9 Hydrologic Processes

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9.1 INTRODUCTION

A catchment is a basic unit of landscape particularly for investigations of hydrologic processes. Typically, the topographic boundary of a catchment coincides with the hydrologic boundary causing any precipitation falling on to the catchment to be routed to a stream where it is transported out of the catchment. Fundamental components of the hydrologic cycle, such as precipitation, runoff and evapotranspiration (computed by difference between precipitation and runoff over long periods), have been documented from water balance studies on small catchments. Observations and time series data collected from small catchments provide a basis for the development of hydrologic models, and many such models have been used for flood forecasting. However, one of the more recent goals of hydrologic investigations in small catchments is to understand better how streamflow is generated and how this process relates to water quality genesis.

Prior to the last few decades, studies of the sources of streamflow during storms or snowmelt were concerned primarily with the physics of the processes involved. Horton (1933) developed a hypothesis stating that the source of runoff during storms is the excess rainfall over infiltration capacity of basin surficial materials and that the water infiltrated would become groundwater which was the source of the baseflow part of the hydrograph. Horton's thesis is effectively a two-component mixing model. However, Hewlett (1961) showed that water draining from the soil, i.e. unsaturated flow, also contributed to baseflow. Betson (1964) suggested that only certain parts of drainage basins contributed runoff during most storms (the partial-area concept), which was supported by a study by Dunne and Black (1970) in the humid northeastern USA. In addition, Hewlett and Hibbert (1967) proposed that during storms, ephemeral streams expand upstream by collecting overland flow and shallow subsurface runoff along their channels (the variable-source area concept). On the whole, these physically based models came to the quite reasonable conclusion that new rainwater was the dominant source of runoff and several techniques, graphical and mathematical, were developed to subdivide the hydrograph into corresponding source waters (e.g. see Hewlett and Hibbert, 1967).

Recently, the use of environmental tracers, such as naturally-occurring isotopes (^{18}O, D), solutes (Cl^-, Br^-) and other physical and chemical characteristics (tem-

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perature, specific conductance and alkalinity), to track the movement of water has gained widespread acceptance. When isotopic tracers were used in a two-component mixing model, prestorm ("old") water was found to be the dominant component of storm runoff (Sklash *et al.*, 1976; Sklash and Farvolden, 1979; Hooper and Shoemaker, 1986; Pearce *et al.*, 1986; Sklash *et al.*, 1986; Turner *et al.*, 1987). This contradiction between the physical models and chemical or isotopic mixing models inspired a wide spectrum of interpretations of the hydrologic processes which are subsequently compounded in the interpretation of processes controlling streamwater quality.

Most information on hydrologic processes in small catchments has been acquired from investigations on forested and agricultural ecosystems. The need for scientifically based forest resource and agricultural management predicated sound hydrologic research programmes worldwide. For example, hydrologic studies focused on the effect of various types of forest management practices such as the various types of harvesting and reforestation led to studies of the effects of these practices on runoff timing and basin yields. Also, the importance of water management in maximizing agricultural yields, has led to a variety of studies on agricultural catchments. Much of the information gained from these studies is central to the issue of the role of small catchments in understanding hydrologic processes. However, the hydrologic results from small catchment studies in agricultural or forested areas will be presented primarily in the corresponding chapters on agriculture and forest management (e.g. Chapters 16 and 17, respectively), because the themes central to these chapters are well suited to include this information as part of the historical development of the use of small catchments in these particular fields.

The objective of this chapter is to expand on several aspects of the knowledge gained about hydrological processes from catchment studies. The information herein is not meant to provide the reader with an exhaustive review of the scientific literature, although references are listed for each of the topics discussed. Rather, this chapter contains results as they relate to a variety of methods that have been applied to understand hydrologic processes in small catchments.

9.2 RUNOFF CHARACTERISTICS

One of the most accurate measurements made in small catchments is streamflow or discharge. Streamflow is the integrated result of all meteorological and hydrologic processes in the catchment. Considerable effort has been expended over the past several decades to evaluate the information contained in the surface water hydrograph, i.e. the factors producing it, and to try to relate these factors quantitatively to the discharge. A wide range of approaches have been developed and used. For example, hydrologists concerned with flood prediction typically are not concerned with baseflow characteristics of the hydrograph and approaches taken for their analysis range from statistical assessments or flood frequency analysis to more physically based, deterministic modelling. In this section, discussed topics include flow-duration analysis, recession-curve analysis, timing or dynamics of runoff, the water budget and the recent use of remote sensing and geographic information systems (GIS) to understand hydrologic processes.

9.2.1 FLOW DURATION

The shape of the flow-duration curve is determined by the hydrologic and geologic characteristics of the drainage area, and the curve may be used to study the hydrologic response of a drainage basin to various types and distributions of inputs, i.e. snowmelt or rainstorms, or to compare the responses of one basin with those of another. A curve with a steep slope throughout results from streamflow that varies markedly and is largely fed by direct runoff, whereas a curve with flat slope results from streamflow that is well sustained by surface releases or groundwater discharges. The slope of the lower end of the duration curve, i.e. low flow characteristics, shows the behaviour of the perennial storage in the drainage basin; a flat slope at the lower end indicates a large amount of storage and a steep slope indicates a negligible amount.

In unregulated streams, the distribution of low flows is controlled chiefly by the geology of the basin. Thus, the lower end of the flow-duration curve is often used to study the effect of geology on the groundwater runoff to the stream (Ayers and Ding, 1967; Peters and Murdoch, 1985; Peters and Driscoll, 1987). For example, the type, thickness and distribution of surficial materials, particularly for catchments in glaciated terrain, determine the hydrologic characteristics of the groundwater storage (Figure 9.1). Flow-duration curves for streams underlain by varying percentages of stratified drift and till produce a characteristic unit flow response attributable to groundwater discharge from these basin materials in Connecticut, USA (Thomas, 1966). Also, watersheds containing expansive deep deposits of till will store more water and release it more slowly than those containing shallow deposits of till interspersed with outcrops of underlying bedrock (Peters and Murdoch, 1985; Newton *et al.*, 1987; Peters and Driscoll, 1987).

