SCOPE 51 - Biogeochemistry of Small Catchments

1 Small Catchment Research

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1.1 INTRODUCTION

The International Conference on an Agenda of Science for Environment and Development into the

twenty-first century ASCEND 21. held in Vienna, Austria on 24-29 November 1991 stated that (Dooge *et al.*, 1992):

> Achievement of a sustainable world society requires an improved understanding of the complex forces which generate global environmental problems and hinder social and economic development...Scientists and technologists cannot by themselves solve the problems, but they can supply knowledge and informed opinion for consideration by governments and society, and they can assist in devising solutions.

One of the most important subjects of contemporary environmental science is biogeochemistry: the study of complex processes of pools and fluxes of chemical elements and/or molecules within ecosystems governed by both abiotic and biotic forces. Most efforts have been focused on global elemental cycles and related problems, as reflected in numerous SCOPE Reports (Nos 7, 13, 16, 17, 19, 21, 23, 33, 39, 42, 43 and 48). This book directs attention to smaller scale biogeochemical processes: those operating in small catchments.

A "small catchment" in the context of this book is a drainage basin or watershed with surface area usually less than 5 km^2. It has an easily recognizable natural topographic boundary which is defined by the watershed divide. Most often the catchment is situated in a comparatively undisturbed landscape covered by natural or semi-natural forest. Small catchment studies have also been conducted within other environments, such as high mountains, deforested areas, meadows, agricultural fields (Chapter 16 of this volume) and even urbanized or semi-urbanized areas.

A small catchment is the smallest unit of a landscape. It is large enough to encompass all the interacting components: atmosphere and vegetation, plants and soils, bedrock and groundwater, brook or lake, and surrounding land. The minimum size of the catchment should be large enough to support a perennial stream.

Microcatchments, with an area less than one hectare, were used since the 1970s in Scandinavia for evaluation of processes controlling the chemistry of runoff formed on bedrock extremely sparsely covered with soil (Abrahamsen *et al.*, 1978; Seip *et al.*, 1979; Jacks and Paces, 1987).
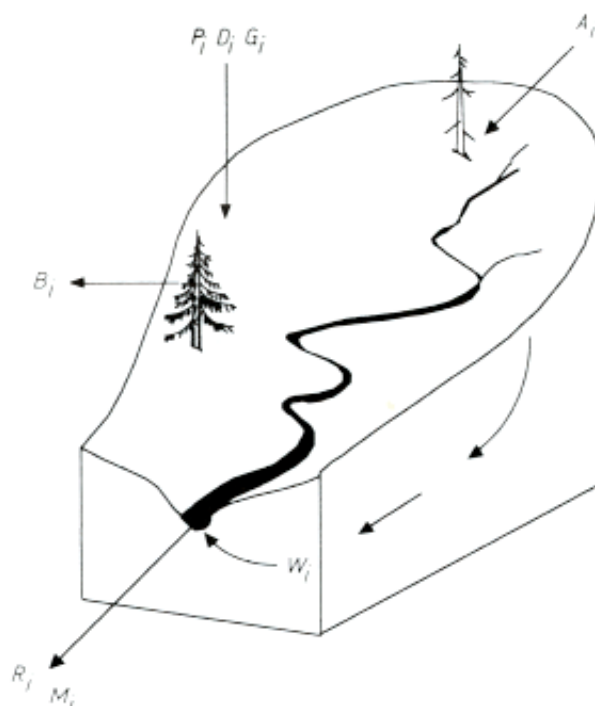
Figure 1.1 Conceptual scheme of a small catchment ecosystem (modified after Paces, 1986 and reproduced by permission of the Geological Society Publ. House). Fluxes of element i between a hydrological basin and its surroundings. W_i, total weathering of bedrock; P_i. atmosphere precipitation; A_i, anthropogenic inputs (e.g. fertilization); R_i, runoff of water; M_i, mechanical erosion due to output of particulate matter (suspension and bedrock); B_i, biomass export (lumbering, harvesting); D_i, dry deposition of particles; G_i, dry deposition of gases.

Precipitation falling on the catchment drains from the area through an unambiguous water outlet, the location of a gauging station. The position of the gauging station determines the catchment area.

A small catchment comprises a terrestrial ecosystem, e.g. usually a forest ecosystem with a linked aquatic system of an adjacent brook. Some basins contain one or more ponds or lakes. A terrestrial ecosystem is conventionally viewed as an assemblage of living organisms interacting in complex ways with one another and with their environment, air, soil and water.

The 'whole ecosystem' processes studied traditionally within an arbitrarily defined plot are part of a broader and more complex set of interconnected biological and abiotic processes of nature. Processes such as biogeochemical cycles of nutrients, accumulation or depletion of toxic substances, rock weathering, erosion and transport of weathered materials can be studied and understood better within a catchment than in a plot study. Figure 1.1 provides a conceptual scheme of a small catchment ecosystem.

Two well-known small catchment studies have to be noted as powerful examples of ecosystem research in small catchments. The Coweeta Hydrological Laboratory was established in 1933 in order to evaluate an impact of various forest- and land- management techniques on water budget (Swank and Crossley, 1988b). Hydrological and climatological measurements were used for an evaluation of experimental manipulations (such as deforestation, agricultural usage of the land, strip cuts and species conversion from hardwood to pine). Paired catchments design is extensively used for comparison of the manipulation effect relative to a control site. Swank and Crossley (1988a) summarize the complex ecological research, running since the late 1960s.

