STATE OF ART REPORT

INDIAN NATIONAL COMMITTEE ON HYDROLOGY
(Committee Constituted by Ministry of Water Resources, Govt. of India)

Scientific Contribution
No. : INCOH/SAR-1/95

LONG TERM BASEFLOW STUDIES

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INCOH SECRETARIAT
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA
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Published by
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PREAMBLE

It has been estimated that the total world population will increase from 4.5 billion in 1980 to about 6.5 billion by the year 2000, with the most rapid growth in the developing countries. By that time, the countries within the humid tropics and the other warm humid regions will represent almost one-third of the total world population. This proportion will continue to rise in the twenty-first century. The developing and under-developed countries thus quite clearly are the regions facing potentially serious water problems. Hence, it is urgent to question as to whether the fields of hydrology and water resources management have the appropriate methods in place to meet the rising demands that will be made on the water resources. Hence it becomes very important and expeditious to review and update the state-of-art in different facets of hydrology and component processes. This call for compiling and reporting present day technology in assessment of water resources and determining the quality of these water resources.

The flow in the rivers during the lean period i.e. winter and summer season is called lowflow. It is defined on a seasonal basis and is linked with annual solar cycle and its regional or even local climatic effects. Several studies have been carried out on low flows as a part of project feasibility investigations in case of irrigation and power projects but very little has been done on ong term base flow/low flow studies and on studies relating them to drainage characteristics. In this report an attempt has been made to review the state-of-art in the area of long term base flow studies.

The Indian National Committee on Hydrology is the apex body on hydrology constituted by the Government of India with the responsibility of coordinating the various activities concerning hydrology in the country. The committee is also effectively participating in the activities of Unesco and is the National Committee for International Hydrology Programme (IHP) of Unesco. In pursuance of its objective of preparing and periodically updating the state-of-art in hydrology in the world in general and India in particular, the committee invites experts in the country to prepare these reports on important areas of hydrology.

The Indian National Committee on Hydrology with the assistance of its Panel on Ground Water has identified this important topic for preparation of this state-of-art report and the report has been prepared by Mr.T.S.Raju of Central Ground Water Board, Dr.G.C. Mishra of National Institute of Hydrology and Dr.A.G.Chachadi of Goa University. The guidance, assistance and review etc. provided by the Ground Water Panel are worth mentioning. The report has been compiled and finalised by Dr.K.K.S.Bhatia, Member Secretary of the Indian National Committee on Hydrology.

It is hoped that this state-of-art report would serve as a useful reference material to practicing engineers, researchers, field engineers, planners and implementation authorities, who are involved in correct estimation and optimal utilization of the water resources of the country.

(S.M.Seth)
Executive Member, INCOH
& Director, NIH

Roorkee,
April 10, 1995.

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INTRODUCTION

The flow in the rivers during the lean period i.e. winter and summer season is called low flow and when there is no effective rain fall and snow melt and the entire flow originates from the groundwater it is called baseflow. The release of water from the groundwater reservoir into the river channels is controlled by the drainage and the geotechnical properties of the river basins.

Low flow is defined on a seasonal basis and is linked with the annual solar cycle and its regional or even local climatic effects. A simple regime, such as tropical regime, has only one dry season during which there is only one period of low flow. An equitorial regime on the other hand is marked by two rainy seasons and two dry seasons, usually of unequal length. Seasonal irregularities and hence the severity of low flow differ considerably according to a basin's physiography and its climatology.

The connection between quantitative and qualitative aspect of water resources is especially sensitive during low water periods. For various reasons (health, environmental conditions) it is necessary to maintain a minimum discharge in rivers, consequently this water is not available for other water users. The question of quality of the environment often depends on the availability of low river flows, particularly in areas of urban living, or on problems of public health, such as combating endemic diseases, as well as for thermal or chemical pollution.

A knowledge of low flows is based normally on direct observation of the natural flow of a stream. When measured data are lacking, low flow knowledge depends upon methods of calculation which make it possible to estimate with varying degrees of accuracy the basic information needed for projects. It is necessary to know how to use these data and to extract from them the characteristics of the regime which, in any given project, will enable the parameters of the scheme to be determined. It is also important to be able to forecast low flow volumes in the short and long term, since this is an essential factor in the management of some water projects.

The period of low flow, which may occur once or several times a year, is virtually constant for each basin or sub-basin but varies among basins. During these periods, the inflow from the basin to the river system is substantially reduced. During a period when discharge decreases, there is little or no precipitation contributing to flow and no water is contributed from the basin's surface-water storages, rivers are fed entirely by groundwater.

During low flow periods, the groundwater regime is characterized by a gradual depletion of seasonal storage, the capacity of which is impossible to evaluate accurately. Where there is a well defined dry season, the river flow decreases at the same rate as the seasonal groundwater storage decreases and in many situations, the river attains a relatively stable minimum flow governed by the inflow from deep groundwater. Depletion or recession curves can be studied to understand the regimes of water courses and groundwater storages.

Many factors determine the regime and discharge during a low water period. Climatic factors are often more important than basin characteristics. However, the influence of man's activity of the catchment and hence on low flow, is of enormous importance.

According to Vladimirov (1976) natural factors can be grouped into three categories taking into account their primary importance in the genesis of flow. The first category which relates to the generation of flow, determines directly minimum discharge. The major factor is precipitation. This is the principal source of surface flows and groundwater. Groundwater, of course depends upon the surface flows and determines the low flow in the absence of precipitation over a prolonged period.

The second group of factors affects the regime and discharge of low flow through temporal and spatial reduction or distribution of precipitation. These are called indirect factors and include all those that do not directly contribute to the formation of the low flow but affect the variation of its rate. This category includes : evaporation losses (temperature and air humidity deficit, wind, velocity) type of soil and plant cover, relief, number of lakes and swamps, hydrogeological characteristics of the basin. With respect to the last factor, Nassar (1973) points out that the storage capacity of an aquifer mainly determines the fluctuations observed in low flow discharges.

The third category is composed of factors that determine the relationship between river discharges and subsequent impact of the direct and indirect factors described above. This category includes factors that are most frequently used for practical computation purposes and comprises the azonal characteristics of the basin (area, mean altitude, slope, drainage density and channel embedment) and the characteristics of flow (annual runoff, annual groundwater flow to the river, self-regulation of stream flow and other factors).

The influence of man's activity on the regime and discharge of low flows of a river varies, both in nature and intensity, according to the level of man's social, economic and technical development, the type of economic activity involved, the climatic conditions governing the basin and the hydrological regime of the river. Some of the factors due to human activity, influencing the regime and discharge of low flows are, urbanisation, irrigation, hydraulic works, urban water supply, intrabasin transfers, hydroelectric stations, mining, navigation, treatment of urban and industrial effluents, drainage works, land use changes etc.

METHODS OF MEASUREMENT AND ESTIMATION OF BASEFLOW OR LOW FLOW

The water which constitutes stream flow may reach the stream channel by any of several paths from the point where it first reaches the earth as precipitation. Some water flows over the soil surface as surface runoff and reaches the stream soon after its occurrence as rainfall. Other water infiltrates through the soil surface, some of which may move laterally through the upper soil layers until it enters a stream channel. This water, called interflow or sub-surface flow, moves more slowly than the surface runoff and reaches the stream some what later. The proportion of the total runoff which occurs as interflow is dependent on the geology of the basin. Some precipitation percolates downward until it reaches the water table. This groundwater accretion may eventually discharge into the streams, called baseflow. The distinctions which have been drawn between the three components of flow are arbitrary. In practice, it is customary to consider the total flow to be divided into only two parts i.e. direct runoff and baseflow. Direct runoff is presumed to consist of overland flow and a substantial portion of the interflow, whereas baseflow is considered to be largely groundwater.

Baseflow or low flow at a specific stream gauging station can be directly measured using Area-Velocity method. The velocity of flow can be most accurately and conveniently measured using a current meter, (pigmy current meter when the depth of water and velocity of flow are low). When the depth of water in a stream is more, the current meter is suspended by means of cable or wire rope and lowered to required depth. When the depth of water is shallow, the current meter is mounted on a wading rod or a sounding rod. The velocity (V) of flow at a cross section is measured by dividing the section into a number of verticals to be fixed by the method of segmentation and demarcated by stretching a cable and attaching taps on it. Velocity of flow at each vertical is measured by keeping the meter at 0.6 h. below the water surface when the depth of water (h) is shallow and by two point method if the depth of water is deep. While taking velocity measurement, the observer, should not stand in line of the flow and should hold the current meter by standing one side (0.50 m. apart) and downstream of the section line. The discharge (Q) of a channel at any particular site is given by

$$Q = \sum_{i=1}^{n} v_i a_i \qquad \text{....(A)}$$

where a_i = sub area of the cross section
v_i = mean velocity of the sub area

Estimation of Baseflow by Hydrograph Separation

Since, the distinction between the direct runoff and baseflow in the stream at any instant is arbitrary the method of separation is usually arbitrary.

Practically, the method of separation should be such that the time base of direct runoff remains relatively constant from storm to storm. This is usually provided by terminating the direct runoff at a fixed time after the peak of the hydrograph. As a rule of thumb the time in days N may be approximated by

$$N = A^{0.2} \qquad \text{....(B)}$$

where,

A is the drainage area in square miles

The most widely used separation procedure consists of extending the recession existing prior to the storm to a point under the peak of the hydrograph (AB in Fig.1). From this point a straight line is drawn to the hydrograph at a point N days after the peak. The reasoning behind this procedure is that, as the stream rises, there is flow from the stream into the banks. Hence the baseflow should decrease until stage in the stream begins to drop and the bank storage returns to the channel. While there is some support for this reasoning, there is no justification for assuming that the decrease in baseflow conforms to usual recession. Actually, if the increment of bank storage is greater that the inflow from the groundwater over a long stretch of river reach, the baseflow is effectively negative. Hence this procedure is arbitrary and no better than line AC (Fig. 1) which is simply a straight line from the point of rise to the hydrograph N days after the peak. The difference in volume of baseflow by these two methods is quite small and probably unimportant as long as one method is used consistently.

A third method of separation is illustrated by line ADE (Fig.1). This line is constructed by projecting back the recession of the groundwater after the storm to

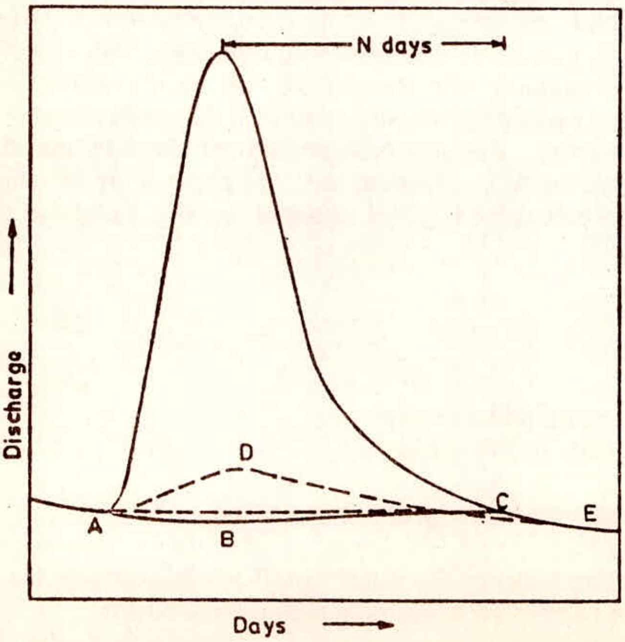


Fig. 1 Some simple Baseflow separation procedures

a point under the inflection point of the falling limb. An arbitrary rising limb is sketched from the point of rise of the hydrograph to connect with the projected baseflow recession. This type of separation may have some advantages where groundwater is relatively large in quantity and reaches the stream fairly rapidly, as in limestone terrain.