Where the stream drains a single geologic formation, the position of the low-flow end of the curve is an index of the contribution to streamflow by the formation. Furthermore, sedimentary rocks, limestone and sandstone, sustain flow better than igneous rocks (Clark, 1955), as do basalts and other extrusive igneous rocks (McDonald and Langbein, 1948). However, fractured igneous rocks can store relatively large amounts of groundwater and can sustain flow better than unfractured igneous rocks (Stafford and Troxell, 1944).

Variations in climate, mainly the type, quantity, intensity and frequency of precipitation, have a pronounced effect on flow. A major limitation in the application of flow-duration characteristics to the quantification of hydrologic processes is that the relations between precipitation quantity and storage within or among

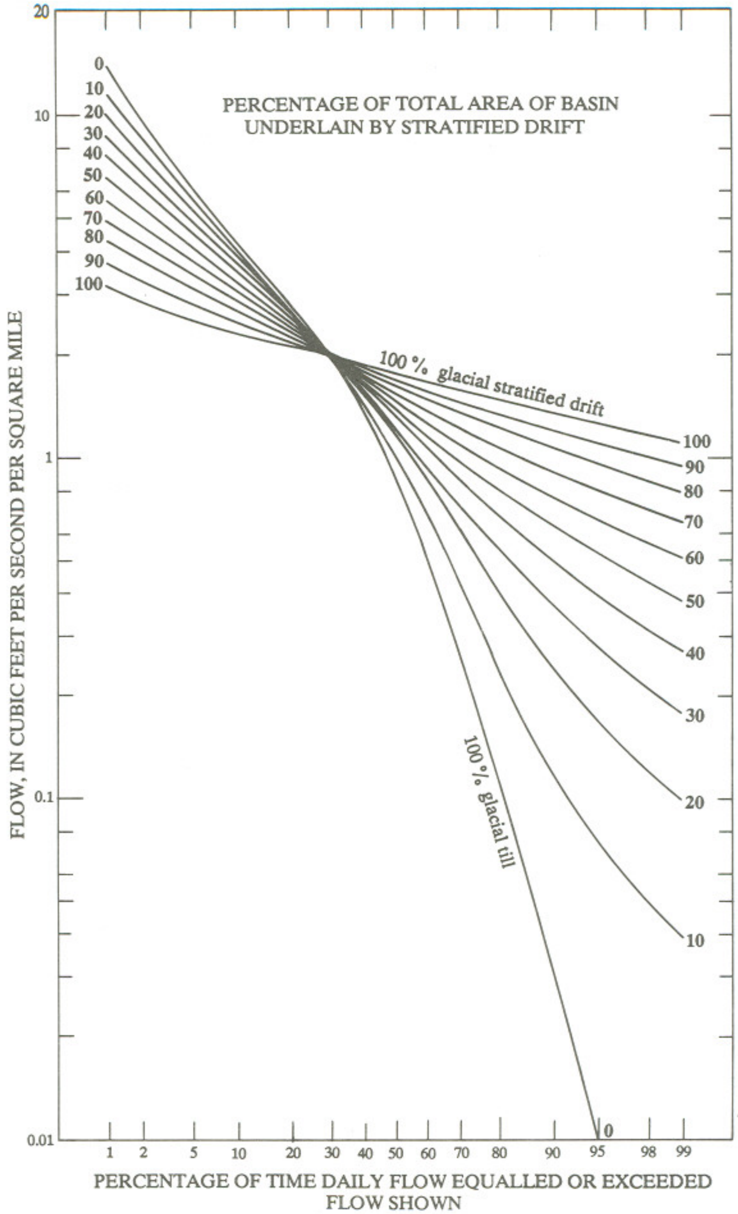

Figure 9.1 Flow-duration curves illustrating the relation between variations in surficial geology and flow of streams. These curves were derived from 30 years of data for 24 unregulated streams in a gently rolling glaciated terrain in Connecticut, USA, that had an average flow of 132 l s^{-1} km^{-2} (from Thomas, 1966).

basins generally are unknown (Lane and Lei, 1950; Dingman, 1978). Except in basins with a highly permeable surface, the distribution of high flows is governed largely by climate, the physiography and the plant cover of the basin. The shape of the flow-duration curve at the high end can indicate something about the storage capacity in the catchment, resistance (routing) and dynamics of reservoirs (surface storage in lakes and wetlands, and groundwater storage in aquifers) and the physiographic characteristics of the basin such as slopes and drainage distribution patterns (Lane and Lei, 1950). Surface water storage features, including swamps, ponds and surface depressions, have a large effect on the shape of flow-duration curves (Searcy, 1959). However, a major contribution of the analysis of flow duration is the qualitative assessment of the primary factors controlling streamflow in a particular basin (Searcy, 1959). A comparative analysis of these characteristics among basins yields the most defensible scientific results, particularly if the hydrology for one of the catchments is known.

Several parameters are typically used to characterize streamflow, but all are common in their attempt to incorporate the temporal variability of flow. In order to extract information on hydrologic processes from an analysis of flow duration, it is necessary to derive a measure that will remove some of the variability in flow characteristics due to climate. For example, if two catchments are identical in all respects except the quantity of precipitation, then the hydrologic processes controlling streamflow should basically be the same. The flow-duration curves may be quite different; the catchment with higher precipitation will have higher streamflows than the other catchment. But, everything else being equal, the shape of the two curves should be quite similar (Swift *et al.*, 1988). Lane and Lei (1950) defined a variability index which was the standard deviation of the common logarithms of the discharges determined at 10% intervals from 5 to 95% of the cumulative frequency distribution. Catchments with more sustained flow, indicative of basins with higher dynamic storage, had a lower variability index than catchments with a higher percentage of surface runoff and lower amount of dynamic storage. Likewise, flow-duration curves with a steep slope are indicative of streams that have more variability than those with a flatter slope. Slopes, therefore, can be used to compare catchment runoff response. Some approaches for estimating slopes include ratios of extremes to the median or mean discharges, or vice versa (Dingman, 1978; Peters and Murdoch, 1985; Peters and Driscoll, 1987).

