, recharge to a spring is variable with time. With the help of the existing models of the springflow, the prediction of volume of live reserve inside the spring is only possible for lumped recharge .A mathematical model for analysing the unsteady flow from a spring has been developed accounting variable recharge. The springflow domain has been hydrologically decomposed into two domains: a recharge zone, and a transition zone. The spring s threshold point lies at the end of the transition zone.In the recharge zone,the flow has been assumed to be only in the vertical direction and in the transition zone the flow has been assumed to follow Dupuit-Forchheimer assumptions and the flow is in the horizontal direction. For solving the problem, the unsteady state has been assumed to be succession of steady states.

With the help of the present model, recharge to the spring flow domain, and live storage in the spring and springflow can be predicted for time variant recharge.

The model developed is applied to Parda spring, Nainital for which several years of springflow and rainfall data are available. These data have been used to calibrate the model and simulate the springflow.

Introduction

Springs are natural outlets through which the groundwater emerges at the ground surface as concentrated discharge from an aquifer and are most conspicuous forms of natural return of groundwater to the surface. Springs are part of the groundwater system and may be treated as a flowing well with constant drawdown. Springs could occur in various sizes from small trickle to large stream. Seepage areas are distinguished from springs because of the slower movement of groundwater from the seepage area unlike the springs. A few large springs may indicate the existence of thick transmissive aquifers whereas frequent small springs indicate thin aquifers of low transmissivity. Therefore,

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the springs can aid in the evaluation of groundwater potential of the area. Conditions necessary to produce springs are many and are related to different combination of geologic, hydrologic, hydraulic, pedologic, climatic and even biological controls. Springs occur where down gradient parts of aquifer or other water bearing materials with their lower boundary are exposed to the surface like at hill sides, canyons or dissection due to erosion channel. Springs also form where discontinuities like faults or tectonic fractures or dikes present hydraulic barriers and force groundwater to flow upward or where faults cause weak spots in confining layers allowing water to flow upward and reach the surface if the piezometric surface in the aquifer is sufficiently high. The rainwater fills up in the fractured rock fissures which then flows through the same fissures system to form spring at lower points. In some areas, springs occur in alluvial deposits filling river valleys. Such groundwater outcrops are found where river valley has become narrower, thus reducing the cross-sectional area of the groundwater flow. Solution activity and karstification of limestone produce sizeable springs. Springs could occur below surface water, fresh or salty. Hydrogeologic investigations have demonstrated that gravity springs (occurring t the contact between an aquifer and aquitard) are mostly found in plains, whereas both gravity and artesian springs occur in the mountains.

There are many descriptive terms for springs based on a single or combined controlling factors.Keilhack (1935) classified the springs on the basis of descending (water table) and ascending water (artesian) flow in the spring. Tolman (1937) classified the springs. On the basis of type of water bearing formation and type of opening. Meinzer (1923) classified springs according to magnitude of the spring's discharge. He also classified the springs on the basis of variability of perennial springs and permanence of discharge.

Discharge rate from a spring depends on the size of the recharge area above it, the rate of precipitation in the area, aquifer geometry, geology and geomorphology of the area, storage coefficient and transmissivity of the aquifer. Fluctuation of spring discharge are in response to variations in rate of recharge,geologic and hydrologic conditions.

The instantaneous rate of discharge of a spring depends on the difference between the elevations of the water table (or piezometric head) in the aquifer of the spring, and the elevation of spring outlet (called as threshold). During dry season, the spring discharge is derived from water stored in the aquifer. Consequently, the water levels in the aquifer will gradually fall and spring discharge decline. During the precipitation period, the aquifer gets recharged and water table rises and spring discharge increases. This fall and rise of water table in the aquifer go on in a cyclic pattern. The relationship between the rate of decrease and increase of discharge and time (dry and wet seasons) depends on storage characteristics of the aquifer (strorativity) and geometry of aquifer (areal extent). Fig.1 shows a typical portion of a spring hydrograph, the recession (or depletion) portion of this hydrogrph, corresponding to dry seasons. On semilog paper (with time on the linear scale), the recession curve usually plots as a straight line.