If continuous discharge records of the stream over a period of a few years is available, N which represents the point at which surface runoff has effectively ceased can be determined by the following methods :

i) By Master Depletion Curve method

If long term continuous records of Q versus time exist, a baseflow recession curve can be prepared by the sliding segment method or master depletion curve method. For this hydrograph recession parts (segments beyond the end of interflow and upto the beginning of the next surface runoff) are plotted as log Q versus t. Then using a sheet of tracing paper, the hydrograph segment of the lowest discharge on record is traced at the right hand end of the abscissa (time axis). The tracing paper is then moved along the time axis (keeping the axis coincident) until the segment of the next lowest discharge tangentially joins into the one drawn before, etc. The tangential line thus established is then converted back to linear vertical scale and is called Master Depletion Curve for the particular gauging station. (Fig. 2). This curve can now be superimposed on any hydrograph of a particular storm and the point of intersection N represent the point at which surface runoff effectively ceases. Then a straight line is drawn to this point from the point of sudden rise (Fig.3). The runoff below this line is taken as base flow.

ii) By Correlation Method

The baseflow recession curve can also be constructed by the correlation method. Values of Q at constant spacing →Δt (eg. daily values) are used from each of the individual dry weather flow hydrograph segments. Starting with an arbitrary value of Q on the segment, this value of Q is plotted against Q at →Δt later (on log log scales) the later value of Q is again plotted against the Q value, another →Δt later and so on, until all the points of the segment have been plotted. This is repeated with all the other segments (Fig.4). An envelope line is fitted to the points. Points above this line belong to surface runoff or inflow.

iii) By Establishing the Point of Greatest Curvature

The ratio between Q at any time and Q after 't' time interval is computed for a recession curve and the ratio Vs. the time interval is plotted on a graph (Fig.5). The plot depicts two separate slopes, the line with steeper slope deplicting runoff/interflow and the line with flatter slope depicting groundwater depletion. At their intersection, the critical ratio may be determined and the first point beyond the region of intersection, on the groundwater depletion side gives a conservative position of N, the point of separation of run-off and baseflow.

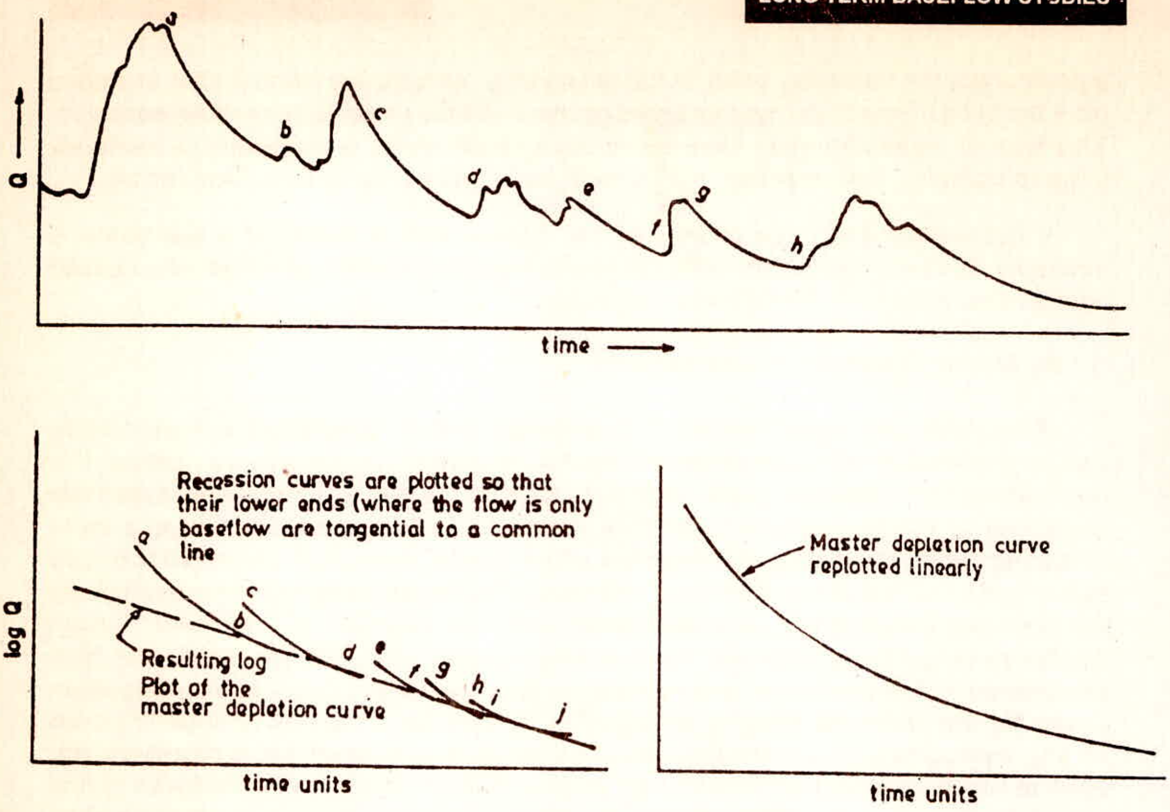


Fig. 2 Derivation of a master depletion curve (a) Normal Hydrograph with recession curves selected (b) Log plot of recession curves (c) Liner plot of master depletion curve.

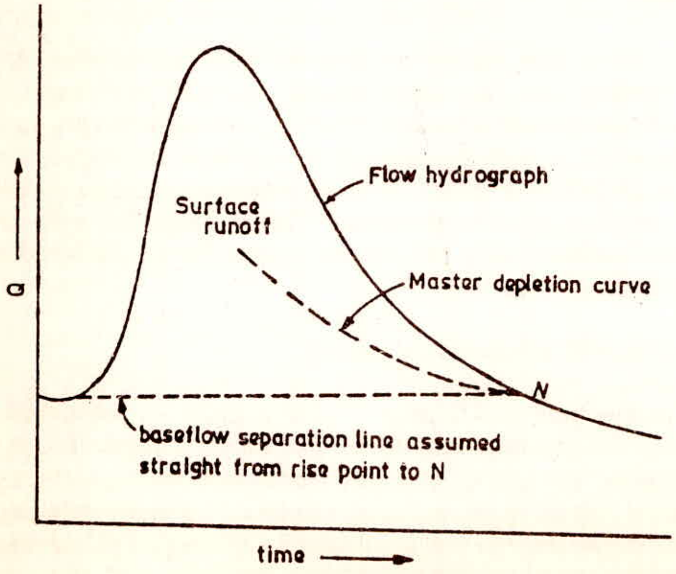


Fig. 3 Procedure to separate Baseflow

iv) Analysis of a Complex Hydrograph

When two storms are so close together (Fig.6) that direct runoff does not end between the storm, the groundwater recession cannot be extended to a time earlier than the peak of the second storm. A depletion curve for direct runoff is therefore required and such a curve can be constructed by using ordinates between the groundwater recession and total hydrograph for several storms. Both the direct run-off and groundwater depletion curves are then replotted to show the change in discharge per unit time as a function of initial discharge (Fig.7). A point on the ground water hydrograph beneath the recession AB (Fig.6) may be located as follows :

1. Determine the change in discharge AB (in unit time) and read a first estimate of direct runoff corresponding to this rate of change from Fig. 6.
2. Subtract the estimated direct runoff Aa from the total ordinate Ad. The balance a'd is first approximation to the groundwater ordinate.
3. Determine the change in discharge corresponding to ground water flow a'd from Fig.7 and substract this from the total change AB. The remainder is essentially the change in discharge for direct runoff Aa. The ordinate ad represents groundwater flow.

Following the procedure outlined above, a segment of the groundwater underneath the recession of the first storm may be determined. The balance of the groundwater hydrograph must be sketched arbitrarily. The direct runoff recession of the first flood event can be extended under the second rise by the use of the direct runoff depletion curve.

An obvious application of the baseflow recession curve is also for prediction of flows. If the flow today is known, the flow for example, 10 days later can be read off the curve, provided no rainfall falls in this period. The curve can also be used for filling in missing records using rainfall records for cross check, integration of the baseflow rate, yields of relationship between the flow rate and volume of water in storage.

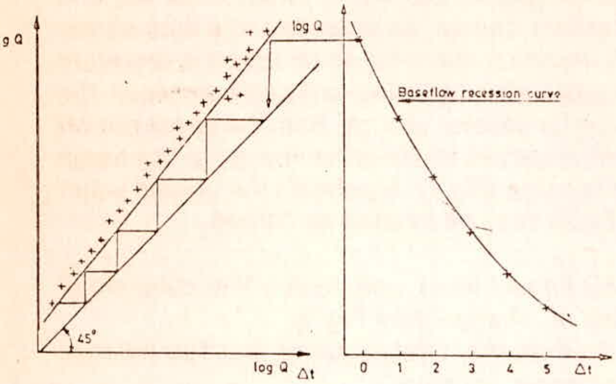


Fig. 4 Construction of the Baseflow recession curve by the correlation method

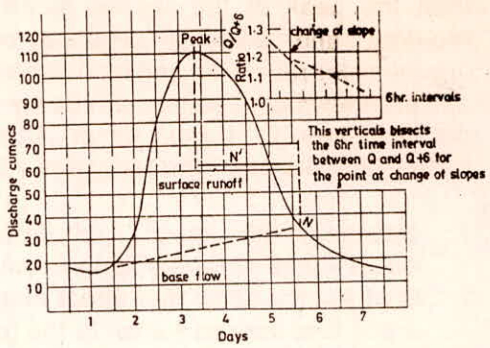
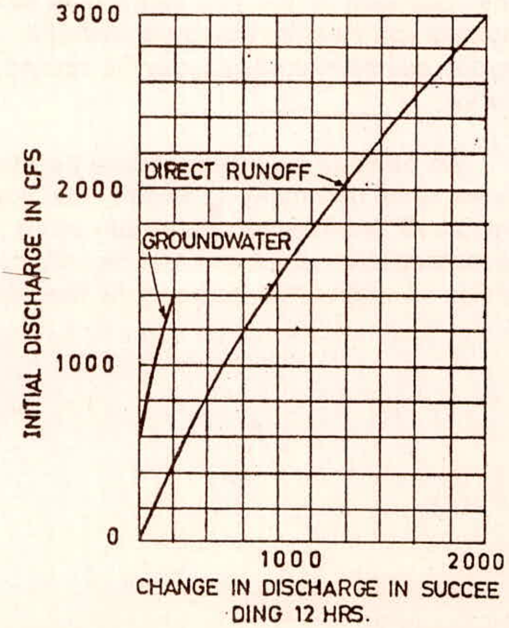


Fig. 5 Alternative method of separating Baseflow



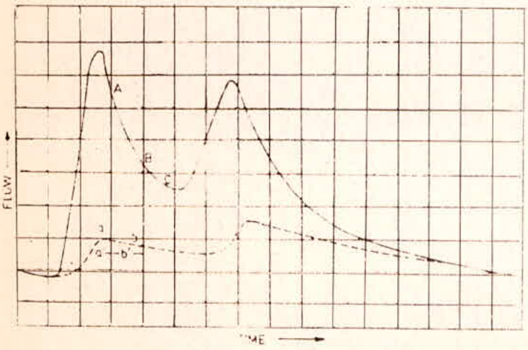


Fig. 6 Analyasis of a complex hydrograph

Fig. 7 Rate of change in flow curves for valley river at Tomatia, North Carolina

REVIEW OF LITERATURE ON THE PARAMETERS AFFECTING BASEFLOW

Many authors have discussed particular aspects of baseflow but few have undertaken comprehensive reviews of the broader features. Horton (1933b) in a classic paper not only discussed his own contributions but also reviewed earlier work on baseflow in the United States and Europe. In an investigation of rainfall and runoff, Hoyt et al. (1936) described methods for determining baseflow and included an extensive list of references of baseflow for the period 1893 through 1934. An annotated bibliography on parametric hydrology covers the period 1921 through 1967 (Dickinson et al., 1967). The report containing the bibliography also has a brief review of hydrograph separation methods.