9.2.2 RECESSION-RATE ANALYSIS

Because base flow generally is controlled by groundwater, several approaches have been developed to assess groundwater storage from characteristics of the recession hydrograph (Hall, 1968). Hursh and Brater (1941) used recession rates, called discharge depletion-ratios, to test whether streamflow was generated by channel precipitation or subsurface flow during storms at a small catchment in the Coweeta Hydrologic Laboratory, Franklin, North Carolina, USA (Figure 9.2).Their

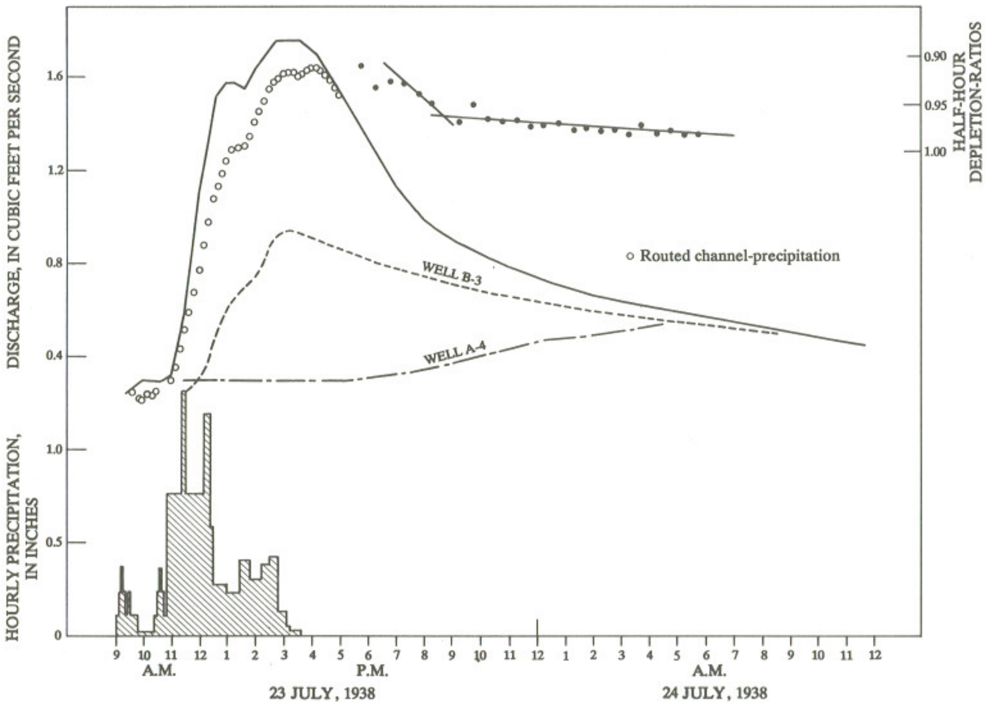

Figure 9.2 Variations in streamflow, direct channel interception and groundwater levels in a 16.2-ha watershed (No. 13) at the Coweeta Hydrologic Laboratory, Franklin, North Carolina, USA, during a 63.5-mm rainstorm on 23–24 July 1938 (from Hursh and Brater, 1941; published with permission of the American Geophysical Union). Half-hour depletion ratios were calculated for discharge recession by dividing the instantaneous streamflow with the streamflow from the previous half hour. Depletion ratios for direct runoff known to be of surface origin were 0.88 or less.