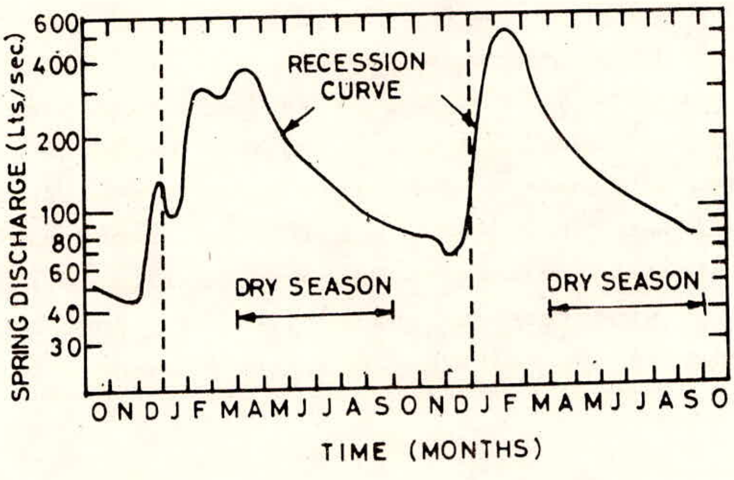

FIG.1-A TYPICAL SPRING HYDROGRAM WITH SEASONAL FLUCTUATION (after Bear, 1979)

For the groundwater flow domain analysis on a regional basis, the spring serves as a boundary condition. The elevation of the threshold or outlet of the spring is considered as fixed head. But. when the water table in the vicinity of the spring drops below the spring outlet at some point of time (which is a priori unknown). the spring does not act as a boundary of the flow domain.

The mathematical model developed to study springflow and spring s flow domain has been assumed to be linear. The linear system is one which has the property of superposition. Any number of time variant inputs can be added together in a linear system and the output will be the sum of individual corresponding output. The derivation of the equation for a linear system depends on the use of the concept of an impulse function and the impulse response. For the continuous forms of the convolution technique, the impulse function or Dirac delta function is visualized as the limiting form of a pulse of some particular shape as the duration of the pulse goes to zero. But, for the discrete form of input with a time interval, the input can be defined in terms of input histogram ordinate and the impulse response is replaced by pulse response which is defined as the output from the linear system when the input is given by rectangular pulse.

Development of the Model

The springflow models which are available (Mero, 1963; Bear,1979; Mandel and Shiftan, 1981) are based on the assumption of lumped recharge in the recharge zone of the spring. But in reality, the recharge to a spring is variable with time.

A mathematical model for analysing the unsteady flow of a spring has been developed to take into account the variability in recharge(Fig.2).The springflow domain has been hydrologically decomposed into two domains;-(i)recharge zone and (ii)transition zone.The spring s threshold point lies at the end of the transition zone. In the recharge zone, the flow has been assumed