Fairly complete discussions of baseflow equations, mathematical derivations, and applications are given in recent French works by Schoeller (1962), Roch (1963), and Castany (1967). A compilation of a number of equations used in baseflow studies and a discussion of methods of hydrograph analysis and application have been presented by Toebes and Strang (1964). In a study of stream connected aquifer system, Spiegel (!962) reviews some of the early work on baseflow and gives an extensive mathematical treatment with emphasis on leaky aquifer theory.

Modern interest in baseflow recession can be traced back at least to the 1840's and the law of Dausse' (Dausse, 1842), which states, as interpreted by Horton (1933a), that "there is no accretion to the water table as long as water losses exceed the rainfall". The nature of the hydrologic cycle was becoming well understood, and much of the basic mathematics and some methods of hydrograph analysis were known by the early 1900's when Maillet (1902, 1905) began publishing the results of studies on the Vanne, a major supply of water for Paris. He obtained recession curves for various sources and fitted equations to them.

Problems similar to those in France were beginning to arise at about the same time in the eastern United States. Vermeule (1894) and Horton (1903) began Investigations of runoff and low flow in New Jersey and New York, respectively. Vermeule took essentially a hydrologic budget approach to developing his 'Diagram Showing Groundwater Flow of Various Streams for a Given Depletion', which is a form of what would now be called a storage-discharge curve. Horton analysed hydrographs and obtained recession curves for a number of streams. He also began to consider the mathematical aspects of baseflow, but did not begian to publish this phase of his work until 1914. In contrast to the French, very little mathematical application of development, with the exception of Horton's work, came from America during this early period. The reason may well be that the Americans were dealing with streams fed by shallow, unconsolidated aquifers that responded to summer rains. On the other hand, the French had smooth long term recession curves from streams fed by extensive aquifers that were relatively unaffected by summer rains.

Early work in Great Britain does not appear to have lagged very far behind that in France and the United States, and it appears to have been in response to similar problems. Beardmore (1862) realized that summer low flows were supplied by groundwater, and Hall (1918) presented a paper on components of the hydrograph and methods of hydrograph separation. For much the same reasons comparable efforts were also underway elsewhere in Europe and Japan (Horton, 1933b, Forchheimer, 1930, Twasaki, 1934, Roessel, 1950).

The basic differential equation governing flow in an aquifer was presented by Boussinesq (1877). The equation is nonlinear and difficult to solve exactly. Boussinesq lineraized the equation by making simplifying assumptions, and the result was a form of the heat flow or diffusion equation that can be solved more readily. His linear solution is used widely in baseflow work either as equation 1 or in the alternative forms (1a) or (1b) as given below :

$$Q = Q_0 \ \exp(-\alpha t) \qquad .....(1)$$
$$Q = Q_0 \ K_r t \qquad .....(1a)$$
$$Q = Q_0 \ (10)^{-\beta t} \qquad .....(1b)$$

In a series of papers published during 1903 and 1904, of which only the most comprehensive is cited herein, Boussinesq (1904) further developed his linear solution and introduced one nonlinear solution for the case where a stream is located on a horizontal, impermeable lower boundary with an initial curvilinear water table and zero water level elevation in the stream.

$$Q = Q_0 /(1+\sigma t)^2 \qquad .....(2)$$

This equation has been used for many studies in Europe, especially for spring discharge, but rarely in the United States.

The first applications of equations 1 and 2 appear to be by Maillet. He published a series of papers in 1902 and 1903, of which only one is cited herein, and a book in 1905. In the book, Maillet (1905) demonstrated the applicability of equations 1 and 2 and gave a number of other cases for different boundary conditions based on his own and Boussinesq's work. He discussed steady-state flow problems of stability of flow, influence of basin size and geometry, and the effects of antecedent precipitation. Also, he made an early application of the correlation method of finding recession curves.

One difficulty with many recession curves obtained from hydrograph is that although they are nonlinear they do not fit equation 2. Maillet (1905, and ~~In~~ Boussinesq, 1904) coped with this problem by assuming two components or sources of baseflow one constant and one declining either as

$$Q = (Q_0 - B')/(1 + \sigma t)^2 + B' \qquad .....(3)$$

or

$$Q = (Q_0 - B')\exp(-\alpha t) + B' \qquad .....(4)$$

but Boussinesq (1904) showed that a recession fitted by equation 3 could be given equally well by

$$Q = Q_1 \exp(-\alpha_1 t) + Q_2 \exp(-\alpha t) \qquad .....(5)$$

Equations 3,4 and 5 show that a nonlinear recession curve can be decomposed into or obtained from combinations of linear or linear and nonlinear curves. Furthermore, the same nonlinear curve may be obtained from various combinations. Equations 4 and 5 are of course examples of the principle of superposition of linear solutions, which is particularly useful because of the relative ease of manipulation of exponentials. For example, Barnes (1939, 1944) has separated hydrographs into the three linear components of baseflow, interflow, and direct runoff. Dooge (1960) and Kraijenhoff van de Leur (1958) have shown the advantages of using linear solutions of approximate nonlinear systems.

Storage volume can be obtained by integration of equations 1 through 5 between specific time limits. The results led Maillet (1905) to suggest that storage volume was a function of discharge. Horton (1935, 1936b, 1937) and Langbein (1938) have shown that a general relationship for channel storage is

$$Q = K'V^{n'} \qquad .....(6)$$

Coutagne (1948) and Denisov (1961) assumed that such a relation should hold for baseflow and combined equation 6 with a simple inflow outflow equation for periods of no recharge.

$$dV/dt + Q = 0 \qquad .....(7)$$

For $n'=1$, the result is equation 1, and for $n'\neq1$, the result is a general nonlinear equation

$$Q = Q_0 \, (1 + \mu t)^{n'/(1-n')}, \; n'\neq 1 \qquad .....(8)$$

Schoellar (1962), Coutagne (1948) and Denisov (1961) gave solutions for a number of values of n. One feature worth noting is that equations derived by Cooper and Rorabaugh (1963) and Rorabaugh (1964) for bank storage in an aquifer with infinite distance to the valley wall can be reduced to equation 8 for $n' = -1$ when other time terms drop out.

Equation 8 may be put in a form used for drainage of soil moisture (Richards et al., 1956), and more recently for unsaturated drainage in groundwater recharge and baseflow (Nixon and Lawless, 1960, Hewlett and Hibbert, 1963)

$$Q = aT^b \qquad .....(8a)$$

Another nonlinear relationship was proposed by Horton (1933b, 1935), who believed that any one phreatic basin would have a linear response (in fact, he considered this to be a law), but that two or more contributing sub-basins would give a nonlinear curve. Horton suggested that two exponential curves could be added together as in equation 5, or that an equation of the form

$$Q = Q_0 \ \exp(-\alpha f^{m'}) \qquad .....(9)$$

could be used. Equation 9 is sometimes referred to as the Horton double exponential. Some writers have referred to equation 9 as empirical, but it can be derived from equation 1 by a simple time transformation (Hall, 1968).

More elegant or more complete solutions of the Boussinesq differential equation have been derived in recent years, mainly by workers interested in drainage and bank storage. One advantage of the recent efforts, although they are to some extent repetitive of earlier efforts, has been the attention devoted to assessing the effects of simplifying assumptions (Brutsaert and Ibrahim, 1966, Butler, 1967, Cooper and Rorabaugh, 1963, Guyon, 1966, Maasland and Bittinger, 1963, Rorabaugh, 1964, Singh, 1968, Van Schilfgaarde, 1963, Van Schilfgaarde et al., 1956, Werner, 1957, Werner and Sundquist, 1951).

Efforts to obtain and apply baseflow recessions are complicated by problems arising from the assumptions used in the mathematical development and from difficulties in interpreting the stream hydrograph. The equations are derived for flow from a single source or storage component, generally of unit width, under onditions of no recharge. Furthermore, the storage component is filled and allowed to drain without interruption or change. The real stream hydrograph, on the other hand,is an integrated curve of prior hydrologic events,as stated by Kraijenhoff van de Leur (1958).

Problems arise with all of the assumptions, but perhaps the most troublesome assumptions are that discharge comes only from one source and that there is no recharge during recession. Horton (1914) recognized that sources other than groundwater including lakes, marshes, snow and ice, and stream channel and bank storage could supply baseflow. In a detailed study of small basins Hursh and Brater (1941) pointed out that the various possible sources could have regular characteristic responses and should thus contributed to the hydrograph in a determinable manner. If the responses were not regular, then hydrograph separation would be much more difficult. Brater (1940) also suggested that a quick stream rise could cause water to flow back into the aquifer, thereby creating a period of negative groundwater flow. Work by Todd (1954, 1955), Rorabaugh (1964), and Cooper and Rorabaugh (1963) not only has confirmed Brater's concept but has shown that considerable time may be required for the resulting bank storage to drain. In fact, a large part of baseflow may be supplied by bank storage (Kunkle, 1962, 1968, Meyboom, 1961).

Precipitation on stream channels, as well as direct runoff and interflow, affects channel storage (Hursh and Brater, 1941). However, during periods of minor recharge, channel storage should be a function mainly of seepage inflow along the channel. Meinzer et al., (1936) utilize this as a method of determining influent seepage between gauging stations.

Losses of stream flow by evapotranspiration, by underflow beneath the gauging station, by vertical leakage through semipermeable layers, or by groundwater moving through aquifers that discharge outside the basins, present difficulties in interpretation. The same is true of course for groundwater inflow from another basin. Underflow and groundwater movement generally have been coped with by field investigations. Singh (1968) has discussed the effect on hydrographs where water leaks upward through a semipermeable layer. Evapotranspiration losses have been considered in more details, most workers being concerned with the effect of evapotranspiration on the stream hydrograph (Miller, 1965, Singh, 1968, Troxell, 1936, Croft, 1948). Riggs (1953) and Whelan (1950) have demonstrated the value of obtaining recession curves for various times of the year as a method of assessing evapotranspiration losses. Langbein (1942) has used baseflow recession to compute evapotranspiration losses. Another approach has been the use of seasonal fluctuations of the hydrograph to calculate daily withdrawals by evapotranspiration (Reigner, 1966, Tschinkel, 1963).