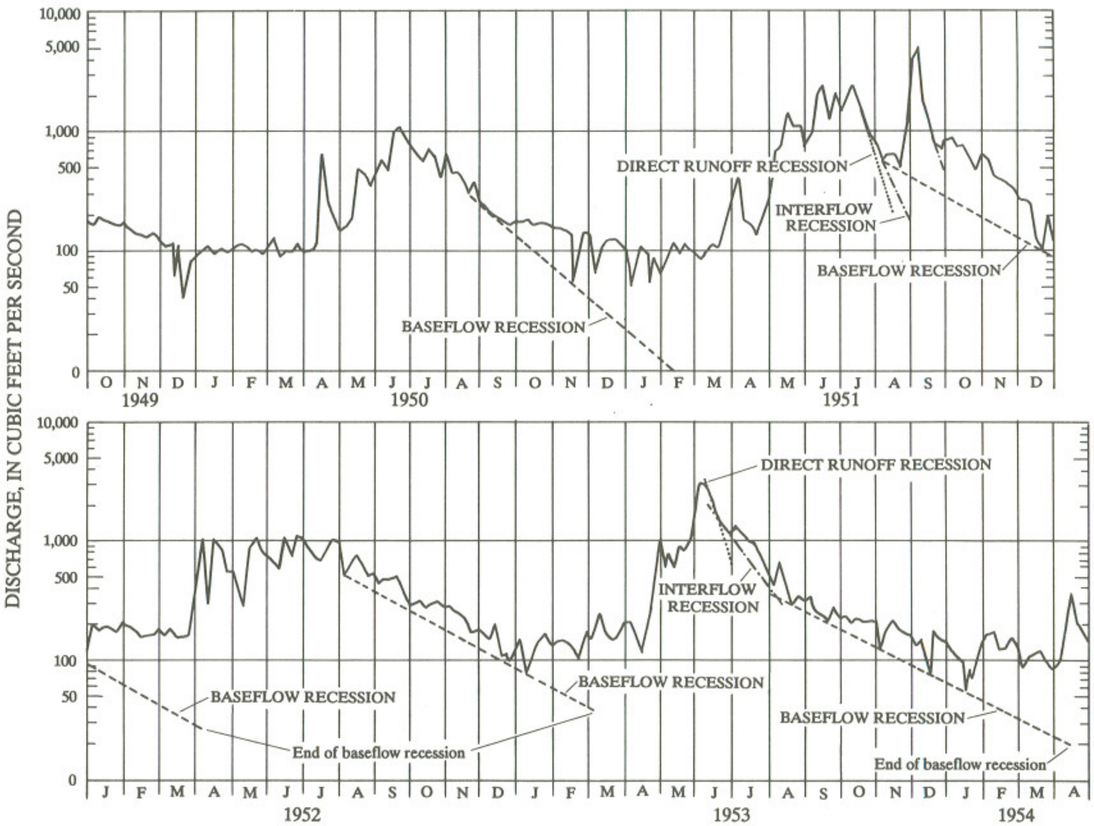

Figure 9.3 Stream hydrograph for the Elbow River, Calgary, Canada, 1949-54 (from Meybroom, 1961; reproduced by permission of the American Geophysical Union).

assessment demonstrated that the streamflow during storms was generally driven by subsurface discharge and not direct interception of precipitation on the channel.

Knisel (1963) developed a relatively objective graphical approach for assessing the groundwater contribution to streamflow. In this study, the baseflow recession curve was assumed to be a decay-type curve, and the maximum aquifer capacity could be determined from an integration of the maximum recession curve; daily flows were used for this analysis.

Meybroom (1961) graphically constructed baseflow recessions over longer time periods by connecting the lowest flows observed throughout a season (Figure 9.3). Subtracting the discharge at the end of a time period (potential groundwater discharge) from the discharge at the beginning of the recession (total potential groundwater discharge), gave an estimate of the groundwater recharge. Although Meybroom applied this technique to fairly large basins, it seems that it would be applicable to small catchments as well.

9.2.3 RUNOFF DYNAMICS

Modelling runoff processes in small catchments requires an understanding of the sources of the runoff and consequently routing of the water from these "reservoirs" to the stream. Several investigators have analysed the relations between the dynamics of the streamwater and groundwater hydrographs in an attempt to quantify sources. For example, for small forested catchments in the Coweeta Hydrologic Laboratory, North Carolina, USA, Hursh and Brater's (1941) assessment of groundwater hydrographs during storms indicated relations among rates of change and the timing of the change relative to that of the stream and the topographic position in the catchment. They concluded that these relations provide a measure of the potential for a given area actively to contribute subsurface discharge to streamflow during storms. Hoover and Hursh (1943) evaluated the effects of topography and soil depth on runoff in the same geographic area. In two small wetland basins in eastern Massachusetts, USA, O'Brien (1980) used the moment of maximum groundwater discharge and the recession rate (Barnes, 1939) to determine graphically the contribution of groundwater to streamflow during storms.

In a slightly different assessment, Dunne and Black (1970) investigated the mechanisms of storm runoff production and their relative importance by measuring the flow contribution of each form of runoff. The timings of these contributions were assessed relative to the stream hydrograph. These studies were conducted for both natural and artificial rainstorms at the Sleepers Rivers Watershed, Vermont, USA. They concluded that most of the storm runoff is produced as overland flow from saturated areas in the watershed, consistent with the partial-area concept (Betson, 1964).

Although sources within the catchment are of primary importance to streamflow generation, in some areas losses due to evapotranspiration should be considered as well. In an evaluation of diurnal variations in streamflow, Reigner (1966) observed, as did Croft (1948) and Troxell (1936), that the time of the maximum and minimum discharge did not coincide with the respective time of lowest and highest loss to evapotranspiation (ET). In fact the point of greatest loss occurred at the steepest part of the descending limb of the hydrograph.

9.2.4 WATER BUDGET

The fundamental aspect of the catchment that makes it amenable for use as a unit for hydrologic investigations is that its topographic divide typically defines hydrologic boundaries that enable water budgets to be computed. Consequently, one of the main building blocks of a small catchment study is the water balance. The primary components of the water balance are precipitation, runoff and, by difference, an estimate of evapotranspiration. In fact, for longer term studies, for which changes in the amount of water stored in the basin are zero and the underlying strata are impermeable, this method of estimating evapotranspiration can be more accurate than other means of determining evapotranspiration.

Although several methods have been developed to estimate ET, typically from meteorological parameters, such as solar radiation, temperature, relative humidity,

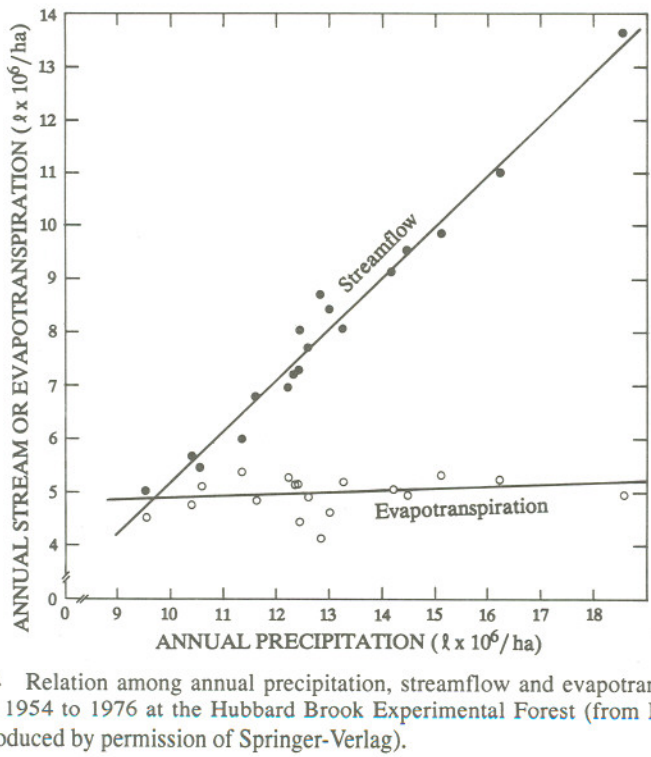

Figure 9.4 Relation among annual precipitation, streamflow and evapotranspiration for the period 1954 to 1976 at the Hubbard Brook Experimental Forest (from Likens *et al.*, 1977; reproduced by permission of Springer-Verlag).