Biogeochemical cycles of individual elements have been studied at the Hubbard Brook Experimental Forest (HBEF) in New Hampshire, USA since 1963, pioneering the use of the small catchment concept for understanding the processes in an ecosystem. Observations from HBEF represent the longest record of precipitation and stream water chemistry available in the USA. The first 15 years of research were presented by Likens *et al*. (1977). Numerous other studies of small catchments were performed in the last two decades, mainly in connection with acid rain research in North America and Europe; many of these sites are referred to throughout the book.

1.1.1 NATURAL FACTORS INFLUENCING SMALL CATCHMENTS

The *site characteristics* of the catchments are usually not subject to significant changes on the time scale of years to decades, and they cover a wide spectrum of parameters. The most prominent static characteristics are: *relief of the catchment* (directly affects hydrological pattern of the catchment, its storage capacity and transit time), *altitude above sea level* (presence or absence of vegetation; mean air temperature decrease and precipitation increase with altitude), *climatological variables* (precipitation amount, duration of snow cover, relative humidity, temperature, occurrence of fogs), *bedrock geology* (mineralogy, chemical composition and degree of tectonic disruption of the bedrock determine weathering rates, i.e. the rate of supply of nutrients to plants), *soil cover* (its depth, chemical characteristics, particle size distribution and permeability are important for evolution of plant life and for development of hydrological pathways), *vegetation cover* (its distribution inside the catchment, nature of

understorey vegetation, depth of roots, state of health of the forest and its age-a successional forest accumulates more substances than a climax forest), *human impact* (magnitude of atmospheric deposition into the catchment, land-use).

An important natural factor is the occurrence of *events,* which may significantly alter the general picture which seems adequate most of the time (see Chapters 7, 8 and 12, this volume). *Site characteristics* forming this general picture are frequently treated as the product of a dynamic steady state; events represent external disturbances. Study of the way that a system reacts to an external disturbance can help us evaluate the relative importance of site characteristics at a particular site.

1.1.2 ANTHROPOGENIC FACTORS INFLUENCING SMALL CATCHMENTS

Natural processes are affected by numerous anthropogenic activities. There are few sites where there is no traceable human impact on the processes operating inside the small catchment.

Chronic human impact on the landscape is mainly the impact of management: human settlements, industrial regions and managed forests contrast with pristine nature, preserved in unmanaged forests, national parks and wilderness areas. Land management practices play a central part in determining which kind of ecosystem will be ultimately created.

Even unmanaged areas can, however, undergo measurable impacts of human activities, for instance under the chronic influence of air pollution.

Another kind of human influence is the impact of unforeseen events, *by-products of human activity, disasters*. Among prominent examples are the Chernobyl disaster, forest dieback in Central Europe, desertification in the Sahel Region. Global warming and acid rain are further examples of this kind of influence. Twenty-five years of observation of element budgets at Hubbard Brook, USA, provides a prominent example of the small catchment research interpreted in a wider environmental context (Driscoll *et al*., 1989).

1.1.3 EVENTS

Traditionally, most attention was paid to site characteristics. There are numerous techniques for extrapolating, lumping or pooling data describing site characteristics such as precipitation amounts or chemical properties of soil. There is, however, no extensive methodological apparatus available yet for dealing with episodic events, scaling them between catchments of different sizes and describing them in a quantitative way (see Chapters 7, 8 and 12, this volume).

The most relevant example of an event changing the general picture gained during stable conditions is a hydrologic event which significantly alters the chemistry of the stream. Mulder *et al*. (1990) reported on the impact of a sea-storm which produced a high pulse of NaCl in the Birkenes catchment in autumn 1987. Cerny (1987, 1989) reported a rain-induced flood during which one-third of the catchment's sulphate annual export occurred and stream water chemistry was strongly affected. In both cases, an event of unusual magnitude helped scientists to understand how catchments function.

Some events (snowmelt) have no long-term impact on the ecosystems, others (fire) affect the very nature of the site. To the most prominent events (episodes) belong sudden *hydrologic events* like storms or snowmelt, severe *episodes of air pollution, fire, pest outbreak,* drastic *change in land-use* (deforestation, species conversion, urbanization), etc. (see Chapters 16 and 17, this volume).

1.1.4 MEASUREMENTS IN SMALL CATCHMENTS

Relatively inexpensive instrumentation can transform a unit of landscape, a selected small catchment, into a true natural laboratory enabling quantitative study. A group of three to five researchers with access to a chemical laboratory and data- handling facility can easily conduct the basic measurements and data evaluation. However, one has to bear in mind that the amount of expended funds relates closely to the intensity of the study and the scope of its objectives.

A recommended set of measurements in small catchments is given in Table 1.1 (Hornung *et al*., 1990). Although extensive, this list includes only those measurements providing a framework for more detailed work according to specifically stated objectives. The list of measured parameters is extensive and growing.

Table 1.1 Basic measurements recommended for all catchments in a network (after Hornung *et al*., 1990)

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1. Sitedata

Vegetation-main vegetation types and their spatial distribution, above-ground biomass of the main vegetation types. Leaf chemistry from main forest species at three-year intervals- for total C, N, P, Na, Mg, Ca.

Soils-description of main soil types and their distribution. For main soil horizons of main soil types- cation exchange capacity, base saturation, exchangeable cations, organic matter content, total C and total N, SO_4^{2-} adsorption, texture.

Parent material mineralogy, if different from bedrock.

Geology-main rock type and spatial distribution, mainly of each rock type.

2. Meteorological data

Mean monthly temperature, weekly precipitation---the number of gauges being determined by variation in altitude and aspect within the catchment.