The matter of whether an aquifer or other sources of baseflow has a linear or nonlinear response must also be resolved. Riggs (1964) has shown, however, that combinations of two linear sources such as a large artesian aquifer with long response time and a water table aquifer with short response will yield nonlinear recession curves. On the other hand, it can also be shown (Hall, 1968) that one nonlinear recession curve may be fitted by at least four nonlinear equations such as (3), (5), (8) and (9). Furthermore, nonlinearity may be caused by factors not accounted for in the mathematics. Riggs (1964) and Ineson and Downing (1964) have studied the relationships between baseflow and groundwater. They conclude that nonlinearity can be a function of factors such as carry-over storage from a prior period of recharge, multiple sources, variations in areal pattern of recharge, channel, bank and flood plain storage, and evapotranspiration. These same authors also discuss the difficulties of determining wnether what is observed on the hydrograph is baseflow, to say nothing of determining whether it is exclusively from groundwater.

Another problem, particularly in humid or subhumid areas, is that recharge may occur frequently. The major consequences depending on hydrologic and geologic conditions are that baseflow may be fed by pluses of recharge or by drainage of soil moisture. Roessel (1950) has shown that pulses of recharge induce a nonlinear response from an aquifer. Work by Hewlett (1961) and Hewlett and Hibbert (1963, 1967) indicates that in mountain watersheds in humid areas baseflow is supplied in part by soil moisture, which appears to drain in a nonlinear fashion according to equation 81. Therefore, the stream hydrograph would probably be nonlinear too. Their work seems to cast doubts on the traditional separation of baseflow and interflow.

Hewlett (1961) also suggests that the area supplying baseflow is not constant but is expanding or shrinking in response to the interactions between recharge, soil moisture, and precipitation. Therefore, baseflow as commonly defined may occur, strictly speaking, only in arid or semi arid areas, or where aquifers are relatively unaffected by precipitation during the growing season.

Hydrologists have long been aware that if baseflow is supplied by groundwater, then a relationship should exist between stream discharge and groundwater levels (Pochet, 1905). Ideally, analysis of baseflow recessions could yield a groundwater depletion curve for the drainage basin. Thomson (1921) made an early application of equation 4 to the recession of groundwater levels in an area where nearly all flow was in the subsurface. Harrold (1934) observed a good relationship between recession in a stream and water levels in a nearby well. The possible effect of maximum water level, before recession begins on the stream hydrograph was considered by Horton (1936a). Hursh and Brater (1941) attempted to relate baseflow to water level fluctuations in a small basin, and Merriam (1956) developed a relationship for a very large basin. Clark (1956) obtained a good relationship for dry weather flows, and he concluded that groundwater discharge was nearly costant and that variations in stream flow were due to charges in stream level and evapotranspiration close to the stream. Detailed treatments of the fluctuations of groundwater levels have been given by Jacob (1943) and Tison (1965).

Another application of baseflow recession has been the attempt to determine the relations between hydrologic and geologic parameters in a drainage basin. Such studies may also involve low flow forecasting, but usually the emphasis is on hydrologic or geomorphic interpretations. A consideration of the recession constants for the various baseflow equations shows that they are a function of transmissivity, specific yield or coefficient of storage, and a characteristic length (normally the distance from stream bank to valley wall). Langbein (1960) has indicated that the recession constant is a function of drainage density, and Carlston (1963, 1966) has attempted to correlate minimum flows with drainage density. Most attempts to relate these factors in real basins seem to have been unsatisfactory or inconclusive.

Studies of problems arising from multiple sources, localized and regional aquifer systems, connected between stream and aquifer or unusual climatic conditions have been made by Curtis (1966), Dingman (1966), Kilpatrick (1964), McGuinness et al. (1961), and Renard et al. (1964). Efforts to study the hydrogeology of drainage basins by use of recession fitted to equation 1 have been made by Farvolden (1963) and Knisel (1963).

Some workers have preferred to use flow duration and frequency analysis rather than recessions. Cross (1949) showed that a flow in cubic feet per second per square mile that is exceeded 90% of the time was a reasonable criterion for dry weather flow in Ohio. As the result of his observations, Cross also put the whole problem of hydrogeologic interpretations into perspective when he stated : 'It is concluded that stream flow records provide useful inferences to groundwater geology, but the converse is not true'. Applications similar to Cross and in some cases including frequency analysis for various geologic conditions have been made by Schneider (1957, 1965), LaSala (1967), Thomas (1966), and Hely and Olmsted (1963).

Studies by Lenz and Sawyer (1944), Durum (1953), Langbein and Dawdy (1964), and Gunnerson (1967) have indicated that good correlations may be obtained between stream discharge and chemical content of water. None of these authors was concerned directly with baseflow but their results suggest that chemical content could be used to find the amount of groundwater in base flow or to determine if base flow is from groundwater. Kunkle (1965, 1968) has used conductivity to estimate groundwater contribution to base flow, and Toler (1965a, 1965b) has used conductivity to determine quantity of baseflow from two different sources, as well as to determine total groundwater contribution.

The study of stream aquifer interaction with various boundary and initial conditions has done by many investigators. Singh (1969), Pinder and Saun (1971) have analysed the flow from an unconfined aquifer to drainage ditches corresponding to certain sequence of infiltration inputs constant within time. Skaggs (1975) has investigated the flow in an unconfined aquifer between two drains for time invariant evapotranspiration. The response of an unconfined aquifer bounded by two rivers, to time variant : - recharge and change in river stage has been found by Chandra et al (1979), using the solution of Boussinesq's equation for one dimensional seepage corresponding to uniform time invariant recharge and a step rise in river stage by making use of Duhamal's approach. The recharge rate and one of the two river stages are assumed to be exponentially decaying function of time. The variation of base flow with time resulting from recharge and river stage fluctuation are presented separately for different lengths of the aquifer and for different coefficients of transmissivity. The base flow due to simultaneous change in rive stage and unsteady recharge can be found out from these results by algebraic addition.

The free-aquifer base flow curves have been derived by Singh (1969) using the Boussinesq equation. The following assumptions have been made during the analysis:

i) The aquifer is homogeneous and isotropic, it overlies a horizontal impervious layer.
ii) Inclination of the water table is low.
iii) The hydraulic gradient equals the slope of the water table and is invariant with depth at any given section.
iv) There is no recharge to or depletion from the water table because of infiltration, evapotranspiration, and leakage, etc.

Dimensionless baseflow curves for fully penetrating as well as partially penetrating streams have been obtained using a finite difference solution for initial elliptical as well as parabolic water table profile curves. It has been found that baseflow curves for an initial elliptic water table profile yield a little higher discharge than the initial parabolic profile curves. However, they became practically parallel for the dimensionless time greater than 0.3. Thus, the baseflow recession rates are only slightly affected by the assumption of different initial water profiles.

In the analysis the idealized baseflow curves are modified by variation in evapotranspiration, leakage downward into the underlying artesian aquifers or leakage upward from them into the overlying free aquifer, and recharge from infiltration and deep percolation of rain water etc. With increase in dimensionless height of the water table or reduction in stream entrenchment, the baseflow recession steepens, and the magnitude of baseflow decreases.

Boundary conditions at the outlet end, such as height of the stream bed above the impervious layer, variation in stream stage for essentially a baseflow regime, and the relative magnitude of this variation as compared with the height of the stream bed are found to have an pronounced effect on the baseflow curves, which may vary from a straight line to pronounced curvature when plotted on a semi logarithmic paper. The effect of downward leakage into the underlying aquifer and evapotranspiration can render the stream influent and thus dry it up in extended rainless periods.

Flow and head variations in stationary linear stream-aquifer systems have been obtained through application of the convolution equation (Hall, 1972). Four highly idealized cases involving finite and semi-finite aquifers with and without semipervious stream banks, are considered. Equations for the instantaneous unit impulse response function, the unit step response function, and the derivation of the unit step response function have been presented for each case. Head fluctuations in the aquifer due to an arbitrary varying flood pulse have been obtained for the cases involving a finite aquifer with and without a semipervious stream bank. Flow in and out of the aquifer at the stream bank has been determined. Head variations, and to a lesser extend flow variations, are apparently relatively insensitive to variations in aquifer diffusivity. This insensitivity suggests that perhaps less emphasis be placed on evaluation of transmissivity from a determination of diffusivity (unless coefficient of storage is known, Hall, 1972) and more attention be given to groundwater contribution to stream flow.

A study of recession curves of the stream gauging stations of the Upper Betwa river basin (Raju et al. 1981) and the values of the recession constant c indicated that the changes in the recession constant reflects the hydrogeological situation in the basin.

The intraction among a stream and two aquifers which are separated by an aquitard has been studied for varying river stages (Mishra, 1987). A mathematical model has been developed to study recharge from a river to a multiaquifer system for varying river stages. The analytical solution is tractable for numerical calculation. The solution has been obtained by discretising the time parameter and using unit response function coefficients. It is found that the storage coefficient of the lower aquifer controls the recharge from the upper aquifer, besides the aquitard resistance. If two identical layers are separated by an aquitard with resistance of 100 day, 45% of the river recharge enters to the lower aquifer. A decrease in river width from 200 m to 80 m does not change the recharge rate appreciably. A window in the aquitard located under the river with width equal to that of the river can cause 43% of the recharge that would take place through a window of very large width.

COMPUTATIONAL PROCEDURES RELATING TO LOW FLOW ANALYSIS

The three main characteristic that are important in the analysis of low flow data are

1. The magnitude of low flow
2. The duration of low flow and
3. The frequency of occurrence of low flow.

The magnitude of low flow is the quantity of water flowing through a given section of a stream for a specified period of time and it determines the amount of water available for use. The duration depends on natural conditions as well as man-made effects and may reflect some specified water use practices (eg. Irrigation cycles). The frequency of occurrence of low flow reflects the risk of failure of a water supply scheme.

For low flow studies, therefore, data are normally specified in terms of the magnitude of flow for a given period of time (the duration) within a year or a season. The given period of time is usually taken as 1 day, 7 day, 10 day, or 30 days. One day flows are used as data in flow duration analysis, while periods upto one year and longer are required for some storage-yield studies.

In low flow analysis, with data of adequate length (say 30 years or more) flow estimates are sufficiently reliable. If less than 30 years data are available, the results will have larger probable errors.

In assessing the low flow characteristics of a basin, it is often desirable to know the general flow characteristics of the stream in question. To do this several parameters need to be defined. Some or all of them are required in specifying the theoretical distribution appropriate to flow events under consideration. The most common parameters are measures of central tendency, variability, skewness and persistence.