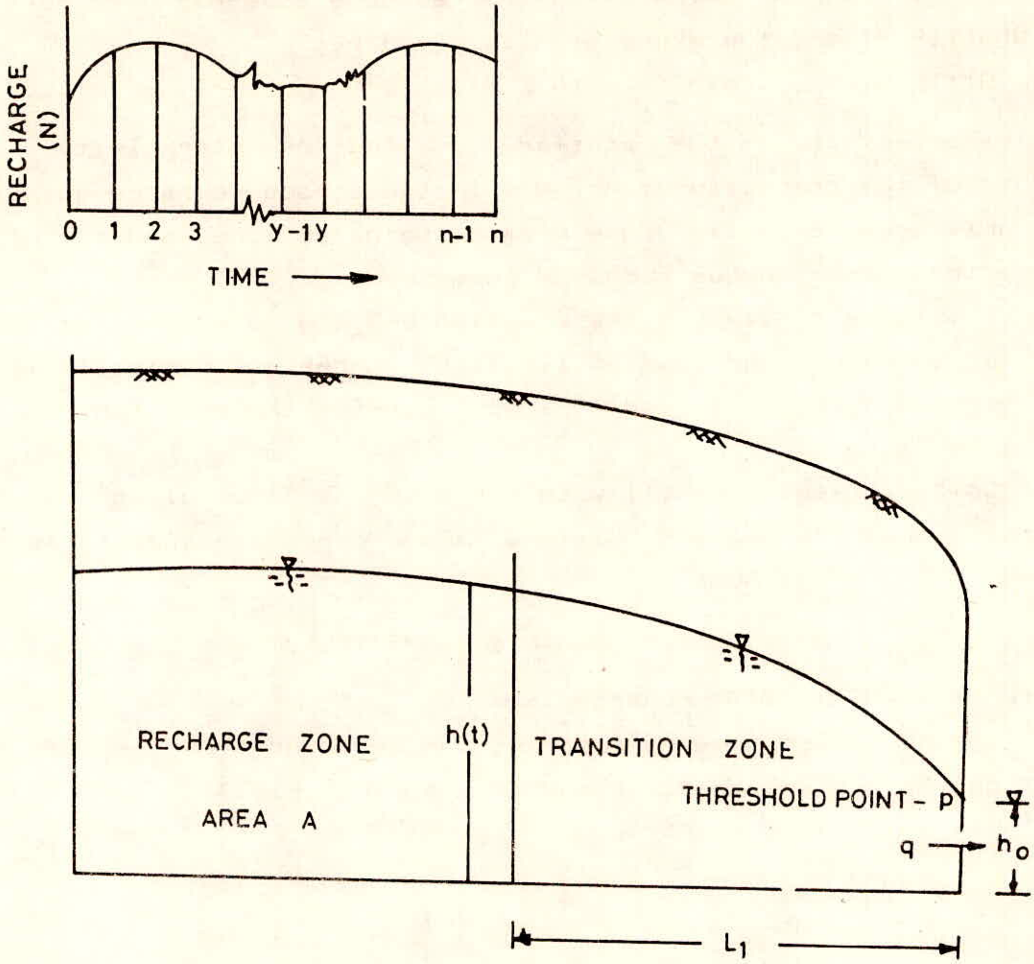

FIG. 2- PROPOSED MODEL CONFIGURATION

to be in vertical direction and in the transition zone, the flow has been assumed to satisfy Dupuit-Forchhemier conditions. For solving the problem, the unsteady state has been assumed to be succession of steady state. An expression for spring discharge due to an instantaneous recharge in the recharge zone has been derived by Bhar(1989) and the expression is given by;

$$Q(t)=TN/(L_1\phi)\ \exp\{-Tt/(A\ L_1\phi)\} \qquad ...(1)$$

where

T= Transmissivity of the aquifer , ϕ= Aquifer storativity, L_1= Length of the transition zone, N = Instantaneous recharge quantity per unit area to aquifer, A = Area of recharge zone, and t = Time since the instantaneous recharge commenced.

Eq.(1) is similar to the equation $Q=Q_o e^{-t/t_o}$ which has been derived by Mandel and Shiftan(1981). A conceptual Unicell model has been used by Mandel and Shiftan to derive the equation.

Depletion time (t_o)

Comparing equation (1) with $Q = Q_o\ e^{-t/t_o}$ given by the Unicell model (Mandel and Shiftan, 1981), depletion time t_o is

$$t_o= AL_1\phi\ /\ T \qquad ...(2)$$

$$Q_o = Q(o) = TN\ /(L_1\phi) = RT/(AL_1\phi) \qquad ...(3)$$

where R = AN = total recharge .

The depletion time of a spring can be found from the semilog plot of the dry season discharge of a spring (Fig.3).

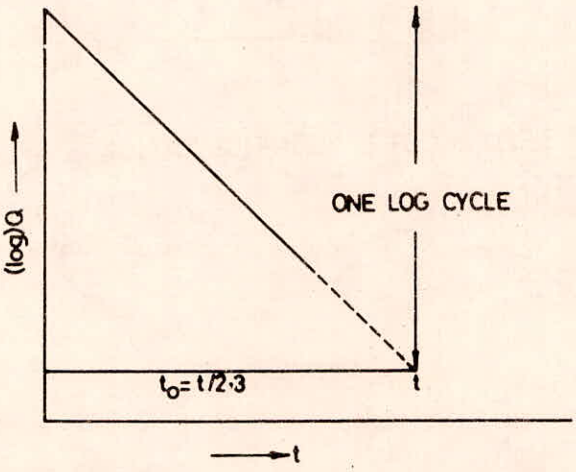

FIG.3. DETERMINATION OF DEPLETION TIME (t_o)

The volume of water, $V(t)$, which is present in the dynamic storage of the spring at time t can be expressed as

$$V(t)=\int_t^{\infty} Q(t)\ dt = \int_t^{\infty} \frac{TN}{L_1\phi}\, e^{-Tt/(AL_1\phi)}\ dt$$

$$=AN\ [\ e^{-Tt/(AL_1\phi)}\ ]$$

$$= R\ [\ e^{-Tt/AL_1\phi}\ ] \qquad \ldots(4)$$

Also the live storage of groundwater at time, t, that maintains spring discharge, is equal to product of depletion time and outflow rate of the spring at that time. The live reserve at time, t, in the spring flow domain is, therefore, equal to $Q(t).t_o$.

Using eqs. (1) and (2), the following expression for live storage has been derived;

$$Q(t).t_O= [\ \frac{TN}{L_1\phi}\ e^{-Tt/AL_1\phi}\ ]\ [\ \frac{AL_1\ \phi}{T}\ ]$$

$$=A\ N\ e^{-Tt/AL_1\phi} =R\ e^{-Tt/AL_1\ \phi} \qquad \ldots(5)$$

Thus, the validity of the expression for the depletion time given in eq. (2) which incorporate the hydrogeological parameters and the geometry of the aquifer is verified.