3. Air pollution and dry deposition

Measurement of atmospheric concentrations of NH_3, NO_2 and SO_2 using simple adsorption techniques. Sampling interval to depend on ambient concentrations at each site.

4. Inputs

Bulk precipitation-weekly samples composed for monthly analysis.

Throughfall-weekly collections for monthly analysis from each forest type within the catchment. Several throughfall sites may be necessary if there is a large variation in aspect, altitude or age.

All samples to be analysed for pH, conductivity, calcium, magnesium, sodium, potassium, ammonium, nitrate, chloride, sulphate, filtered aluminium, alkalinity. Occasional samples to be evaluated for SiO_2, DOC, total P, Mn, organic N, Fe, Al speciation.

5. Outputs

Daily mean flow. Weekly spot samples analysed in the same way as bulk precipitation and throughfall.

The frequency of the measurements differs: at least daily resolution is obligatory for meteorological and hydrological parameters, sampling for chemical analysis is usually done weekly while some kinds of surveys are conducted once a year or even less frequently, e.g. the sampling of biomass or soil for chemical analyses.

The basic equipment for small catchment studies is relatively cheap, nevertheless it is beneficial to take advantage of technological progress in data acquisition and processing. Today a wide selection of reliable instruments exists for deployment in remote places. Some automatic recording devices, such as precipitation gauges, are capable of proper functioning without human intervention for several months.

The roofed catchment G1 in Lake Gårdsjön area (SW Sweden) may serve as an example of a well-equipped site. There are several high-technology systems, e.g. microcomputer-controlled watering of the catchment and an extensive set of meteorological and other data collection devices. All data may be transmitted by modem using an ordinary phone line to the Swedish Environmental Institute in Göteborg (Table 1.2).

Table 1.2 Parameters measured continuously in catchment G1 of Lake Gårdsjön, Sweden, available on-line by means of data loggers, modem and telephone line (F.Moldan, personal communication)

Parameter	Number of measuring points	Type of measuring device
Precipitation amount	2	Tipping bucket
Throughfall amount	1	Tipping bucket
Groundwater level	5	Pressure transducer
Runoff amount	4	Pressure transducer
Runoff pH	1	pH electrode

Runoff conductivity	1	Cond. electrode
Runoff water temperature	1	Thermometer
Air temperature	7	Thermometer
Soil temperature	2 profiles	Thermometer
Air relative humidity	3	Humidity sensor
Global radiation	1	Radiation sensor
Wind speed	1	Anemometer
Wind direction	1	Wind direction sensor

The increased technological standard of instruments reflects the general trend to collect more detailed, precise and accurate data on natural processes. Much attention has to be devoted to data quality assurance.

Virtually no study on the small catchment level is confined to the framework of a single scientific discipline. A multidisciplinary approach is not a proclaimed goal but the essential concept and practical method of any study.

1.1.5 MODELLING

An important part of biogeochemical research in small catchments is the development of mathematical models of different types. Many of them are referred to in almost all of the chapters of this volume. Crucial is simulation of the water cycle, but most models take into account also geochemical, hydrochemical, soil and biological processes (see Chapters 2 and 9). As the findings of many disciplines are exploited and synthesized, the models help to establish new understanding and integrate information. The investigators can exploit the abundance of rather precise, laboratory-type data gained *in situ*. Consequently, models can be formulated, developed, tested and finally used for forecasting of future evolutions and changes.

A successful model is a remarkable achievement of its own but modelling has other important spin-offs. Modelling efforts often put pressure on the quality of existing data and lead to filling of data-gaps and therefore stimulate the development of new approaches and methodological advances.

The development of mathematical models should not be seen as a scientific aim. A model once calibrated and verified on a particular catchment provides a multipurpose tool for further analysis. The model can be used to test hypotheses and gain a better understanding of how the catchment behaves

under different conditions in the future, that is, to make predictions. Models also provide a means of integrating measured data collected spatially and temporally from within the catchment and can be used to provide estimates for missing data, again, on a spatial and temporal scale. There are many mathematical models used in individual disciplines of small catchment research. Some of the models try to encompass most of the catchment processes.

The BIRKENES model in its early version built in the late-1970s was a simple hydrological model capable of simulating the pattern of a hydrograph. Later algorithms for predictions of runoff chemistry, namely concentrations of sulphate, chloride, aluminium and base cations were added (Christophersen and Wright, 1981; Christophersen *et al.,* 1982). Further work has shown weaknesses of this model, namely problems with close ties between hydrology and chemistry and inability to deal with dampened signals, such as chloride or oxygen stable isotopes (Christophersen and Neal, 1990). Instead of refinement of the hydrology-based model, the authors of the BIRKENES model prefer today to model streamwater chemistry on the basis of mixing waters of different origins, and, therefore to elucidate water pathways through analysis of chemical composition of the mixing product (Christophersen *et al.,* 1990a).

MAGIC (Model of Acidification of Groundwater In Catchments) is a suitable tool for long-term prediction of changes in average (annual volume-weighted) chemistry of runoff in relation to changes in atmospheric deposition (Cosby *et al.,* 1985, 1986). MAGIC was used for modelling exercises spanning over 150 years in the USA, the United Kingdom and Scandinavia. The logic of this model is the opposite of that of the Birkenes model; hydrological changes are not taken in account, and streamwater chemistry is a function of soil chemical parameters and atmospheric input (see Sections 4.3.2.1 and 12.4 of this volume). MAGIC was modified for regional predictions of acid rain effects on streamwater over Europe.