A flow duration curve is a cumulative frequency curve that shows the percentage of time during which specified discharge were equaled or exceeded during the period of a record. It represents a non-sequential series of stream flow characteristics of a stream throughout the range of discharge without regard to the sequence of occurrence. Flow duration values of 90, 95 and 99% are used as measures of a stream's low flow potential. The 90% value is used as a measure of groundwater contribution to stream flow (Cross, 1949). This same value has been used as a measure of run-of-the-river hydropower potential (Searcy, 1959). Other potential uses of the low flow portion of a duration curve include analysis relating to irrigation and urban water supplies.

The low flow portion of the curve is an index of the amount of groundwater being contributed to stream flow from natural catchment storage. If the slope of the curve in the low flow portion is flat, groundwater contributions are significant. On the other hand a steep curve indicates poor baseflow and probable cease-to-flow conditions. Thus a duration curve is a valuable tool for comparing drainage basin characteristics, particularly the effect of geology on low flows.

Low flow frequency curves use data sequences that are independent and homogeneous and therefore they can be used to determine the possibility of occurrence of a flow event of specified magnitude. In practice, two types of low frequency curves are used. In one type the annual series is based on the minimum flow event in each year of record and is used for events of less than 12 months duration. The second type-the partial series-is used where frequencies of events longer than 12 month's duration are required.

For constructing annual low flow frequency curves, for given durations of lengths n-days, minimum consecutive n-day flows for each year of the record are ranked with the lowest flow being ranked. 1. Generally n equals 1, 7, 10, 15, 30, 60, 120, 183 and 284 days. Plotting positions are assigned to each flow value in terms of recurrence interval of probability, and observed flows for the given duration are plotted on probability paper. For estimation of low flows of high recurrence interval, a number of theoretical distributions have been used to estimate the flow magnitude (normal, log-normal Gamma, pearson Type III, Log pearson Type III, Kritsky-Menkel, extreme value Type I-Gumble, extreme value Type III-weibull distributions). A goodness of fit test indicated the agreement between an observed sample of low flows and an assumed theoretical distribution.

Using annual minimum daily and 7-day low flows for 34 streams, Matalas (1963) concluded that the extreme value Type III and pearson Type III distributions fitted the data equally well and recommended the use of maximum likelihood estimates of parameters rather than moment estimates. Based on analysis of 37 streams, Joseph (1970) concluded that the Gamma distribution was the best of the five distributions tested.

An important use of low flow frequency curves is in reservoir capacity-yield analysis. However, this approach gives biased results in that the flows into the storage are over estimated, consequently, storage need is underestimated. Another major use of low frequency curves relates to the estimation of recurrence interval (or probability of occurrence of low flow conditions).

Recession Analysis

The diminishing discharge in the recession limb of a hydrograph reflects the depletion of stored water, both surface and sub-surface. The most widely used approach is the simple exponential form i.e.

$$q_t = q_0 k^t$$

where q_t = the discharge at time after some initial time t=0

q_0 = the discharge at time t=0 (both q_t and q_0 are in the same units) and;

k = a recession constant, dependent in value on the units of t.

A common method used to determine the recession constant, K, consists of plotting daily discharge data in m /s on semi-Log paper and fitting upto three straight lines to the recession limb. The period should be such that replenishment of stored water by precipitation during the period for which the data are recorded is negligible. The line with least slope is assumed to represent base flow, that with medium slope to represent mainly inter flow and that with steepest slope to represent surface runoff plus a small component of inter flow.

Recession analysis (Recession constants), is a basic tool used in the separation of baseflow from flood hydrographs. It is used in low flow forecasting during prolonged dry periods and is also used as an index of base flow. The recession constant is particularly important in investigations relating to hydrogeology and geomorphology.

Determination of Low Flow Characteristics Using Inadequate Stream Flow Data

The methods of computation of low flow characteristics using inadequate stream flow data and the accuracy of the results depend on the hydrological knowledge of the region and on the variability of the natural factors affecting the regime and the low flows. A detailed analysis of the influence of natural factors on the low flows and on design values is possible only when sufficient data are available.

i) Method of analogy

The method of hydrological analogy is used when it is necessary to extend a short length of record or to estimate missing years of observation at a particular gauging station. To apply the method of analogy simultaneous observations during 3-5 years (or seasons) of low flows at both the station under review and the long term of analogue station are made. In selecting an analogue basin, the following conditions should be taken into account.

1. The basin analogue should have a long period of low flow observations.
2. It should be climatically similar to the study basin.
3. There must be simultaneous data at both stations.
4. The basin analogue should have similar relief, soils, lithology, hydrogeology (i.e. a similar number, capacity and discharge of aquifers contributing to river recharge) and similar forest, lake and swamp areas as the study basin.
5. Both the basins should belong to the same category of rivers (small, medium, large) and areas should differ by no more than five times. The mean basin elevations in mountain rivers should not differ by more than 300 m.
6. The basin analogue should not have specific features that might affect the value of low stream flow (for example, reservoirs, off-takes to channels, industrial waste discharges or effluents from mines and quarries).

High correlations between low flow at the station under review and the analogue stations are observed when both stations are located on the same stream and there is no significant distortion of low flow along the reach between the stations.

The computation of long-term statistical parameters of low flow can be carried out graphically, analytically graphically or using hydrometric survey data.

ii) Equations for low flow computation

Low flow discharge in small rivers with similar regional characteristics are related to the volume of groundwater drained by the river and to the important of local effects. Medium rivers usually have abundant and stable groundwater flow. In contrast, the effect of local conditions (for example, swamps, lakes, karst) is more evident for small rivers. Therefore, for small and medium rivers, methods of low flow computation vary. For large rivers, multi-zonal effects predominate. To determine the limits of these basins, the effects of geographical zones on minimum specific discharge are used (Rivers with drainage area of less than 1500 km are small, with 1500-60000 km are medium and with more than 60000 km are large). All rivers with basins smaller than a critical area are designated as small rivers (The critical area is defined by the area of a basin for which an increase in size does not produce a change in the specific low flow discharge. Investigations of low flows in the U.S.S.R. show that the critical basin area in west regions with water surpluses ranges generally from 1000 to 1500 km . For regions with water deficits where permanent aquifers are very deep, the critical area is between 2000 to 2500 km. For arid and permafrost regions, the critical area increases.

In establishing the relationships between low flow characteristics and natural factors, it is important to use those factors that best reflect the specific peculiarities of low flow formation in the region under view. It has been found that in plain and hilly regions, catchment area, is the main factor. In mountain regions, mean elevation is also important. However, in some regions other factors should be included for ex. precipitation depth, karst development and lake, swamp or forest areas.

Various low flow characteristics are used in design curves and equations. Example are mean minimum discharge, low flow discharge at some probability of excedance and dry season low flow.

For low flow calculations, the relationship between minimum discharge or specific discharge to basin area is used frequently. Basin area may be the independent variable or it may be used together with precipitation or annual flow. Some examples area -

$$Q = b A^n \qquad \text{....(10)}$$

$$Q = b(A \pm a)^n \qquad \text{....(11)}$$

$$Q = b A^n P^m \qquad \text{....(12)}$$

$$Q = b A^n Q^m_0 \qquad \text{....(13)}$$

Where Q = mean minimum flow discharge or low flow discharge at some probability of excedance in m^3 /s (or a specific discharge in m^3 /sq km) for a 30-day period (or 7, 10, 15 days) during dry seasons.
A = basin area (km^2)
P = mean annual precipitation (mm)
Q_0 = mean annual discharge (m^3/s)
b,n,m = regional coefficients and
a = area depending on hydrological conditions.

It precipitation significantly contributes to low flow, design equation of the form Q = f(P) may be used.

In regions where low flow results mainly from groundwater the density or length of the river network or the depth of the river embedment, may be used as the main design parameter. e.g.

$$Q = a D^n \quad \text{....(14)}$$

where Q = minimum specific discharge
D = river network density determined as a ratio of the total length of river network and the basin area, and
a,n = regional coefficients.

The use of river embedment instead of network density is based on the observations that as the embedment becomes deeper, the river recharge from groundwater also increase.

In mountain regions, specific low flow (Q) is often related to mean (or mean weighted) basin elevation Hm i.e. Q = f(Hm).

To determine low stream flow for medium rivers, isogram maps are used. Such maps reflect zonal changes of a particular characteristic of low flow corresponding to the changes in physiography and lithology of the region.

On large rivers, there are usually stream flow measurements which permit the computation of low flow at the design station by interpolating upstream gauging station data in relation to changes in low flow and the length of the area.

Anand Prakash (1979) presented a deterministic model to estimate low stream flows for effluents streams when the variations in flow are small and the water surface elevation in a particular reach of the stream can be assumed to be invariant with time.

Verma (1979) proposed a non-linear storage routing equation in combination with baseflow recessions to predict low flows for effluent streams and developed a physical model for predicting low flows during droughts. However, the model was yet to be tested with field data.

Malik and Banerjee (1979) studied the influence of drought on ground water storage particularly in shallow, unconfined aquifers and proposed an exponential decay function to identify recession characteristics of the aquifer which can be used to predict ground water levels under future drought conditions.

STUDIES ON ESTIMATION OF LOW FLOWS OF UNGAUGED BASINS

Extensive literature is available on low flow processes, in particular the surface or groundwater interaction and description of the low flow regime of individual basins. However relatively little work has been reported on techniques for estimating low flow measures at ungauged sites.

There are many references to the use of more or less informal techniques of classifying catchments into physiographic types and transferring low flow data in dimensionless or specific form between catchments within the same region. Most of these studies employed catchment characteristics indexing catchment size, shape and climate and most refer to the additional need to consider the geology of the catchment in order to explain more of the variability of low flows.

Write (1970) presents a prediction equation for the mean lowest flow in a year using catchment slope and area as independent variables. The prediction error was then associated with catchment geology and a table of numerical geological indices for different classes of material was derived.

Klaarssen et al (1975) studied the rate of recession following flood hydrographs on 29 catchments in New South Wales. An index of aquifer and alluvium behaviour is developed from these data and tabulated for different types of material. This index is then used to predict the recession constant.

Armbruster (1976) describes the development of an infiltration index for improving the predictive ability of low flow regression equations. Data from 100 gauging stations in the Susquehanna river basin (U.S.A.) were used to derive 10, 20 and 50 year return period 7 day flows. The U.S. Soil Conservation Service soil classification procedure was used with numerical weights assigned to each soil class. Different weights were tried in order to optimise the regression prediction.

The estimation of low flow by correlation with neighbouring gauged catchment data is described in U.S.G.S publications, in particular, Riggs (1973). For the United Kingdom, more general information on the behaviour of British rivers is given by Ward (1968) and also in Rodda et al (1976). Flow duration curves were published in early surface water year book (HMSO 1959-60) and until 1975 in many River Authority Annual Reports. The interaction between surface water and groundwater for major aquifers is discussed in Ineson et al. (1965).

The research report of the Institute of Hydrology, Wallingford, U.K. (1980) summarizes the main conclusions of a 3 years study of low flow estimation procedures for United Kingdom rivers carried out at the Institute. The philosophy underlying the study was that low flow indices extracted from flow records could be related statistically to catchment characteristics to yield formulae enabling low flow to be predicted at ungauged sites for preliminary design purpose. Salient points of this study are briefly given below.

Fig.8 shows the handling system and represents the computer routine for archiving and accessing data according to station number and required period of record and the subsequent hydrograph analysis programs.