The variation of spring discharge with time can be plotted in a semilog paper (discharge being in the log scale). The slope of such a plot will provide the depletion time, t_o. It is likely that the slope of the discharge time plot may vary. Any variation in the slope of the discharge-time plot from year to year is indicative of interference in the ground water system. A progressive flattening and steepening of the slope indicate the replenishment of the aquifer in the supposedly dry season (probably due to return flow of irrigation/urban effluent or seepage from reservoirs) and ground water abstraction from the aquifer respectively. Occurrence of rare natural catastrophe like earthquake can also have effect on spring discharge and the slope of the time discharge plot could change considerably

Use of convolution technique

Generally the recharge occurs over a period of time either during the rainy season or during the snow melt period. In such cases, the model should consider the time variant recharge rate. The present conceptual model being linear, the response of the model to a time variant input can be obtained using convolution technique.

The response of linear system which is initially at rest to a unit pulse excitation given to the system during the first unit time step has been designated as discrete kernel coefficients, $\delta(.)$, (Morel Seytoux and Daly, 1975). In the present case, if unit recharge takes place during unit time period, the discharge of the spring at different time period are the discrete kernel coefficients for the spring. These coefficients are the properties of the spring and are independent of the excitation. Using these coefficients, the spring discharge for variable recharge can be found. The unit step may be one day, one week or one month. The discrete kernel coefficient can be derived as follows:

Replacing N by R/A in eqn.(1), and assuming R=1, the unit impulse response function coefficient is found to be

$$k(t) = \frac{T}{AL_1} [\frac{1}{\phi} \exp \{-Tt/(AL_1\phi)\}] \qquad \ldots(6)$$

The discrete kernel coefficient which is defined as $\delta(n) = \int_0^1 k(t-\tau)d\tau$ is given by:

$$\delta(n) = \exp(-n/t_0) [\exp (1/t_0 - 1)] \qquad \ldots(7)$$

The springflow for varying recharge is given by

$$q(n) = \sum_{\gamma=1}^{n} \delta (n-\gamma+1) N(\gamma) \qquad \ldots(8)$$

The basic assumption of the model that the outflow from the spring is linearly varied with the storage inside the spring, is identical with Bear's assumption for his model (Bear,1979). But the improvement incorporated in the present model are:

1. The flow domain of the spring is hydrologically decomposed to a recharge zone and a transition zone.

2. The model has one parameter, i.e., depletion time (t_o).

3. The model is capable of analysing the case for variable recharge in the recharge domain of the spring. The model can predict the outflow from spring both for wet and dry seasons.

Application of the Model for a Case Study

Water emanating through cavities and channels in dolomite and limestone gives rise to spring such as are seen in Nainital township. Parda spring is one of them and is classified as a karst spring. Sharma(1981) describes Parda spring as controlled by the Nainital fault, but the investigators from Kumaon University consider it as a karst spring(Valdiya and Bartarya, 1988) because it is located in karst of dolomite, and is related to the underground channels and cavities. Nainital fault has played a major role in localisation of the Parda spring and other springs in the region. But the solution channels and cavities have got opened due to faulting.

Data available

The monthly springflow data for the Parda spring for 1973-74, 1977-78, 1980-81, 1982-83 to 1985-86 (for 7 years) and monthly rainfall data for two stations in the area viz, Nainital (for 13 years), Nainital observatory (for 10 years) along with some hydrometeorological data are available.

Determination of depletion time (t_o)

The monthly springflow data available are plotted in semilog graph paper (springflow in log scale) year wise and the recession portion of the plots which have been fitted into a straight line, were extended to meet the time axis and depletion time (t_o) for each year were determined (Fig.4). The value of t_o for the years 1982-83 to 1985-86 for which continuous springflow data were available are 5.6 , 5.2 ,3.9 and 6.5 month respectively. The average depletion time (t_o) is taken to be 5.3 month for the Parda spring (Fig.4).