The Trickle Down Model and Enhanced Trickle Down Model are essentially models based on the concept of alkalinity generation and losses (ETD; Schnoor *et al.,* 1986; Nikolaidis, 1987).

ILWAS (Integrated Lake-Watershed Acidification Study) is probably the most complex model of small catchment biogeochemistry and hydrology. The catchment is subdivided into segments, the soil profile is split into layers of different hydraulic and chemical parameters (Chen *et al.,* 1982; Goldstein *et al.,* 1984; Gherini *et al.,* 1985). The model requires an extensive data base, which makes it difficult to use in studies, which were not specifically planned to produce input data for this model.

1.2 SMALL CATCHMENT PROGRAMMES

The hydrologist's interest in small catchments is very old; the tradition of hydrologic studies of small catchments started more than 100 years ago. Early hydrological studies were summarized for instance by Keller (1988). In spite of this tradition, "hydrochemical" or rather "biogeochemical" studies started much later. The first such data came from the Hubbard Brook Experimental Forest in the early 1960s (Bormann and Likens, 1967). However, about ten years later extensive biogeochemical studies were initiated in other parts of the world: in the USA (Correll, 1977), in Scandinavia (Drabløs and Tollan, 1980) in Germany, Switzerland, Czechoslovakia and elsewhere. Recently Hornung *et al.* (1990) have compiled data of hydrochemical budgets for 35 small catchments in Western Europe; most probably other studies, especially outside the European Community, remain unnoticed.

Small catchment research is no longer restricted to intensive work on a single site, isolated from the outer world. It is obvious that it is highly beneficial to compare data gained at a suite of different sites to seek commonalities and differences and patterns within the observed web.

Small catchments are coupled to networks, aimed at comparison, notably testing of hypotheses derived at

a particular site under different conditions. Already three decades ago Leopold (1962) proposed an extensive network of "benchmark" stations for the United States. The programme of measurements at these sites gradually expanded from purely hydrological observations to more complex projects involving measurements of chemical parameters. These chemical data were used for regional evaluation of the sulphur deposition pattern across the United States (Smith and Alexander, 1986; Lins, 1986).

In several European countries, national networks of small catchments are used as a tool for integrated environmental monitoring. The so-called PMK system. (integrated monitoring) in Sweden is comprised of 18 catchments (Bernes, 1985), and a similar GEOMON network in Czechoslovakia (Moldan and Fottovlaala, 1989) of 14 catchments. Monitoring programmes based on small catchment studies exist in Norway, Finland (Anonymous, 1990) and the United Kingdom.

Under the auspices of the United Nations Economic Commission for Europe, a European programme called Integrated Monitoring (ECE-IM) is under way. Its centre was established in Helsinki, Finland. To date, results from 35 sites in 16 countries have been reported to Helsinki in the pilot phase of the program. Networks of existing catchments are standardized in terms of sampling protocols to enable detection of trends (Nihlgård and Pylvänäinen, 1992). In Scandinavia several monitoring networks employing small catchments are in operation.

The ECE-IM programme extends into Canada, where several well-equipped small catchments have been studied for many years.

Small catchment sites are used in connection with several international projects such as European mapping of critical loads of nitrogen and sulphur or the NITREX (NITRogen exclusion or addition EXperiment), trying to establish criteria for conditions of nitrogen saturation (Wright *et al*., 1992; Dise and Wright, 1992).

ENCORE (European Network of Catchments Organized for Research on Ecosystems) is a programme of the European Community promoting development and testing of process-oriented models describing the behaviour of small catchments in a broad sense (hydrochemical changes, hydrologic pathways, rates of weathering, manipulations) (Hornung *et al*., 1990).

In the USA small catchments are widely used: Herrmann (1990) is proposing their use for national parks monitoring. An actual national network based on small catchments is the Long-Term Ecological Research Network, where both Coweeta and Hubbard Brook are included (Brenneman, 1989). Another small catchment research programme is United States Geological Survey's WEBB (Water, Energy and Biogeochemical Budgets), containing sites in Colorado, Georgia, Puerto Rico, Vermont and Wisconsin (Huntington *et al*., 1993). In Norway, already in 1980 a landmark study on the effects of acid deposition was published, based on small catchment research (Drabløs and Tollan, 1980). The network established in the 1970s is still in operation.

Small catchment studies are also under way in other parts of the world (see Chapter 16). In developing countries, they should be used more extensively as an inexpensive tool for integrated environmental monitoring and assessment. The expansion of small catchment research is directed not only towards new areas but also towards a wider range of natural environments and also towards small catchments on agricultural lands.

1.3 IMPORTANT SCIENTIFIC FINDINGS

1.3.1 HYDROLOGY

The fundamental aspect of the catchment that makes it amenable for use as a unit for hydrologic investigations is the possibility to compute the water budget (see Chapters 2 and 9, this volume). The primary components of the water balance are precipitation, runoff, evapotranspiration and change in water storage inside the catchment. For long-term studies, where the net change in the amount of water stored in the basin is essentially zero, the best estimate of evapotranspiration is obtained as the difference between measured precipitation and runoff, this is better than model-derived values.

Although several methods have been developed to estimate evapotranspiration from meteorological parameters (solar radiation, temperature, relative humidity, wind speed and surface wetness), 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). Evapotranspiration, computed as a residual, has been documented in many catchment studies, e.g. Dunin (1969), Pegg (1970), Ward (1971), Likens *et al.*, (1977), Peters and Murdoch (1985) and Avila and Roda (1990).