wind speed and surface wetness, the errors associated with such computations typically are larger than those associated with its determination by the water balance, but neither is error-free (Lee, 1970). The ET component of the water budget, computed as a residual, has been documented in many catchment studies, for example see Dunin (1969), Pegg (1970), Ward (1971), Likens *et al.*, (1977), Peters and Murdoch (1985) and Avila and Rodá (1990).

A graph of annual precipitation and runoff for a control watershed at the Hubbard Brook Experimental Forest, New Hampshire, USA, demonstrates the utility of water-balance computations for assessing long-term trends in evapotranspiration (Figure 9.4). The water-balance components at this forested catchment indicate that ET calculated by the difference between precipitation and runoff, was relatively invariant from year to year, regardless of the amount of precipitation. Similar results were reported for a small catchment in the Montseny Mountains in northeast Spain (Avila and Rodá, 1990). Both of these areas are humid and streamflow is a major component of the water budget. In contrast, the annual ET for forested catchments in more xeric climates, where ET dominates the water budget, is much more variable. This variability has been attributed to variations in climate and hydrology (Swift *et al.*, 1988; Avila and Rodá, 1990). By monitoring precipitation and runoff over the long term, the estimates of ET (by difference) from small catchments can provide data for testing effects of changes in land-use, particularly for forest and agricultural resources, and for testing alternative methods of estimating ET.

Understanding the effects of management practices on water yield has been a major objective of small catchment research in forestry and agriculture. Although these topics are more thoroughly covered in the corresponding chapters, studies of the effects of land-use changes on experimental catchments in these areas have made substantial contribution to the understanding of hydrological processes. As summarized from 94 catchment experiments in a review article by Bosch and Hewlett (1982), the direction of change in water yield following forest operations can be predicted with fair accuracy, i.e. approximate magnitude of the changes. A major qualitative conclusion from their assessment was that increases in vegetative cover result in decreases in water yield.

Changes in basin storage need to be quantified to construct water budgets for shorter time periods such as months, weeks or during individual storms. The shorter the time period, the more one needs to be concerned with identifying all storage changes (see Clarke and Newson, 1978, for results from detailed water budgets from small catchments). For example, an evaluation of annual and shorter-term hydrologic budgets for small catchments in California demonstrated the necessity of considering changes in groundwater storage in the budget (Lewis and Burgy, 1964). Likewise for areas affected by inputs and storage of snow, estimates of changes in the snowpack are critical for the evaluation of hydrology (Peters and Murdoch, 1985).

Several investigators have observed diurnal variations in streamflow during the growing season and they have attempted to evaluate and, for some, quantify the processes controlling these variations. Croft (1948) evaluated the diurnal variations in streamflow with respect to short- and long-term changes in weather for a catchment in northern Utah, USA, to quantify near-channel evapotranspiration. Croft estimated that, during the middle of the summer growing season, up to one-third of the baseflow of a stream can be lost to evapotranspiration, primarily by in- and near-channel vegetation. Tschinkel (1963) used the water-balance equation for the riparian zone to compute evapotranspiration losses during the summer dry season from a watershed in the San Gabriel Mountains, southern California, USA. The relations among daily streamflow fluctuation, the total daily evaporation and the mean daily discharge for "dry" days were derived, which when used together with the water balance yielded the potential streamflow depletion curve. The result provided an estimate of evapotranspiration losses.

9.2.5 REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS

Recent advances in computer technology have provided a means to rapidly process large arrays of spectral data for remote sensing and to combine these data with other geographical information, such as topography (including slope classes and aspect), vegetation types, soil types and geology. The most important contribution made from the processing of spatial data is the assessment of hydrologically based indices estimated from digital terrain analysis with digital elevation models (see e.g., the special issue of *Hydrological Processes* (vol. 5, no. 1, 1991) on digital terrain modelling in hydrology). Assumptions regarding the effects of topography and related features, such as slope, aspect and indices of soil wetness, on hydrologic processes can be evaluated using digital elevation data. The topography now can be used directly in more physically realistic structures for hydrologic modelling, such as in predicting hillslope flowpaths using digital terrain models (Quinn *et al*., 1991) and assessing soil water status (O'Loughlin, 1986, 1990). The topography is a dominant control on how the energy is distributed, particularly in complex terrain, and the surface energy budget in turn is a primary control of evaporation, transpiration, sublimation and melting of snow. Several digital terrain models have been developed and evaluated for predicting shortwave radiation (Isard, 1986). In cold regions where snowmelt is a dominant control on hydrology, accurate characterization of snow accumulation and distribution is important. An evaluation of point data of snow depth and snow water equivalence with topographic attributes using a digital elevation model for a small alpine catchment indicated that estimates of basin loadings can probably be improved by partitioning the watershed on the basis of topographic and radiation variables (Elder *et al*., 1991). In addition, the development of GIS representations of model output provides an improved visualization of the hydrologic processes by combining several spatial characteristics to evaluate cause and effect relations or correlations (Vieux, 1991).