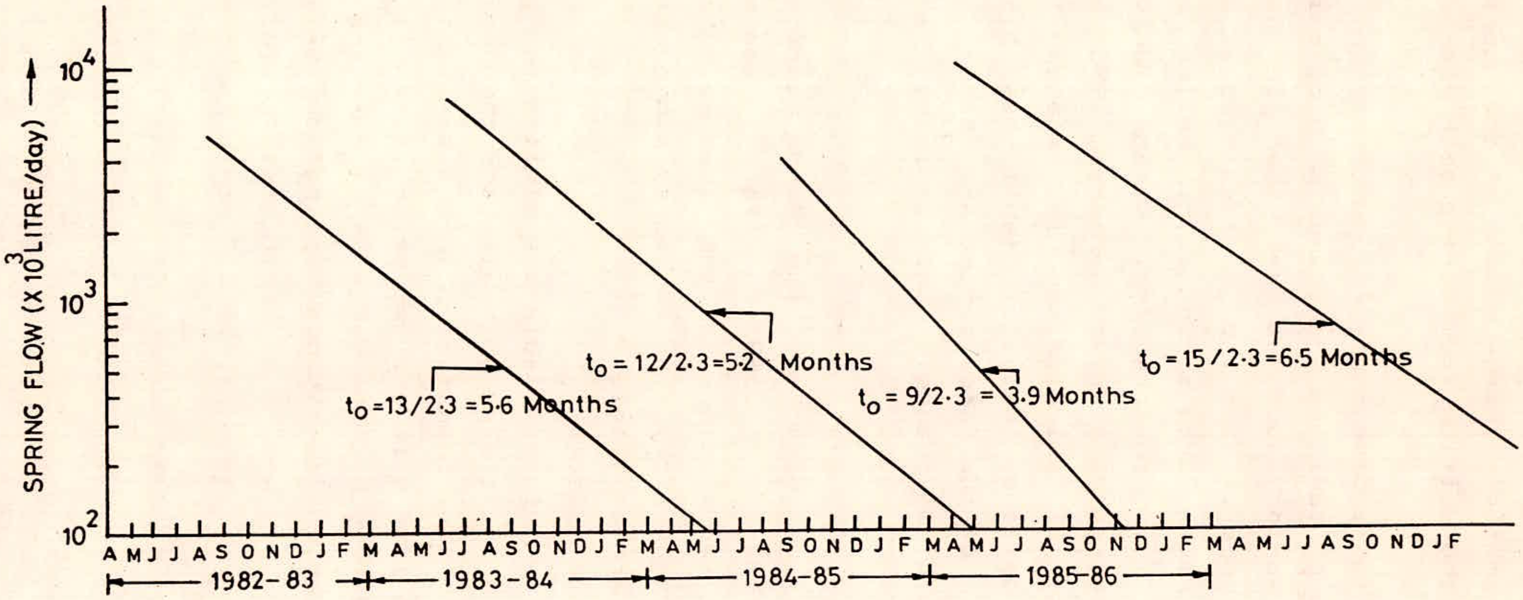

FIG. 4 - DETERMINATION OF DEPLETION TIME FOR PARDA SPRING

Estimation of Recharge to Aquifer

Water balance approach

Aquifer replenishment(AR) between the end of one dry season and the beginning of the next one can be estimated by the following equation with the aid of principle of continuity.

$$AR = Q_2 t_o - Q_1 t_o + \int_{t_1}^{t_2} Q \, dt \qquad \ldots(9)$$

where, AR is the aquifer replenishment in the springflow domain; t_1, t_2 are the instances of time at the end of one dry season and the beginning of the next one, and Q_1, Q_2 are the springflow at time t_1, t_2 respectively.

From the springflow data and with the estimated, t_o, yearwise aquifer replenishment were calculated using equation (9) for the seven years. The calculated recharge to spring aquifer from rainfall is furnished in Table-1.

Springflow hydrograph approach

The aquifer recharge due to rainfall has also been estimated from the area bounded by springflow hydrographs before the onset and after the cessation of rainfall for those years. The recession curve before and after the onset of rainfall have been extended with the aid of the equation $Q = Q_o \exp(-t/t_o)$. The estimated values of aquifer recharge by planimetering the area between two hydrographs is given in Table 1. The estimated aquifer recharge by these two approaches tallies fairly well.

Discrete kernel approach

Estimation of recharge to aquifer can be treated as an inverse problem. The equation (8) can be expanded

$$
\begin{aligned}
&R(1)\,\delta(1) && = q(1) \\
&R(1)\,\delta(2) + R(2)\,\delta(1) && = q(2) \\
&R(1)\,\delta(3) + R(2)\,\delta(2) + R(3)\,\delta(1) && = q(3) \\
&\quad\ldots \qquad \ldots && \quad \ldots \\
&R(1)\,\delta(n) + R(2)\,\delta(n-1) + \ldots + R(n)\,\delta(1) && = q(n) \qquad \ldots(10)
\end{aligned}
$$

$\delta(j)$ and $q(i)$ are known, therefore, R(1), R(2), R(3) ...R(n) etc. could be determined. The sum of such monthly recharges, i.e., R(1), R(2), R(3)..is the total recharge to aquifer for an year. Annual recharges to spring aquifer were estimated by generation of the $\delta(.)$. The estimation is incorporated in Table-1 along with the estimated recharge value from other two approaches. The recharge values obtained by different approaches compare well.

Operation of the model with continuous springflow data

Out of the available monthly springflow data, the data from April, 1982 to March, 1986 (4 years) are available without any break. This continuous data of springflow has been used to compute the monthly recharges of the corresponding months. As the rainfall usually starts in the month of June and from the perusal of springflow hydrograph, July seems to be the first month after the onset of monsoon to receive perceptible recharge in the aquifer in the vicinity of the spring. So, the springflow for June, 1982 has been taken as the end of the recession curve and the inflection point from where the rising curve of the springflow hydrograph starts due to recharge. The recession curve has been extended through June 1982 following the decay curve equation $Q=Q_0 e^{-t/t_0}$ and ordinate of the extended curve is taken to be as that portion of the present springflow due to recharge of earlier years. The values of the ordinate was taken out from the present springflow data to obtain the modified monthly springflow (q_m) data arising out of recharge of present year (Fig. 5). This modified monthly discharge values are used for computing monthly recharge.