Crucial to the understanding of catchment processes, and so to the ability to predict future changes in an ecosystem, is identification of hydrologic pathways within the catchment and the related transit times for water in various biogeological surroundings. Each catchment may be dominated by a particular mechanism depending on climatology and geology and different processes may be dominant in a given catchment at various times as a function of storm intensity and duration, and catchment antecedent wetness.

Transit times for discharging water in a small catchment, that is the time from input to output of single water particles (or equivalently the age of the water at the moment of discharge), vary widely. They may range from minutes, for channel precipitation and water reaching the stream as overland flow, to hours, or a few days for the most shallow groundwater recharged close to the discharge area, to several years for deep groundwater. The transit times are determined by the velocity and pathways of the water particles which in turn are determined by the hydraulic conductivity and the porosity of the soil and bedrock, the rate of groundwater recharge and topography. Transit times also vary from storm to storm in that the wetter the soil and the higher the groundwater table, the larger will be the fraction of short-residence-time water in the runoff. Many studies have shown that water achieves the chemical or isotopic signature of its flowpath or storage medium (Jenkins *et al.*, 1990, Hooper *et al.*, 1990, Robson and Neal, 1990). Water signatured by surface soils is generally rich in dissolved organics and has low pH. Such water is usually of short residence time but comprises a large component of storm runoff at the basin outlet. Water draining deep soils, on the other hand, is conventionally thought to have a longer residence time and is characterized by high concentrations of weathering products and high alkalinity. At the catchment outlet, the changing mix of these waters with different catchment signatures produces the observed response through time. The situation is complicated, however, in that different signatures may be observed from all compartments in the catchment depending on the type of input that causes a hydrologic event. For example, the release of strong mineral acids during snow melt can produce a very different chemical response than an acidic rainfall, and rainfall rich in sea salt can produce a very different chemical response than rainfall rich in sulphate.

Catchments with different hydrologic characteristics show different chemical responses for the same input. For both cases, a key to understanding the different types of response lies, to a large extent, in the catchment hydrology, and, for variations in response within a given catchment, the most important hydrologic characteristic is the antecedent wetness of the catchment.

1.3.2 ATMOSPHERIC DEPOSITION

The term wet deposition is used to denote the input of chemicals to the ecosystem by precipitation, while cloud deposition is used to denote the input by riming and the impaction of clouds with the surface (see

, and , this volume). Fogs can be considered as clouds that are in contact with the surface. In low-altitude catchments, fog droplet capture is rarely an important process of hydrologic input to catchments, but can be a measurable source of chemical input because of generally higher mineralization of cloudwater. The importance of cloudwater interception to the hydrologic and chemical budgets of high-elevation ecosystems is now well recognized.

Gases and atmospheric particles can also be deposited to the biosphere in the absence of precipitation. This process is referred to as dry deposition. The estimate of dry deposition through direct measurements is difficult and a wide variety of techniques have been developed (Hicks *et al*., 1986). These include micrometeorological approaches where the flux of gases and particles is related to heat and momentum transfer, gradient methods where the concentration of a substance is measured at different heights, models coupled to ambient air data and the use of surrogate surfaces. The most promising natural surface analysis methods include foliar extraction and throughfall. Especially the throughfall methods are used widely. Watershed mass balance is used for estimation of dry deposition (notably sulphur deposition) from the difference between measured runoff export and wet atmospheric deposition.

The input of chemical constituents will depend on the physiography of the catchment (elevation, slope and aspect), the nature of vegetation cover and the location of the catchment relative to natural and anthropogenic sources. High-elevation catchments generally obtain a larger portion of chemical inputs via cloud deposition than from wet deposition. Dry deposition of gaseous SO_2 dominates sulphur inputs of forested catchments in regions of heavy pollution loadings; in more pristine environments the dominant atmospheric input of sulphur is wet deposition of SO_4^{2-}.

1.3.3 GEOLOGY, WEATHERING AND EROSION PROCESSES

Weathering and erosion play a major role in shaping the features of the land Surface (see and , this volume). The major compartments are bedrock regolith (including soil), water, atmosphere and biomass.

Physical and chemical weathering converts bedrock into regolith and into the soil on which terrestrial vegetation grows. Erosional processes act to remove the products of weathering. Chemical weathering also plays a major role in determining the composition of natural waters (Garrels and Christ, 1965). The chemical reactions that govern the conversion of bedrock minerals into soil minerals determine the release of dissolved constituents to the waters. By this mechanism, base cations, silica and other essential nutrients are made available to biological systems.

The more reactive the minerals in the bedrock, the greater the concentration of dissolved substances in the water. The chemical composition of natural waters strongly reflects the geology of the catchments in which they originate. The importance of the very small-scale local geological and geochemical features such as veins and other small geochemical bodies may be disproportionately important for the biogeochemical processes in catchments. Erosive processes remove the products of physical and chemical weathering. Water is the primary agent for erosion and transport of the residual materials formed by weathering. Wind becomes an increasingly important agent in arid climates. The thickness of weathering products in a catchment is dependent on the rate of production (weathering) vs. the rate of removal (erosion). Water quality is also influenced by erosional processes. Waters draining catchments in which erosion is rapid usually contain a heavy load of suspended sediment and are turbid.

A decrease in soil thickness leads to decreases in water retention capacity and consequently to an increase in runoff from the catchment. Stream response to storm events is more rapid in catchments with thin soils. The opportunity for water to contact and react with bedrock minerals is greater in catchments with thin soils than in those with a thick cover of weathering products, consequently, water chemistry

reflects the bedrock mineralogy more closely in these catchments.