Procedures for evaluation of following low flow measures and indices have been developed (often in diagrammatic form) for summarising the low flow regime of a river.

1. Flow duration curves for different durations. Flows are expressed as a percentage of average daily flow (ADF) over the recorded period as it permits comparison between catchments, by reducing the effect on the slope and location of the flow duration curve of differences in catchment area and higher or lower than average flows during the recorded period. The low flow index from the flow duration curve used to generalise to ungauged locations was the 95 percentile 10 day discharge, Q95(10).

2. Flow frequency curves for different durations show the proportion of years or equivalently the average interval between years (return period) in which the river falls below a given discharge.

3. Low flow spells below a given threshold discharge-frequency of spell durations and frequency of deficiency volumes.

4. Storage yield diagram is used to determine the volume of storage required in a reservoir to yield a given uniform supply rate with a given probability of failure.

5. Recession constant: the rate of decay of river flows in the absence of rain, is applied in flow forecasting where an estimate of the discharge at some future date is required, given the current river discharge, and assuming there is no effective rainfall. It is also an important property relating to aquifer storage.

6. Base flow index (BFI) is a measure of the proportion of the river's runoff that derives from stored sources. Its use in this study is as a catchment characteristic. Fig. 9 shows that calculation of base flow index from data.

7. Catchment characteristics: Catchments size represented by catchment area (AREA) and the length of main stream (L), catchment climate SAAR (Average annual rainfall in standard period), Catchment slope S1085, the stream channel slope measured between 10% and 85% up the main stream above the point of interest, steam frequency (STMFRQ) measured as the number of stream junctions per square kilometer, land use, geology etc.

External relationships between the low flow indices and catchment characteristics have been developed (eg. relationship between BFI and Q95(10). After exploring a number of combinations of independent variables, the following regression equations have been developed:

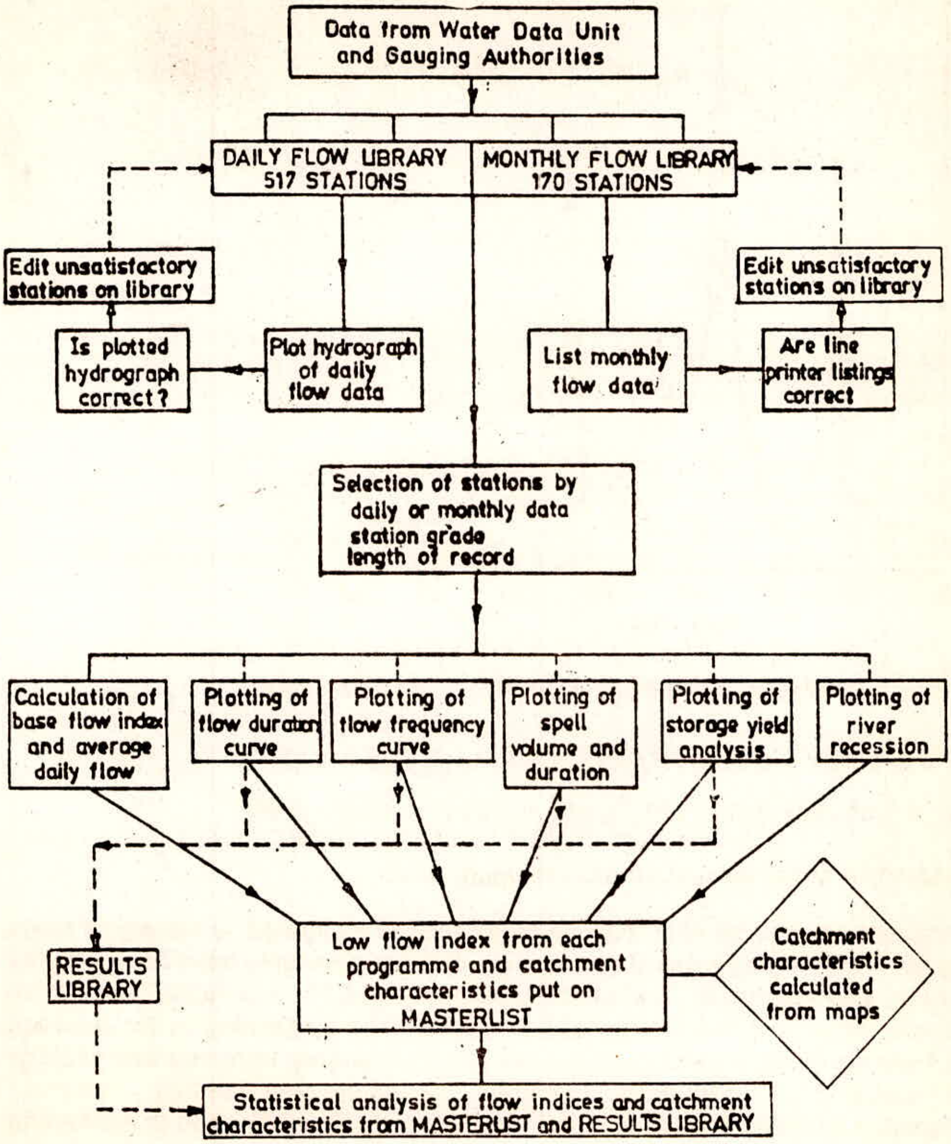


Fig. 8 Data processing flow chart

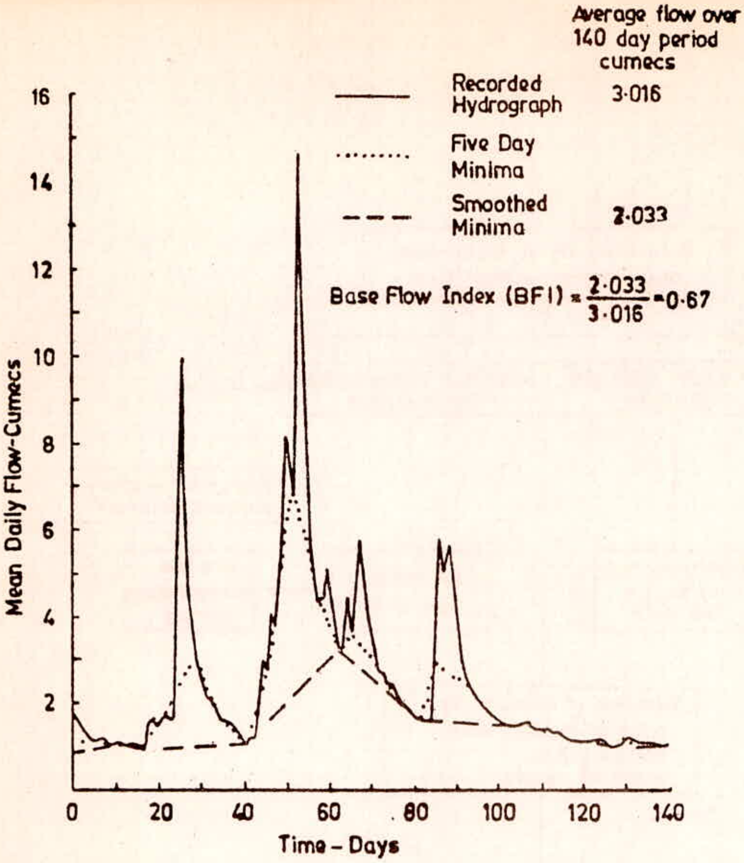


Fig. 9 Calculation of Baseflow index from data

$$\sqrt{Q95(10)} = 8.6\sqrt{BFI} + 0.00377\sqrt{AREA} + 0.0414\sqrt{SAAR} - 3.22 \qquad ....(15)$$

$$\sqrt{MAM(10)} = 9.39\sqrt{BFI} + 0.00199\sqrt{AREA} + 0.0144\sqrt{SAAR} - 2.98 \qquad ....(16)$$

where MAM(10) = Mean Annual 10 day minimum flow

In conclusion, it may be said that the study has investigated a variety of ways describing the low flow properties of rivers. Two of these measures have been related to catchment characteristics and procedures developed for estimating them at an ungauged site. When low flow measures are standardized by dividing by the average daily flow, then the effect of catchment are and rainfall is largely removed and geology has been found to be the most important remaining characteristic. The study has developed a method of indexing this characteristic using flow and of estimating it from maps of catchment geology.

SUGGESTIONS ON FURTHER RESEARCH WORK

Several studies have been carried out on low flows as a part of project feasibility investigations in case of irrigation and power projects, but very little work has been done on long term base flow/low flow studies and on studies relating them to drainage characteristics of the basin and geotechnological properties of the groundwater reservoirs of the basin. Thi is more true for India.

A lot of work has yet to be done to understand the low flow regimes of our river basins, to enable us to evolve sound plans for optimal utilisation of our water resource during this vital period of lean months, when normally demand exceeds supply and there is great stress on the limited water resources available during this lean period. Following are a few suggestions on further research work to be done on long term base flow/low flow studies in the country:

1. To study the effects of transmissivity (T), specific yield/storage coefficient (S), and length of aquifer, on base flow contribution to a partially penetrating river.
2. To study the effects of aquifer parameters, layering of aquifer zones etc. typical of hard rock terrain on base flow contribution to a fully or partially penetrating river.
3. Studies on base flow, relating it to the basin characteristic, aquifer parameters and water level fluctuations to be taken up in selected river basins, for which long term base flow data is available.
4. To estimate the basic characteristics i.e. magnitude, duration and frequency of occurrence of low flows of all the rivers for which long term low flow data is available and to bring out manuals on use of such data for optimum and safe use of low flows.
5. To establish relationships between the low flow parameters and the drainage characteristics/geotechnical properties of the selected river basins, and based on them to evolve methodology for estimation of low flow of ungauged basins.
6. To study the effects of meteorological droughts on low flows.
7. In case of rivers of the Indo-Gangetic Plain, which receive snow melt during summers, it is necesssary to estimate the contribution of different components of flow i.e. snowment and base flow from groundwater; to the total flow during the lean period. The effect of temperature variations on the component of snowmelt has also to be carefully evaluated. Intensive studies on snow hydrology of the region should form a part of the study of low flows in this region.
8. To study the influence of man's activities on the catchment and hence on low flows.

REFERENCES

Abd-El-Al, Ibrahim (1953), Statics and dynamics of water in the Syro- Lebanese limestone massive, Proc. Ankara Symp. on Arid Zone Hydrol., Arid Zone Programme II, UNESCO, 60-76.

Amorocho, J., (1967), The nonlinear prediction problem in the study of the runoff cycle, Water Resources Res.3, 861-888.

Barnes, B.S., (1939), The structure of discharge recession curves, Trans. Am. Geophys, Union, 20, 721-725.

Barnes, B.S., (1944), Subsurface flow, Trans. Am. Geophys. Union, 25, 746, Beardmore, Nathanial, Manual of Hydrology, Waterlow and Sons, London, 1862.

Boussinesq, J., (1877), Essai sur la theories des eaux courantes, Memories presentes par divers savants a l'Academic des Sciences de l'Institut National de France, Tome XXIII, No.1.