The equations(8) can be written in a generalised form

$$[A]\ [B] = [C] \qquad ...(12)$$

where

[A] = Matrix of nxn dimension involving $\delta(.)$

[B] = Matrix of nx1 dimension involving monthly recharges, R

[C] = Matrix of nx1 dimension involving monthly observed springflow after removing the effect of earlier recharge.

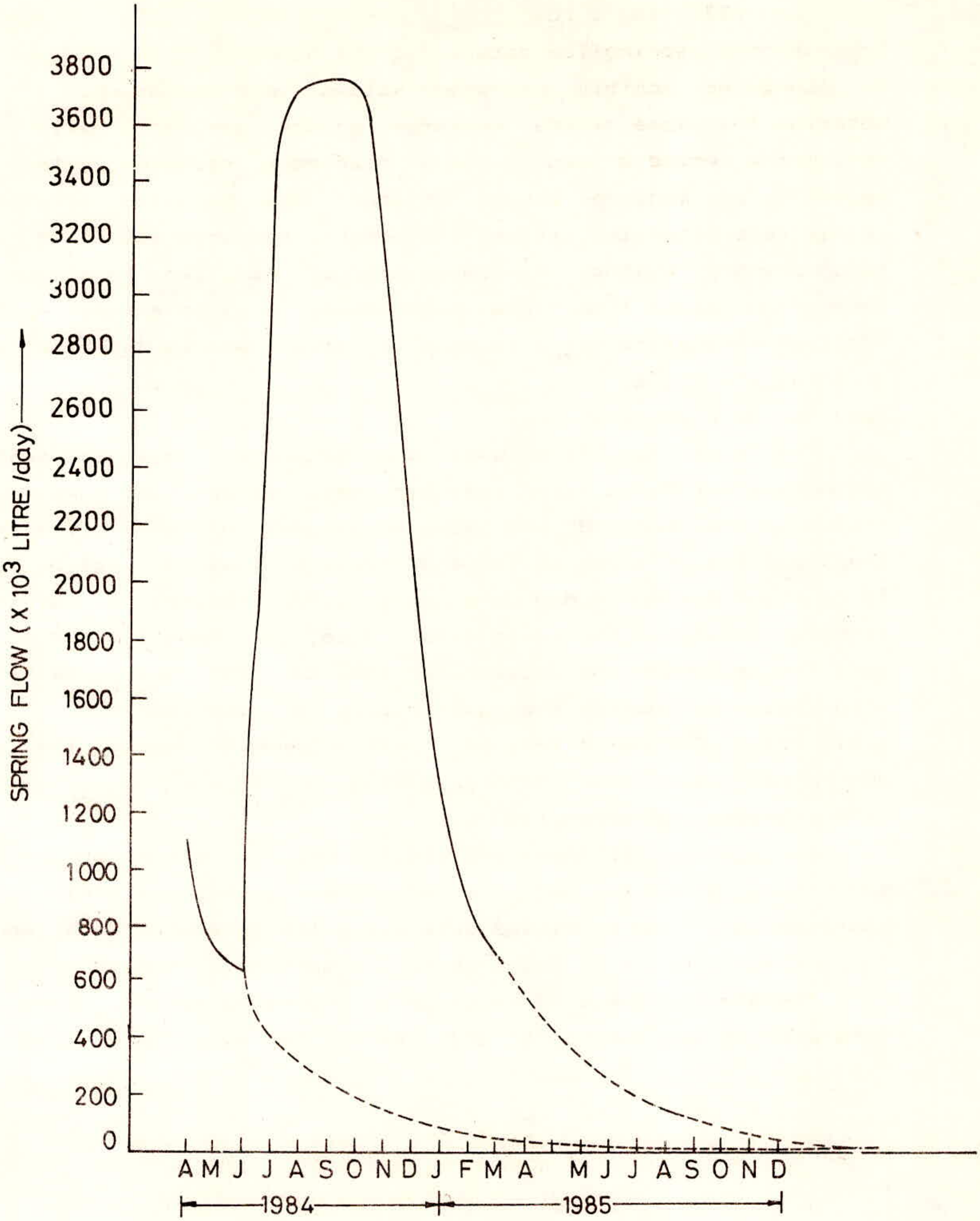

FIG. 5 . SEPARATION OF EFFECT OF EARLIER RECHARGE

Solving for recharge,

$$[B] = [A^{-1}]\ [C] \qquad \ldots(11)$$

Generation of springflow data using the model

Computed monthly recharge values were examined. It was observed that some of the recharge values are abnormally high during the period of negligible or near zero recharge after the cessation of monsoon around October. The modified springflow values were generated setting the monthly recharge values (q_{mg}) as zero for dry months. A comparison of modified (q_m) monthly springflow values from field measurement and generated monthly modified springflow (q_{mg}) is made in Table 2 and is furnished as a plotting in Fig.6.