9.3 TRACER HYDROLOGY/MIXING MODELS

Of all of the methods used to understand hydrologic processes in small catchments, the use of tracers has been one of the most productive in terms of providing most of the new insight to hydrologic processes. However, it should be stressed that tracers need to be interpreted with care because each tracer has associated assumptions regarding its interaction with its surroundings. In some cases, the assumptions that have been validated for one environment may not be applicable to another environment. Regardless, tracers are a powerful tool in hydrologic research. This section has been divided into two sub-sections: the first sub-section deals with research in which natural and artificial tracers have been used and the second sub-section elaborates on the applicability of tracers to hydrograph separation.

9.3.1 NATURAL AND ARTIFICIAL TRACERS

The stable isotopes of oxygen and hydrogen have been used quite extensively in hydrologic investigations such as determining water budgets (Herrmann *et al.*, 1986) and streamflow generation processes (Martinec *et al.*, 1974; Fritz *et al.*, 1976; Sklash *et al.*, 1976; Sklash and Farvolden, 1979; Rodhe, 1981; Stichler and Herrmann, 1983; Bottomley *et al.*, 1984; Kennedy *et al.*, 1984; Rodhe, 1984; Bottomley *et al.*, 1986; Herrmann *et al.*, 1986; Lindström and Rodhe, 1986; Pearce *et al.*, 1986; Sklash *et al.*, 1986; Stichler *et al.*, 1986; Turner *et al.*, 1987).

A variety of chemical tracers has been used to understand the processes of water movement, residence time and reactivity of catchment materials. In most cases, the natural variability of some solute or parameter either in precipitation (rain or snow), or in waters evolved from source materials (biota or mineral soils/bedrock) has been used to understand catchment hydrology. Examples include the use of Cl^- (Rascher *et al.*, 1987; Neal *et al.*, 1988; Peters and Driscoll, 1989), SO_4^{2-} (Brimblecombe *et al.*, 1988; Tranter *et al.*, 1988), specific conductance (Pilgrim *et al.*, 1979; Kobayashi, 1986), and SiO_2 (Hooper and Shoemaker, 1986; Kennedy *et al.*, 1986; Peters and Driscoll, 1987; Hooper *et al.*, 1990).

The mobility of Cl^- and Br^- in most systems results from the fact that they are not easily adsorbed on to surfaces, nor are they incorporated into minerals that form in soils. These properties have made them useful as tracers to investigate residence time and hydrologic flow paths (Johnston, 1987; Hauhs, 1987; Williamson *et al.*, 1987), and to compute water budgets (Cleaves *et al.*, 1970; Claussen *et al.*, 1986). In addition, Cl^- and Br^- have been used to evaluate release or retention of other constituents (Bencala, 1983; Bencala *et al.*, 1983; Kennedy *et al.*, 1984; Bencala *et al.*, 1986; Rascher *et al.*, 1987; Peters and Driscoll, 1989).

Environmental tracers are used most productively in experiments where tracer application can be controlled. Relatively inert or mobile solutes have been applied to snowpacks, soils (Jardine *et al.*, 1989; Hultberg *et al.*, 1990) and streams (Bencala, 1983; Bencala *et al.*, 1983; Kennedy *et al.*, 1984; Bencala *et al.*, 1986) to help elucidate the timing of water movement, the capacity of reservoirs and, in some relatively specific applications, the characteristics of hydrologic pathways (Roberge and Jones, 1991; Hornberger *et al.*, 1991). In other cases, a mixture of solutes that vary in their adsorption characteristics has been applied to streams and soils to investigate hydrologic and hydrochemical processes including mixing of streamwaters with water in the streambed, and the reactivity of the streamwater with the stream substrata (Bencala, 1983; Bencala *et al.*, 1983; Kennedy *et al.*, 1984; Bencala *et al.*, 1986).

9.3.2 HYDROGRAPH SEPARATION

Stable isotopes of oxygen and hydrogen have gained the most widespread use for investigating contributions of source waters to streamflow during storms and snowmelt. Rodhe (1987) extensively studied the relative contributions of new water (rain or snowmelt) and groundwater to streamflow in several catchments throughout Sweden. The catchments contained a variety of land-use types but the most prevalent was forest. Other studies, such as those by Sklash *et al.* (1976), Sklash and Farvolden (1979), Rodhe (1981), Stichler and Herrmann (1983), Bottomley *et al.* (1984), Hooper and Shoemaker (1986), Pearce *et al.* (1986) and Sklash *et al.* (1986), Rodhe (1987), used a two-component mixing analysis based on ^{18}O and reported that most of the streamflow during the storms is derived from groundwater (Figures 9.5 and 9.6).

Almost all hydrograph separations have been made using only two sources of water, ignoring the possibility that soil (vadose) waters may be significant sources of water (Kennedy *et al.*, 1986; DeWalle *et al.*, 1987). Streamflow during storms (or snowmelt) can be composed of at least four components (Fritz *et al.*, 1976): (1) direct rainfall on the stream channel or on contributing wetlands; (2) overland flow; (3) groundwater discharge into the stream or wetlands; (4) subsurface stormflow (interflow, or mobile unsaturated zone water) into the channel bank. The first component is entirely event or "new" water; the other three may contain various amounts of "new" and "old" water. The compositions of the latter three components are actually mixtures because they represent hydrologic pathways instead of unique single water sources. Consequently, for each of these four components, one might expect spatial and temporal variability (note the large variation in the $\delta^{18}O$ for the rain in Figure 9.5).

The mixing models are also oversimplified and beset with several limitations. Foremost, tracers which are assumed to be conservative may not be. This is the case with many solutes which have been treated as conservative tracers (Pilgrim *et al.*, 1979). Furthermore, the water isotopes (T, D, ^{18}O) are part of the water molecule and hence are more "conservative" than solutes, but can still be affected ("fractionated") by phase changes (Fritz *et al.*, 1976). Although two-component mixing models assume that both the "new" and "old" water are isotopically uniform, their isotopic compositions often show large spatial and temporal variability (Kennedy *et al.*, 1986; Avila and Rodá, 1990).