The geology of the basin is also the main factor controlling the distribution of flow rates and streamwater chemistry, especially at the lowest flows observed. Thus, the lower end of the flow-duration curve is a valuable means for studying the effect of geology on the groundwater runoff to the stream. The type, thickness and distribution of surficial materials, for many catchments particularly in glaciated terrain, determine the hydrologic characteristics of groundwater storage. Watersheds containing 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. 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. Sedimentary rocks, limestone and sandstone sustain flow better than igneous rocks, as do basalts and other extrusive igneous rocks. However, fractured igneous rocks have a larger groundwater storage which can sustain flow better than unfractured igneous rocks.

The development of weathering models applicable to catchment research has suffered from differences of perspective between Earth and ecosystem scientists. Earth scientists have a long tradition of studying weathering and denudation as a control on water chemistry. Recent models developed from this perspective tend to be complex and require information that is difficult, if not impossible, to measure in a catchment. On the other hand, recent interest in the acidification of surface waters and soils has resulted in the development of general-purpose biogeochemical models in which weathering is one of several element "inputs". Models developed from this perspective tend to oversimplify the weathering process. The gap between these two perspectives is gradually narrowing and the development of models suitable for estimating weathering rates in the field is currently one of the most active areas of research in weathering.

1.3.4 SOIL SCIENCE

Biogeochemical processes in the terrestrial environment dominate the hydrochemical response of small catchments, because streamwater is largely made up of drainage water from soils. Apart from biochemical processes including interactions between biota and the atmosphere and interactions between biota and soil solution, most important are interactions between solution and the soil solid phase (e.g. cation exchange, adsorption, chemical weathering) and chemical reactions in solution (e.g. hydrolysis, complexation reactions) or between solution and atmosphere (e.g. degassing of CO_2). Key reactions involve inorganic C, organic C, SO_4^{2-}, PO_4^{3-}, Al, N and cation exchange. Reaction equilibria and kinetics are largely determined by soil chemical properties, which result from geological processes and subsequent soil formation (see Chapter 5, and also Chapters 4, 6, 8, 10, 11 and 16, this volume).

Soil formation is the long-term vertical differentiation of physical, biological and chemical properties of rocks and sediments, under the influence of soil formation factors, including parent material, climate, biota, topography and time. Because soil-forming factors generally differ within one catchment, various soil types may result. The importance of specific soil types for streamwater quality depends on the water pathways in the terrestrial system. These pathways may vary as a function of precipitation intensity. Therefore the contribution of Various soils (or soil horizons) to the stream varies dynamically with runoff.

In this century large emissions of SO_2 and NO_x from burning of fossil fuels and industrial processes have greatly increased the acidity of atmospheric deposition in every major industrialized country. Weathering reactions are capable of neutralizing this increased acidity only in catchments developed on reactive rock types. However, the weathering reactions can be overwhelmed by the increased acidity in catchments on slightly reactive rock types and then the process of acidification starts up, i.e. the pH of soils and waters decreases, dominating cations (Ca, Mg, K) are leached. The detrimental changes in the

soils may become irreversible.

Experimental additions to acidic soils at Lake Gårdsjön showed that about 40% of the acid sulphate input resulted in base cation loss and 60% in leaching of the toxic acidic cations H^+ and Al^{3+} (Hultberg *et al*., 1990). The increased concentrations of Al^{3+} cause a retention of phosphorus that precipitates in the mineral soils and becomes less available for root uptake. Foliar analyses have shown malnutrition for Ca, Mg, K and P in forest-decline areas.

1.3.5 BIOLOGY

Principal biological processes studied at an ecosystem level in forested catchments have been primary productivity and nutrient balance including the effects of leaching of nutrients and organic matter from forest canopies and different soil horizons, forest damage, decomposition and the chemistry of groundwater and surface water. Some studies have also been done on evapotranspiration in whole catchments (see Chapters 6 and 11, this volume). Historical data are of utmost importance in understanding long-term changes within catchments; organic sediments in swamp forests, streams and lakes, their pollen content, plankton species and chemistry have been investigated.

Biota are extremely important for understanding the input-output budgets of catchments. Organisms cause accumulation of organic matter and nutrients most needed for biomass production. These are kept in circulation in the ecosystem, usually with only minor losses when the ecosystem matures and is left undisturbed by man. Nitrogen, often a growth-limiting element, is almost entirely organically bound within the catchment. Different heavy metals, of importance to both the catchment and the neighbouring ecosystems, behave very differently in accumulation and transport mechanisms. We still have insufficient estimates of these elements in catchment biota to understand whether their contents in biota derive from dissolution in the soil or from dry and wet deposition.

Organic matter, alive or dead, changes the incoming precipitation with respect to both quantity and quality. A great part of deposited heavy metals accumulate in the catchment, bound to organic matter. Runoff concentrations seem to be correlated to soil acidification and leaching of soluble humic substances. Greater losses of nutrients may appear after disturbance by insects and larger herbivores, wind-felling, etc. Detritivores within streams have important effects on the amounts of transported organic matter.

Quantitative estimates at a catchment scale are lacking of microbial transformations of nutrients in relation to nutrient availability, mobilization and loss. For example, denitrification is one of the key processess in the cycling of nitrogen, but there are few estimates of this process on a catchment basis. There is also need for concurrent quantification of productivity and nutrient cycling processes on the same catchment for different forest ecosystems.

1.3.6 FORESTRY

The significance of the influence of different forestry practices and forest events on water yield, water quality and other parameters in small catchments has been studied for more than a century. The effects of clearcutting, forest dieback and various manipulations were determined (see Chapter 17, this volume).