Results and Discussion

The modified fielo data and generated data of monthly springflow for Parda river matched well except for the early months in the year 1985 and 1986. A perusal of springflow data available and is given in Table-3 reveals that springflow data is constant for April,May and June ,1985 indicating something wrong somewhere in the field data. Also, the monthly springflow data for September and October for 1982 to 1986 are same which also indicates towards the possibility of shortcomings in the field data. Further effect of local snowmelt during the snow period may induce some recharge during non-monsoon period which will increase the springflow .

Considering all these aspects, it will be better to process the field data to get rid of their inconsistencies and shortcomings. The processed data i.e., the generated data should be used for predicting recharge to the springflow domain.

The monthly computed recharge to the Parda spring using the generated springflow data and usinn the model are given in Table 2.

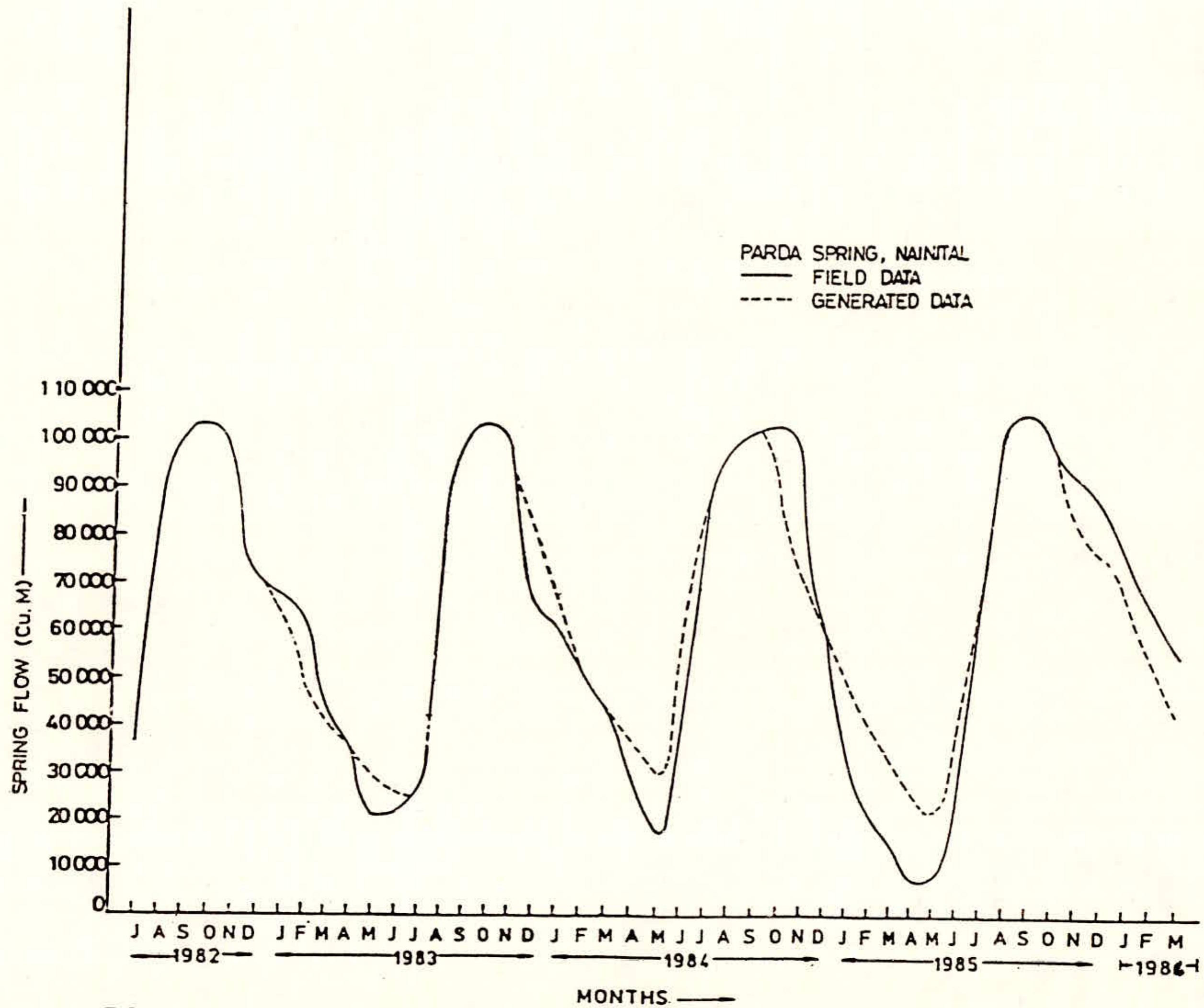

FIG. 6 PLOT OF GENERATED AND FIELD SPRINGFLOW DATA FOR PARDA SPRING

Table 1. Calculated recharge to spring aquifer from rainfall

Year	t_1	t_2	t_0 months	Rain-fall(t_1 to t_2) (mm)	AR ($\times 10^5$ cu m) by water bal-ance	by plan-imete-ring	by δ(.)
1973-74	June'73	oct.'73	5.3	2264.5	6.37	7.68	-
1977-78	July'74	Sep.'74	8.7	1588.9	9.47	9.24	8.63
1980-81	May '80	Sep.'80	6.1	1180.3	9.16	9.00	9.80
1982-83	June'62	Oct.'82	5.6	1507.5	9.24	8.40	9.60
1983-84	June'83	Oct.'83	5.2	N.A.	8.66	7.80	13.30
1984-85	June'84	Oct.'84	3.9	1449.8	8.26	6.84	8.80
1985-86	June'85	Sep.'85	6.5	2370.9	9.72	10.44	8.40

Table 2. Comparison of modified springflow from field (q_m) and generated modified springflow data, Parda spring, Nainital.

Year	Month	Modified springflow in cu.m. from field data	Generated	Computed Recharge ($\times 10^6$ cu.m)
1982	July	36244	36244	0.21
	Aug	89354	89354	0.34