Boussinesq, J., (1904), Recherches theoretique sur l'ecoulement des nappes d'eau infiltrees dans le sol et sur le debit des sources, J.Math. Pure Appl., 10(5th series), 5-78, 363-394.
Barter, E.F., (1904), The unit hydrograph principle applied to small water sheds Trans. Am. Soc. Civil Engrs., 105, 1154-1178.

Brutsaert, Wilfried, and Hassan Ali Ibrahim, (1966), on the first and second linearization of the Boussinesq equation, Geophys. J., 11, 549-554.

Rutler, S.S., (1967), Free-aquifer groundwater depletion hydrographs, J.Irrigation Drainage Divn. Am. Soc. Civil Engrs., 93(IRI), 65-81. Carlston, C.W., (1963), Drainage density and streamflow, U.S. Goel, Surv. Prof. Paper, 422-C.

Carlston, C.W., (1966), The effect of climate on Drainage density and streamflow, Bull. intern. assoc. sci. hydrol., 11(3), 62-69. Carslaw, H.S., and Jaeger, J.C. (1959), Conduction of heat in solids, Oxford University Press.

Castany, G., (1967), Traite partique des eaux souterraines,Dunod, Paris, 2nd ed.

Chapman, T.G., (1964), Effects of groundwater storage and flow on the water balance, Water Resources Use and Management, edited by E.S. Hills, 290-301. Melbourne University Press.

Chandra, S., G.C. Mishra and Trivedi, A., (1979), Response of an unconfined aquifer due to the time variant recharge and river stage fluctuation, Proc. World Congress on Water Resources, Mexico, V.6, 2794-2809.

Chebotarev, N.P., (1966), Theory of stream runoff, translated to English from Russian by Wald. A., Isreal program for scientific translation, Jerusalum, 289-392.

Clark, W.E., (1956), Forecasting dry-weather flow of Pond Creek, Oklahoma, a progress report, Trans. Am. Geophys. Union, 37, 442-450.

Copper, H.H., Jr., and M.I. Rorabaugh, (1963), Groundwater movements and bank storage due to flood stages in surface streams, U.S. Goel. Surv. Water Supply Paper 1536-J.

Coutagne, A., (1948), Meteorologie at hydrologie. Etude generale des variations de debit en fonction des facteurs qui les conditionnent. 2me Parties. Les variations de debit en periode non influence par les precipitations, La Houille Blanche, Septembre-Octobre, 416-436.

Croft, A.R., (1948), Water loss by stream surface evaporation and transpiration by riparian vegetation, Trans. Am. Geophys. Union, 29, 235-239.

Cross, W.P., (1949), The relation of geology to dry-weather streamflow in Ohio, Trans. Am. Geophys. Union, 30, 563-566.

Curtis, W.R., (1966), Response of spring flow to some climatic variables in south-western Wisconsin, Water Resources Res., 2, 311-314.

Dausse, M., (1842), De la pluie et de l'influence des forest sur la cours d'eau. Ann. Ponts Chaussees, Mars-Avril, 184-209.

Denisov, V.M., (1961), A method of computing recession curves (in Russian) Meteorol. Gidrol., 3, 18-24.

Dickinson, W.T., and others, (1967), An experimental rainfall-runoff facility, Colorado State Univ., Hydrol. Paper 25.

Dingman, S.L. (1966), Characteristics of summer runoff from a small watershed in central Alaska, Water Resource., 2, 751-754.

Dooge, J.C.I., (1960), The routing of groundwater recharge through typical elements of linear storage, Intern. Assoc. Sci. Hydrol. Publ. 52, 286-300.

Durum, W.H., (1953), Relationship of the mineral constituents in solution to streamflow, Saline River near Russell, Kansas. Trans. Am. Geophys. Union, 34, 435-443.

Farvolden. R.N. (1963), Geologic controls on groundwater storage and baseflow, J. Hydrol., 1. 219-249.

Forchheimer, Phillip, (1930), Hydraulik, 101-105, 3rd de., Teubner, Leipzig and Berlin. Forkasiewicz, J and H. Paloc, (1967), Regime de tarissement de la Foux-de-la Vis(Gard),Etude Preliminaire, La Houille Blanche, 22(1), 29-32.

Gunnerson, C.G., (1967), Streamflow and quality in the Columbia River Basin, J. Sanit Eng. Div., Am. Soc. Civil. Engrs., 93, SA6. 1-16.

Guyon, Gaston, (1966), Considerations sur l'hydraulique du drainage des nappes, Bull. Tech. du Genie Bural, 79.

Hall, F.R., (1968), A suggested matching curve method for determination of nonlinear baseflow equations (abst.only), Trans. Am. Geophys. Union, 49-164.

Hall, Samuel, (1918), Streamflow adn percolation-water, Trans. Inst. Water Engrs., 23, 92-127.

Hall, F.R. (1972), Application of the convolution equation to stream aquifer relationship, Water Resources Research, 8(Z), pp.487-493.

Hall, F.R. (1968), Base-flow recessions-A review, Water Resour. Res., 4(5), 973-983.

Hall, F.R. (1969), Addendum to base-flow recession review, Water Resour. Res., 5(4, RE14.

Harrold, L.L. (1934), Relation of streamflow to groundwater levels, Trsns. Am. Geophys. Union, 15, 414-416.

Hely, A.G. and F.H. Olmsted, (1963), Some relations between streamflow characteristics and the environment in the Delware river region U.S. Goel, Surv. Prof. Paper 417-B.

Hewlett, J.D., (1961), Soil moisture as a source of base-flow from steep mountain watersheds, South-eastern Forest Expt. Sta. Paper 132.

Hewlett, J.D. and A.R. Hibbert, (1963), Moisture and enregy conditions within a sloping soil mass during drainage, J. geophys. Res., 68, 1081-1087.

Hewlett, J.D. and A.R. Hibbert, (1967), Factors affecting the response of small watersheds to precipitation in humid areas, International Symposium on Forest Hydrology, edited by W.E. Sopper and H.W. Lull, 275-290, Pergamon Press, New York.

Horton, R.E., (1903), Supplement to Annual Report of the State Engineer and Surveyor of New York, 16.

Horton, R.E., (1914), Discussion of report of committee on yield of drainage areas, J.New England Water Works Assoc., 538-542.

Horton, R.E., (1933a), The relation of hydrology to the botanical sciences, Trans. Am. Geophys. Union, 14, 23-25.

Horton, R.E., (1933b), The role of infiltration in the hydrologic cycle, trans. Am. Geophys. Union, 14, 446-460.

Horton, R.E., (1935), Surface Runoff Pheonmena Part I, Analysis of the Hydrograph, Publ. 101, Horton Hydrological Labroatory, Voorheesville, New York.

Horton, R.E., (1936a), Maximum groundwater levels, Trans. Am. Geophys. Union, 17, 334-357.

Horton, R.E., (1936b), Natural Stream channel-storage, Trans. Am. Geophys. Union, 17, 406-415.

Horton, R.E., (1937), Natural Stream channel-storage, Trans. Am. Geophys. Union, 18, 440-456.

Hoyt, W.G., (1936), Studies of rainfall and runoff in the United States, U.S. Goel, Surv. Water-Supply Paper 772.

Hursh, C.R. and E.F. Brater, (1941), Separating stream hydrographs from small drainage areas into surface and subsurface flow, Trans. Am. Geophys. Union, 22, 863-871.

Ibrahim, Hassan Ali, (1964), The groundwater outflow hydrograph from idealized aquifers, unpubl. M.S. thesis, Cornell University.

Ibrahim, Hassan Ali and Wilfried Brutsaert, (1965), Inflow hydrographs from large unconfined aquifers, J. Irrigation Drainage Divn., Am. Soc. Civil Engrs., 91, IR2, 21-38. (Also discussion in 92, IRI, 101-107, 1966).

Indri, E., (1960), Low water flow curves for some streams in the Venetian Alps, Intern. Assoc. Sci. Hydrol., Publ. 51, 124-129.

Ineson, J. and R.A. Dowing, (1964), The groundwater component of river discharge and its relationship to hydrogeology, J. Inst. Water Engrs., 18, 519-541.

Iwasaki, Tomihisi, (1934), A streamflow study of the Tokyo water supply, J. Am. Water Works Assoc., 26, 163-175.

Jacob, C.E., (1043), Correlation of groundwater levels and precipitation on Long Island, New York, Part I, Theory, Trans. Am. Geophys. Union, 24, 564-572.

Johnson, E.A. and R.E. Dils, (1956), Outlines for compiling precipitation, runoff, and groundwater data from small watersheds, Southeastern Forest Expt. Sta. Paper 68.

Kilpatrick, F.A., (1964), Source f baseflow of streams, Intern. Assoc. Sci. Hydrol., Publ. 63, 329-339.

Khisel, W.G., Jr., (1963), Baseflow recession analysis for comparison of drainage basins and geology, J. Geophys. Res., 68, 3649-3653.

Kraijenhoff van de Leur, D.A., (1958), A study of nonsteady groundwater flow, with special reference to a reservoir-coefficient, De Ingenieur, 70(19), B87-94.

Kunkle, G.R., (1962), The baseflow-druation curve, a techique for the study of groundwater discharge from a drainage basin, J. Geophys. Res., 67, 1543-1554.

Kunkle, G.R., (1965), Computation of groundwater discharge to streams during floods, or to individual reaches during baseflow by use of specific conductance, U.S. Goel, Surv. Prof. Paper 525-D, 207-210.

Olmsted, F.H. and A.G. Hely, (1962), Relation between groundwater and surface water in Brandywine Creek basin, Pennsylvania, U.S. Goel, Surv. Prof. Paper 417-A.

Pinder, G.F. and P.S. Sauer, (1977), Numerical simulation of flood wave modification due to bank storage effects, Water Resources Research Vol. 7, No.1, pp. 63-70.

Pinder, G.F., J.D. Brodehoeft and H.H. Cooper,Jr., (1969), Determination of aquifer diffusivity from aquifer response to fluctuations in river stage, Water Resour. Res., 5(4), 850-855.

Pochet, Leon, (1905), Etudes sur les sources hydraulique des nappes aquifers et des sources et applications practiques, 2 vol., inistere de l'Agriculture, Imprimerie Nationale, Paris.

Reigner, I.C, (1966), A method of estimating streamflow loss by evapotranspiration from the riparian zone, Forest Sci., 12, 130-139.

Renard, K.G., (1964), Performance of local aquifers as influenced by transmission losses and reparian vegetation, Trans. Am. Soc. Agr. Engrs., 7, 471-474, 477.

Richard, E.A., W.R. Gardner and G. Ogata, (1956), Psysical processes determining water loss from soil, Soil Sci. Soc. Am. Proc., 20, 310-314.

Riggs, H.C., (1953), A method of forecasting low flow of stream, Trans. Am. Geophys. Union, 34, 427-434.

Riggs, H.C., (1961), Regional low flow frequency analysis, U.S. Goel, Surv. Prof. Paper 424-B, 21-22.

Riggs, H.C., (1964), The baseflow recession curve as an indicator of groundwater, Intern. Assoc. Sci. Hydrol. Publ. 63, 352-363.

Roche, Marcel, (1963), Hydrologie de surface, Gauthier-Villars, Paris.

Rossel, B.W.P., (1950), Hydrologic problems concerning the runoff in headquarter regions, Trans. Am. Geophys. Union, 31, 431-442.