Between the diverse processes operative and studied in forests, we are especially concerned with the study of changes in chemical composition and magnitude of the water flux. Water takes part in the processes of weathering and soil formation, it is consumed by microorganisms and plants and it may be stored in groundwater reservoirs. The exact nature of links of certain processes to the water flux is not obvious. For instance, measurement of groundwater loss across a topographical water divide remains

beyond the possibilities of today's researchers.

Transpiration, interception and, therefore, evapotranspiration are generally reduced with forest harvesting, which produces more soil water available for the remaining plants and/or increased water movement to streams or groundwater. The quantity of extra water produced depends on a combination of factors, including the amount and type of forest vegetation, soil type, intensity and pattern of cutting, and climate of the area. Conversely, establishment of forest cover on sparsely vegetated land generally decreases water yield. The influence of manipulated vegetation on water yield is greatest for conifers, followed by deciduous hardwood, brush and grass cover (Bosch and Hewlett, 1982). Water yield increases due to cutting or yield decreases due to planting are largest in high rainfall areas. However, clearcutting effects are shorter lived in high rainfall areas than in low rainfall ones because vegetation regrowth is more rapid.

Small catchment experiments have also shown that forest management activities such as species conversions can produce dramatic changes in water yield. Conversion of mixed hardwood forests to white pine plantations in the southern Appalachian Mountains reduced water yield only 10 years after planting. By age 15, water yield reductions were about 20 cm (20%) less than expected for a hard- wood forest (Swank and Douglass, 1974).

In some regions quantitative relationships are available to predict water yield responses to silvicultural activities. However, it is difficult to extrapolate single and even multiple catchment results in both time and space with a high degree of confidence and methods are needed that realistically link cause-and-effect relationships.

Reduced evapotranspiration after cutting means less potential storage of soil water during storms which, in turn, contributes to peak flow rates and stormflow volumes. Harvesting has minimum impact on the storm hydrograph in the winter months when both cut and uncut catchments are fully recharged (Lull and Sopper, 1967). Cutting causes more rapid snowmelt in the spring which may increase peak flow rates. The type of harvesting method and associated soil compaction from logging roads and skid trails is the major factor that increases stormflow (Harr *et al*., 1979).

Catchment experiments have provided important insights into the magnitude of the effects of forest management activities on water quality. Characteristics most affected are sediment load, dissolved nutrient concentrations, and temperature. Changes in stream water nutrient concentrations following cutting vary substantially between localities. For example, in Central and Southern Appalachian forests, only marginal increases in concentrations of NO_3^-, K^+, and other constituents have been observed following cutting (Swank, 1988). In contrast, clearcutting in northern hardwood forests may result in large increases in concentrations of some nutrients (Hornbeck *et al*., 1986).

Many hydrological data were collected on catchment basis even before the importance of this concept was fully realized by researchers. Long-lasting records of hydrological phenomena are available for numerous sites, as Coweeta Hydrologic Laboratory in North Carolina, United States or Valdai Hydrological Laboratory in the Russian Republic.

1.3.7 ELEMENT BUDGETS

Determination of input and output budgets for a catchment or a lake is an established research tool in environmental studies and provides insight into the various geochemical and biological processes operative in a lake system or stream catchment (see Chapter 8, this volume). Mass balances carry important information leading to formulation of mathematical models for predicting the chemical concentration and resultant effects of a particular substance under various input-output conditions. For

example, dynamic watershed-acidification models are now widely used to predict the response of surface water chemistry to changes in atmospheric deposition (ILWAS, MAGIC) (see Chapter 12, this volume).

The most accurate estimate of the mass output from a catchment is calculated from continuous concentration and discharge measurements. Numerous methods have been reported for combining continuous flow information with periodic chemical information to estimate dissolved and particulate export from small basins (see Chapter 7, this volume).

One use of input-output studies is to compare the chemical input from atmospheric deposition to export from the catchment for inferring biogeochemical processes active in a particular basin. General observations from diverse catchments in North America and Europe include a strong retention of input H^+ and NH_4^+ in the terrestrial basin, variable rates of NO_3^- export relative to input, and SO_4^{2-} outputs comparable to or greater than deposition input.

The most extensively studied chemical elements in small catchments are sulphur and nitrogen (see Chapters 10 and 11, this volume). Quantification of the total sulphur atmospheric input into a catchment is critical for most studies of biogeochemical cycling of sulphur. Deposition rates vary from 1 to 2 kg ha^{-1} year^{-1} in remote regions to more than 120 kg ha^{-1} year^{-1} in some polluted areas (Hauhs et al., 1989). Over large areas in Europe and North America a large proportion of the sulphur input will be as gaseous SO_2, which is relatively efficiently deposited by dry deposition to forests. Thus in forested catchments in polluted areas normally a greater proportion of the deposition is due to dry deposition.

Although the input of sulphur by precipitation has been monitored in all catchment studies of sulphur biogeochemistry, only the limited number have considered the deposition by dry and cloud deposition, and included this in estimates of the total input to the catchments.

Recently it has been shown that sulphur dry deposition in areas with no or negligible sulphur retention in the soils may be estimated from the difference between streamwater export and wet deposition input. Since this method is indirect it is important to validate this result. A number of studies show that throughfall plus stemflow and runoff can be used in some cases as an independent estimate of total atmospheric input (Hultberg and Grennfelt, 1992; Likens et al., 1990).

Another mean of verification, model prediction, now seems to have reached a standard where it can give reasonably good estimates of the dry and cloud deposition at least to a number of well-defined receptors (Lindberg et al., 1990, Fowler et al., 1991). Monitoring of SO_2 and SO_4^{2-} particulate concentrations as well as wet deposition, fog and cloud concentrations and meteorology are all necessary for modelling the total sulphur deposition to forested catchments and validation of these predictions.