	Sept	101948	101948	0.16
	Oct	103831	103831	0.11
	Nov	88437	88437	0.14
	Dec	71422	73225	0.00
1983	Jan	66695	60622	0.00
	Feb	62444	50188	0.00
	Mar	44259	41550	0.00
	Apr	36757	34400	0.00
	May	20799	30135	0.00

continued

	July	26520	26520	0.15
	Aug	81793	81793	0.35
	Sept	101180	101180	0.19
	Oct.	103195	103195	0.11
	Nov.	94543	94543	0.53
	Dec.	65460	78284	0.00
1984	Jan.	61198	64822	0.00
	Feb.	52194	53674	0.00
	Mar.	44012	44443	0.00
	Apr.	29400	36762	0.00
	May	18049	30408	0.00
	July	86608	86608	0.50
	Aug.	99674	99674	0.16
	Sept.	101948	101948	0.11
	Oct.	103831	84416	0.11
	Nov.	82050	69900	0.00
	Dec.	60490	57878	0.00
1985	Jan.	34532	47925	0.00
	Feb.	21903	39683	0.00
	Mar.	17110	32858	0.00
	Apr.	8870	27210	0.00
	May	9372	22530	0.00
	July	67875	67875	0.40
	Aug.	104813	104813	0.28
	Sept.	106203	106203	0.11
	Oct.	97034	97034	0.05
	Nov.	91355	80347	0.00
	Dec.	85757	75644	0.00
1986	Jan.	74492	62636	0.00
	Feb.	64101	51864	0.00
	Mar.	54699	42945	0.00

Table 3. Monthly average discharge ($\times 10^3$ litre/day) Parda spring, Nainital

Months	Years						
	1973-74	1977-78	1980-81	1982-83	1983-84	1984-85	1985-86
April	1171.2	1199.8	1084.3	1084.3	1322.7	1084.3	393.1
May	874.5	1084.3	688.0	688.0	774.0	688.0	393.1
June	929.6	1084.3	1891.9	642.9	688.0	642.9	393.1
July	2985.3	1084.3	2985.3	1740.9	1453.7	3419.3	2588.0
Aug	2985.3	3419.3	2985.3	3419.3	3198.2	3763.3	3763.3
Sept	2985.3	3763.3	3763.3	3763.3	3763.3	3763.3	3763.3
Oct	2985.3	3419.3	3763.3	3763.3	3763.3	3763.3	3419.3
Nov	2785.1	2985.3	2985.3	3198.2	3419.3	2985.3	3198.2
Dec	2539.4	2785.1	2223.6	2588.0	2403.8	2223.6	2985.3
Jan	1891.9	2403.8	1740.4	2403.8	2223.6	1322.7	2588.0
Feb	1666.7	2223.6	1593.0	2223.6	1891.9	872.7	2223.6
Mar	1453.7	2055.7	1453.7	1593.0	1593.0	688.0	1891.9

(Source:Kumaon Jal Sansthan Vide Project Report on "Geohydrological Investigation of Gaula Catchment,District Nainital ,Kumaon University,1988)

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