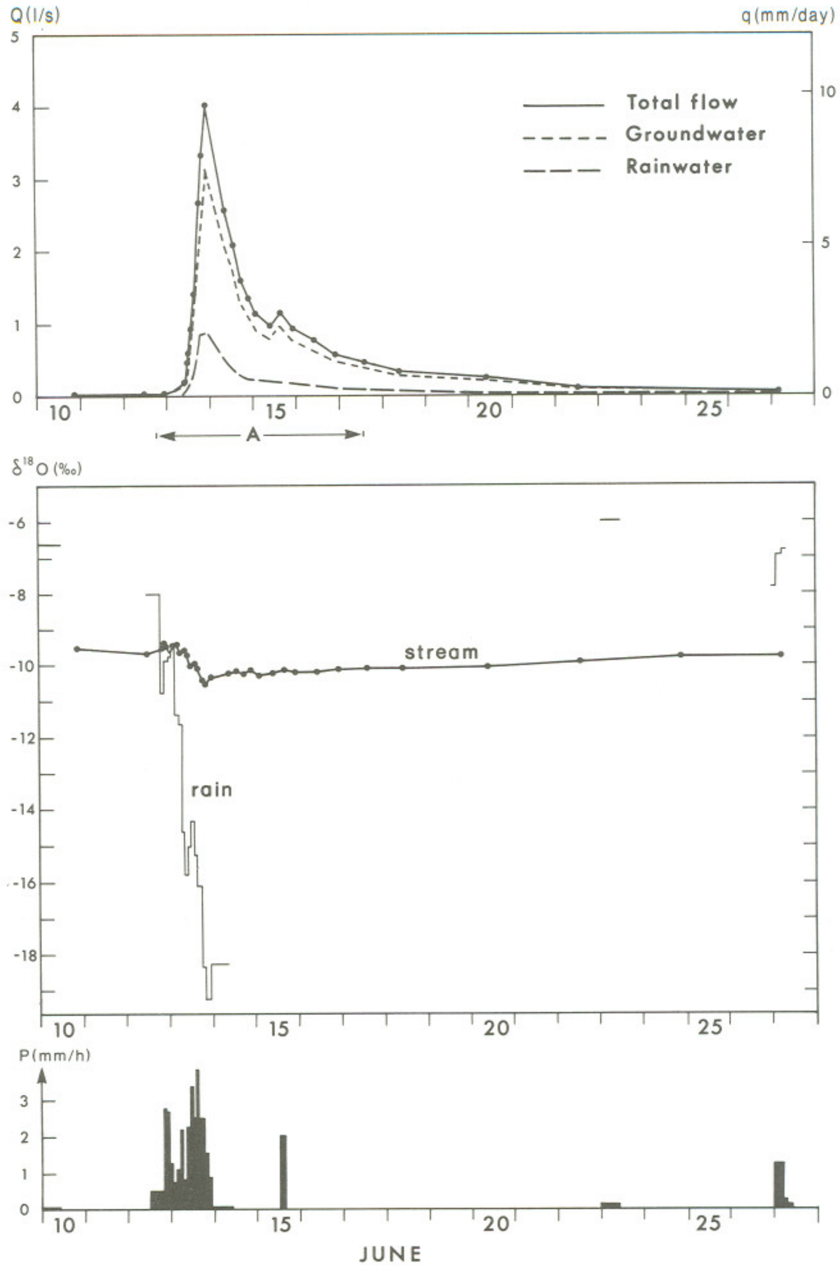

Figure 9.5 Variations in streamflow, calculated groundwater and rainwater contributions, $\delta^{18}O$ of rain and streamwater, and rain intensity for a storm in June 1982 at a 3.6-ha predominantly forested catchment at Lake Gårdsjön, Sweden (from Rodhe, 1987; reprinted by permission of Allan Rodhe).

