LONG TERM BASEFLOW STUDIES

T. S. Raju

Superintending Hydrologist
Central Ground Water Board
Faridabad

G. C. Mishra

Scientist "F"
National Institute of Hydrology
Roorkee

&

A. G. Chachadi

Lecturer
Goa University
Goa

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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,
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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

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

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

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

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
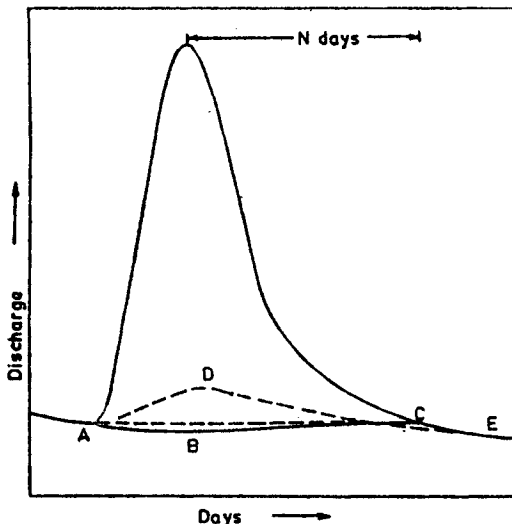

Fig. 1 Some simple Baseflow separation procedures

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 $\rightarrow \Delta t$ (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 $\rightarrow \Delta t$ later (on log log scales) the later value of Q is again plotted against the Q value, another $\rightarrow \Delta t$ 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 depicting 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.
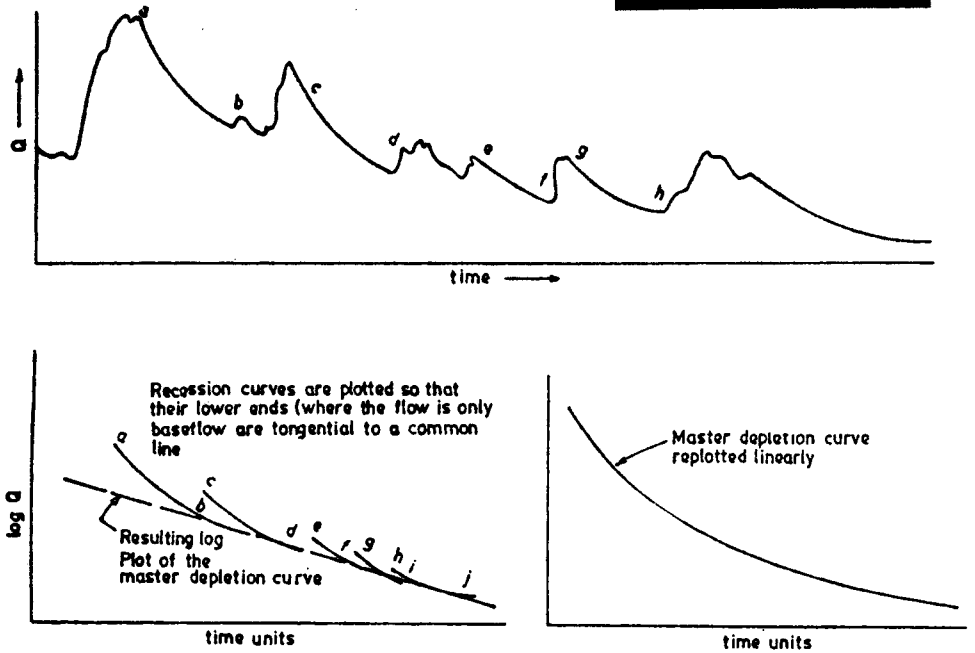
Fig. 2 Derivation of a master depletion curve (a) Normal Hydrograph with recession curves selected (b) Log plot of recession curves (c) Liner plot of master depletion curve.
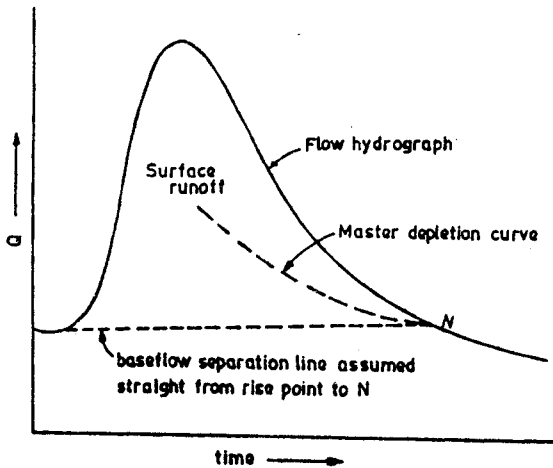

Fig. 3 Procedure to separate Baseflow

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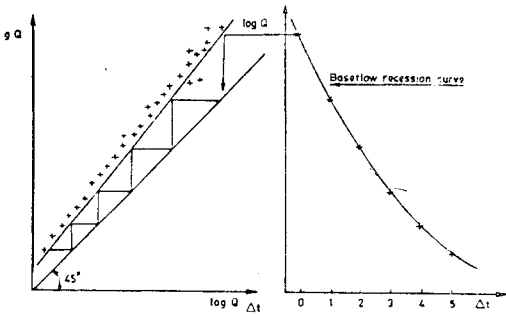
Fig. 4 Construction of the Baseflow recession curve by the correlation method
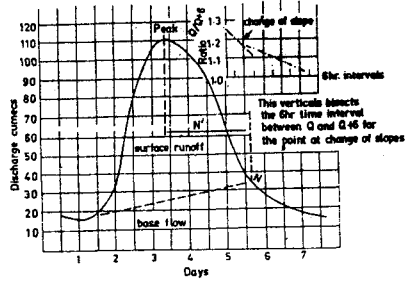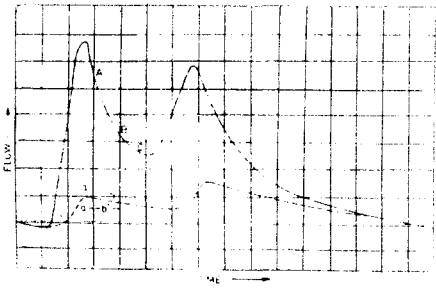

Fig. 5 Alternative method of separating Baseflow
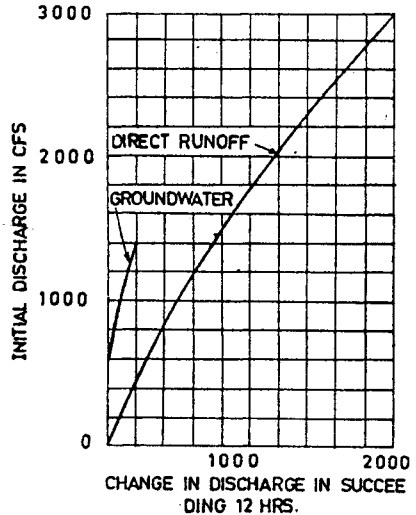

Fig. 6 Analyasis of a complex hydrograph

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 (1962) 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 begin 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 under way 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 :

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

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.

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

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

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

or

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

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

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

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

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

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.

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

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

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

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)

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

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

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

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 ground-water 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 whether 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 ground-water 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 evapotranspi-ration. 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 penetrat-ing 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