Rorabaugh, M.T., (1964), Estimating changes in bank storage and ground water contribution to streamflow, Intern. Assoc. Sci. Hydrol. Publ. 63, 432-441.

Schneider, W.J., (1957), Relation of geology to streamflow in the upper Little Miami basin, Ohio J.Sci., 57(1), 11-14.

Schilfgaarde Van, J., (1970), Theory of flow to drains, in Advances in Hydroscience, vol.6, edited by Van Te Chow, pp.43-106, Academic, New York.

Schneider, W.J., (1965), Areal variability of low flows in a basin of diverse geologic units, Water Resource Res., 1, 509-515.

Schoeller, Henri, (1962), Les eaux souterraines, Masson et Cie, Paris. Singh, K.P., (1968), Some factors affecting baseflow (abst.only), Trans. Am. Geophys. Union, 49, 169.

Singh, K.P., (1969), Theoretical baseflow curves, J. Hydraulic Div. Amer. Soc. Civil Eng., 95(HY 6) 2029-2048.

Skaggs, R.W., (1975), Drawdown solutions for simultaneous drainage and L.F. Irrigation and drainage vol. 101 IR 4, ASCE page 279-291.

Snyder, W.M., (1962), Some possibilities for multivariate analysis in hydrologic studies, J. Geophys. Res. 67, 721-729.

Spiegel, Zane, (1962), Hydraulics of Certain Stream-Connected Aquifer System, New Mexico State Engineer, Special Report.

Sun, P.C.P., J.H., Criner and J.L., Poole, (1963), Large springs of east Tennessee, U.S. Goel Surv. Water-Supply Paper 1855.

Thomas, M.P., (1966), Effect of glacial geology upon the time distribution of streamflow in eastern and southern Connecticut, U.S. Geol. surv. Prof. Paper 550-A, 209-212.

Thomson, S. Halton, (1921), Fluctuations in groundwater levels, Advances in Geophysics edited by H.e. Lal Dsberg and J. Van Mieghan, 11, 303-326, Academic Press.

Todd, D.K., (1954), Untseady flow in porous media by means of a Hele-Shaw viscous fluid model, Trans. Am. Geophys. Union, 35, 905-916.

Todd, D.K., (1954), Groundwater in relation to a flooding stream, Prof. Am. Soc. Civil Engrss., 81(Separate No. 628), 1-20.

Toebes, O. and D.D., Strang, (1964), On recession curves, 1, Recession equations, J. Hydrol., New Zealend, 3(2), 2-15.

Toler, L.G., (1965a), Use of Specific conductance to distinguish two baseflow components in Econfina Creek, Florida, U.S. Goel, Surv. Prof. Paper 525-C, 206-208.

Toler, L.G., (1965b), Relation between chemical quality and water discharge in Spring Creek, South-western Georgia, U.S. Goel, Surv. Prof. Paper 525-C, 209-213.

Troxell, H.C., (1936), The diurnal fluctuation in the groundwater and flow of the Santa Ana River and its meaning, Trans. Am. Geophys. Union, 17, 496-504.

Tschinkel, H.M., (1963), Short-term fluctuations in streamflow as related to evaporation and transpiration, J. Geophys. Res., 68, 6459-6469.

Vab Schilfgaarde, Jan, (1965), Transient design of drainage systems, J. Irrigation Drainage Div., Am. Soc. Civil Engrs., 91, IR3, 9-22.

Kunkle, G.R., (1968), A hydrogeologic study of the ground-water reservoirs contributing base runoff to Four Mile Creek, east-central Iowa, U.S. Goel. Surv. Prof. Water-Supply Paper 1839-0.

Langbein, W.B., (1938), Some channel-storage studies and their application to the determination of infiltration, Trans. Am. Geophys. Union, 19, 435-445.

Langbein, W.B., (1942), Monthly evapotranspiraton losses from natural drainage basins, Trans. Am. Geophys. Union, 23, 604-612.

Langbein, W.B.,, (1960), Water levels as indicators of long-term precipitation or runoff, Intern. Assoc. Sci. Hydrol., Publ.51, 517-525.

Langbein, W.B. and D.R. Dawdy, (1964), Occurrence of dissolved solids is surface waters in the United States, U.S. Goel. Surv. Prof. Paper 501-D., 115-117.

LaSala, A.M., Jr., (1967), New approaches to water resources investigations in upstate New York, Ground Water, 5(4), 6-11.

Lenz, A.T. and C.N. Sawyer, (1944), Estimation of stream-flow alkalinity determinations, Trans. Am. Geophys. Union, 25, 1005-1009.

Maasland, D.E.L. and M.W. Bittinger, (1963), editors, Proceedings of the Symposium on Translent Ground Water Hydraulics, Civil Engineering Section, Colorado State Univeristy.

Maillet, Edmond, (1902), Sur la prevision des debits minima des sources de la Vanne, Compt. Rend. Acad. Sci., 134, 1103-1105.

Maillet, Edmond, (1905), Essai d'hydraulique souterraine et fluviale, Libraire Sci., A. Herman, Paris.

McGuinness, J.L., L.L. Harrold and C.R. Amerman, (1961), Hydrogeologic nature of streamflow on small watersheds, J. Hydraulics Div., Am. Soc. Civil Engrs., 87, HY1, 1-13.

Meinzer, O.E. and others, (1936), The channel-storage method of determining effluent seepage, Trans. Am. Geophys. Union, 17, 415-418.

Merriam, C.P. (1956), Potential value of groundwater data, Trans. Am. Geophys. Union, 37, 463-467.

Meyboom, P., (1961), Estimating groundwater recharge from stream hydrographs, J. Geophys. Res., 66, 1203-1214.

Miller, E.G., (1965), Effect of Great Swamp, New Jersey, on streamflow during baseflow periods, U.S. Goel. Surv. Prof. Paper 525-B., 177-179.

Moench, A.F. and C.C. Kisiel, (1970), Application of the convolution relation to estimating recharge from an ephemeral stream, Water Resour. Res. 6(4), 1087-1094.

Nixon, P.R. and G.P. Lawless, (1960), Translocation of moisture with time in unsaturated soil profiles, J. Geophys. Res., 65-655-661.

van Schilfgaarde, Jan, Don Kirkham and R.d. Frevert, (1956), Physical and mathematical theories of tile and ditch drainage and their usefulness in design, Iowa State Univ. Agri. Exp. Sta. Res. Bull. 436, 667-706.

Vermeule, C.C., (1984), Report on Water Supply, V.III of the Final Report of the State Geologist, Geological Survey of New Jersey.

Venetic, C., (1971), Estimation of unconiined groundwater flow to ditches Journal of Hydrology 13, 338-342.

Venetis, C., (1970), Finite aquifers: Characteristic reponses and applications, J. Hydrol., 12, 53-62.

Werner, P.W., (1957), Some problems in non-artesian groundwater flow, Trans. Am. Geophys. Union, 38, 511-518, (Also discussion, 39, 738-741, 1958).
Warner, P.W. and K.J. Sundquist, (1951), On the groundwater recession curve for large watrershed, Intern. Assoc. Sci. Hydrol. Publ. 33, 202-212.

Whelan, D.E., (1950), A method of evaluating the hydrologic effects of land use on large watersheds, Trans. Am. Geophys. Union, 31, 252-261.

Wicht, C.L., (1943), Determination of the effects of watershed- management on mountain streams, Trans. Am. Geophys. Union, 24, 594-606.

Anand Bakash (1979) 'A deterministic model to estimate low streamflows' Proc. Int. Symp. Hydrol. Aspects of Droughts, New Delhi pp. 131-142.

Armbruster, J.T. (1976) 'An infiltration index useful in estimation low-flow characteristics of drainage basins' Journal Research U.S. Geological Survey. 4,5, 533-538.

Beram, M.A. and Gustard A. (1977) 'A study into low flow characteristics of British rivers' Jour. Hydrology Vol.35,pp. 147-157.

Comer, G.H. and Zimmerman, R.C. (1969) 'Low flow and basin characteristics of two streams in Vermont' Journal of hydrology Vol.7, pp. 98-108.

Chachadi, A.G. and G.C. Mishra (1986-87) 'Study of parameters affecting base flow'. Report TR.II of National Institute of Hydrology, Roorkee.

Chander, Subhash, Spolia, S.K. and Kumar A. (1979) 'Prediction of Hydrological Characteristics of Drooughts' Proc. Int. Symp. Hydrol. Aspects of Droughts, New Delhi pp. 205-318.

Ineson, J. and Downing, R.A. (1964) 'The groundwater component of river discharge and its relationship to hydrogeology' Journal of the Institution of Water Engineers, 18, 7, 43-49.

Institute of Hydrology, Wallingford, Oxon. (1980) 'Low flow studies' Research Report.

Joseph, E.S. (1970) 'Probability Destribution of Annual droughts' Proc. ASCE Jour. Irrig. and Drain. Div. Vol. 96 No. IR4 pp. 461-474.

Klaassen, B.E. and Plagrim, D.H. (1975) 'Hydrograph recession constants for New South Wales Streams' The Institution of Engineers, Australia, Civil Engineering Transations 1975, 43-49.

Linsley, R.K.,Kohler, M.A. and Paulhus J.L.H., (1958) McGraw-Hill Book Co. Inc.

McMohan, A. and Diaz Arenas (Editors) (1982), 'Methods of computation of low stream flow, UNESCO. Studies and reports in hydrology, No.36. Matalas, N.C. (1963) 'Probability distribution of low flows' United State Geological Survey Professional Paper 434-A. Mishra, G.C. (1987) 'Determination of Aquifer Recharge for varying river stages' Tech. Report NIH (Manuscript).

Mallick, S. and Banerji, S. (1979) 'Influence of drought on groundwater sotrage prediction of water levels' Proc. Int. Symp. Hydrol. Aspects of Droughts, New Delhi pp. 38-46. Raudkivi, A.J. (1979) 'Hydrology' Pergamon, Press.

Riggs, H.C. (1973) 'Regional analysis of stream flow techniques' Techniques of water resources investigations, Book 4, Chap B 3 U.S.G.S. Washington D.C.

Rodda, J.C., Downing, R.A. and Law, F.M. (1976) 'Systematic Hydrology' London: Newnes Butterworths.

Raju, T.S., Jha, B.M. and Kidwai, A.L. (1981) 'Evaluation of base flow and groundwater reservoir characteristics of the Upper Betwa River Basin' Proc. Seminar on Development and Management of Groundwater Resources, 15-16 Feb. 1981 at New Delhi.

Shaw, E.M. (1983) 'Hydrology in Practice' Van Nostrand Reinhold (U.K.) Co. Ltd.

Verma, R.D. (1979) 'Prediction of low stream flows during droughts' Proc. Int. Symp. Hydrol. Aspects of Droughts, New Delhi pp. 112-119.

Wilson, E.M. 'Engineering Hydrology'.

Write, C.E. (1970) 'Catchment characteristics influencing low flows, water and water engineering ' Nov. 1970, 468-471.

Ward, R.C. (1968) 'Some runoff characteristics of British rivers' Journal of Hydrology 6, 358-372.

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composed & printed by : anubhav printers, roorkee ✆ 71237, 72007