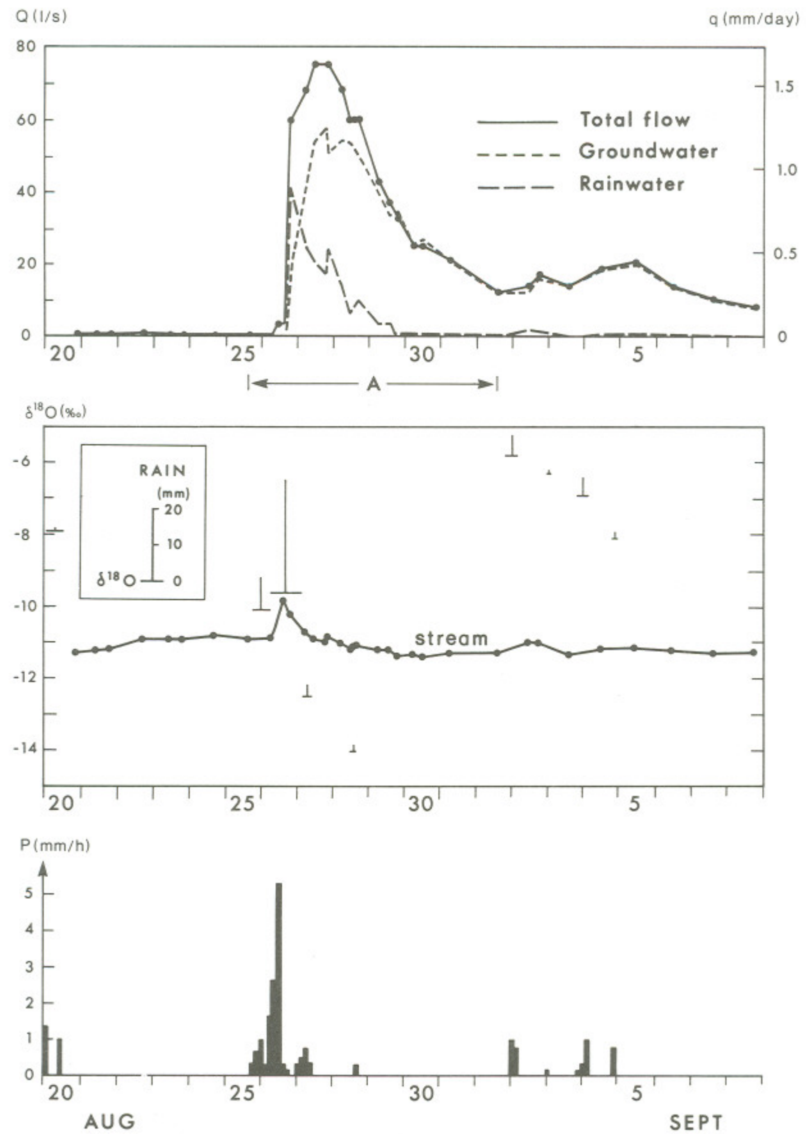

Figure 9.6 Variations in streamflow, calculated groundwater and rainwater contributions, δ ^{18}O of rain and streamwater, and rain intensity for August and September 1979 at a 400-ha predominantly forested catchment at Stormyra, Sweden. The level of the horizontal lines in the δ ^{18}O diagram marks the δ ^{18}O value of the rainfall samples and the length of these lines corresponds to the duration of the rainfall. The vertical lines show the amount of rainfall (from Rodhe, 1987; reprinted with permission of Allan Rodhe).

At the Panola Mountain Research Watershed, a small forested catchment in the southeastern USA, a three-component mixing model was developed using soil solution end members for six solutes which mix conservatively (Hooper *et al.*, 1990). The model could explain 82 to 97% of the variation of individual solute concentrations in streamwater and it could be used to solve for contributions of source waters (hydrologic pathways) using only solute concentrations.

Views differ on the mechanisms controlling water transport and chemical reactions which occur along hydrologic pathways. One of the most comprehensive of the watershed models, the ILWAS model (see Sections 2.3.2 and 4.3.2.1 of this volume), which was developed for understanding the effects of acidic atmospheric deposition on forested lake watersheds in the Adirondack Mountains, New York (Goldstein *et al.*, 1984), treats each of several soil layers as stirred tank reactors (Gherini *et al.*, 1985). In fact, depending on the rate of input to the soil and the physics and chemistry of the soil, the water will move at different rates, of which the slowest occurs through the soil matrix and the fastest along macropores or preferred pathways (Beven, 1983). The travel times (or residence time) and reactivity of the medium through which the water moves likewise control the type of chemical reactions that alter the soil composition. For example, riparian zones may control concentrations of nutrients (Pionke *et al.*, 1988; Triska *et al.*, 1989a,b) but bedrock geology and water residence time may be the dominant control for concentrations of most weathering products (Miller and Drever, 1977; Peters and Murdoch, 1985; Newton *et al.*, 1987; Peters and Driscoll, 1987; Bricker and Rice, 1989; Hooper *et al.*, 1990). During hydrologic events, there is little direct evidence that the whole catchment contributes to streamflow, although a primary control on the streamwater acidification and the mobilization of aluminum is the upper, more organic rich, soil horizon (Hooper *et al.*, 1990), particularly the riparian zone (Bishop *et al.*, 1990).

Consequently, a major uncertainty in hydrologic and chemical modelling of watersheds has been the quantification of the contributions of both water and solutes from various hydrologic pathways. The general conclusion is that hydrologic pathways are inaccurately represented in the models, or the processes that are affecting the water chemistry are not well understood. A specific example of the disparity between model results and observations can be seen for the ILWAS model. Calibration results from the hydrologic module (Chen *et al.*, 1982) indicate that hydraulic conductivity of the surficial material is 100 times greater than that determined from laboratory and field studies (April and Newton, 1985).

Recently, experiments have been designed to trace water movement in catchments by implementing various strategies for controlling the dominant variables in the water cycle, such as the application of rainfall by sprinklers either for roofed catchments (the RAIN Experiment in Norway; Wright *et al.*, 1986) and in the Roof Project at Lake Gårdsjon, Sweden, or unroofed catchments for which the artificial rainfall augments the natural conditions (Dunne and Black, 1970; Corbett *et al.*, 1975). In either case, the recent advances allow the artificial rainfall to be altered chemically by adding conservative tracers. In this way, various hypotheses can be tested regarding the importance of physical characteristics of soils and regolith on hydrologic pathways (for an example see Hauhs, 1987).

9.4 RESEARCH DIRECTIONS/RECOMMENDATIONS

One aspect of hydrology that needs further investigation is the effect of extreme events on water pathways, and runoff timing and yield. Extreme events include droughts and floods, but also include a range of storm types from long-duration, low-intensity storms to short-duration, high-intensity storms. Extreme events also can include major alterations of the landscape through deforestation, conversion from one land-use to another, such as urbanization of agricultural areas, and the effects of fire, landslides and volcanism. Any of these events can have a pronounced effect on the physical, chemical and biological characteristics of a catchment and, in turn, these can affect the hydrology.

One area that has received little attention, probably because management of large data sets was relatively untenable at least until recently, is the comparative analysis of hydrologic characteristics among catchments throughout the world. Recent technological developments, such as computers and digital data recording devices, make intersite comparisons much more attractive, but there remains a need for assessing data quality, and reduction of data accumulated in files other than those on magnetic or electronic media. It is to this end that high technology interdisciplinary studies should be encouraged from plot to larger scales in the same basic units of the landscape, the catchment. It also is to this end that more active participation by researchers in a variety of fields such as hydrogeology and plant physiology be encouraged. A mechanism to accomplish this goal is to establish an international network of experimental catchments where paired catchment studies and experiments can be conducted, and scale issues can be investigated from nested basin results. These catchments can serve as a testing ground for new ideas as they are formulated and for advances in methods of data analysis.

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