In general, the vegetation pool represents less than 10% of the total ecosystem content of sulphur since the forest floor and especially the mineral soil serve as the major reservoirs of this element. Furthermore, the cycling through the vegetation, as reflected in nutrient demand or litterfall, is generally small compared with other fluxes such as total deposition or throughfall for most forest ecosystems. This is due to the relatively low nutrient demand for sulphur compared with other elements such as nitrogen and calcium.

Quantification of sulphur budgets in catchments may also be helpful in evaluating the importance of gaseous emissions with respect to both ecosystem balances and the contribution of terrestrial emissions to the global sulphur cycle. Gaseous emissions of H_2S and other reduced sulphur compounds occur from wetlands and tree canopies from forested catchments in northern Europe, but no quantitative data are available (Hällgren et al., 1982).

One of the most important effects of sulphur deposition on forest ecosystems apart from direct effects of SO_2 and H_2SO_4 on needles and leaves is the extensive acidification and leaching of nutrients that have occurred in forest soils during the last 50 to 100 years in northern/central Europe and probably in large parts of North America (Paces, 1982; Tamm and Hallbäcken, 1988; Reuss and Johnson 1986; Schulze and Freer-Smith, 1991; Hultberg and Likens, 1992). The loss of base cations like calcium, magnesium and potassium causes malnutrition to coniferous and hardwood forests over large parts of Europe. The loss of base cations has been shown to be quantitatively related to the speciation of the cation deposited together with the sulphate, where H^+ and/or NH_4^+ together with the leaching of sulphate cause a concomitant release of either basic nutrients (Ca^{2+}, Mg^{2+}, K^+) or toxic acidic (H^+, Al^{3+}) cations.

Nitrogen is an essential nutrient element required by plants in substantial quantities. The nitrogen cycle is perhaps the most complicated among the plant nutrient cycles. This diversity and complexity complicate the study of nitrogen cycling in ecosystems and even more in complex terrains such as a catchment. Nitrogen is considered as the growth-limiting factor of most terrestrial ecosystems, and natural ecosystems are characterized by a tight internal cycling of nitrogen. Leaching losses and gaseous losses are generally less than a few kg N ha^{-1} year^{-1}. High leaching losses may, however, occur after a disturbance of the system. Nitrogen leaching is easily detected in the stream output of a catchment and may be related to major changes in the catchment such as forest clearcutting or dieback, changes in management or fertilizer input.

Concern about nitrogen in the environment appeared later than in the case of sulphur and was very much stimulated by observations of nitrogen leaching in hydrochemical budgets. The interpretation of the budgets is much more difficult for nitrogen than for sulphur. This problem can be illustrated by the biogeochemical cycling of sulphur and nitrogen in a forest plantation where input and output of these elements are comparable, but the internal cycling and the soil pool of nitrogen is a factor 30 higher than for sulphur.

The atmospheric nitrogen load to forests in Europe and North America has increased dramatically during recent decades due to emissions of NO_x from combustion processes and of NH_3 from agricultural activities. Nitrogen deposition to forest ecosystems generally exceeds 20 kg N ha^{-1} year^{-1} in most of Europe and even reaches 100 kg N ha^{-1} year^{-1} in some areas (Ivens *et al*., 1990; Hauhs *et al*., 1989). Forest ecosystems may accumulate considerable amounts of nitrogen in biomass and soil organic matter, but there is an increasing concern that forest ecosystems may be overloaded with nitrogen from atmospheric deposition. Actually, increased leaching of nitrate has been observed in several areas of high nitrogen deposition. Forest ecosystems have some kind of maximal capacity to immobilize nitrogen in soil and biomass. Other nutrients, water or light may become limiting for the primary production. This state of the ecosystem is often referred to as *nitrogen saturation*.

Nitrogen saturation is a well-known phenomenon in agricultural systems where excess fertilizer nitrogen loadings in combination with crop removal, soil tillage, etc., result in open systems with high input-output fluxes. This cycling situation can be described as *agrogeochemical*. Excess nitrogen deposition and/or fertilizer application causes nitrate leaching by direct leaching (lack of plant uptake or microbial immobilization) and stimulation of mineralization of soil organic matter. These factors contribute to depletion of long-term soil fertility, increasing soil acidity and, eventually, acidification and eutrophication of surface waters. Excess nitrogen availability may increase denitrification and production of nitrous oxide, which affects ozone levels and global warming. Nitrate leaching is an easily measurable indicator of a disruption in the terrestrial nitrogen cycle, and often it may be the only one. Changes in nitrate leaching, i.e. increased leaching or changes in the seasonal pattern, are early warnings of disturbance in the nitrogen cycle.

Among other elements for which the budgets in small catchments were developed, carbon must be mentioned. Of particular hydrochemical importance is dissolved organic carbon (DOC). It often plays a major role in determining the acid-base and metal complexation characteristics of soil water and streamwater (see Chapter 12, this volume).

The small watershed approach is an effective tool to facilitate understanding of transport and cycling of trace metals in forest ecosystems, and subsequent effects on surface waters. However, care must be exercised in the collection and analysis of samples for trace metals. Many values of trace metal concentrations reported in the literature are in error because of contamination (Barrie *et al.*, 1987). The geochemistry and bioavailability of trace metals are strongly influenced by speciation. Studies in small catchments have contributed to the elucidation of biogeochemical cycling of trace metals, as shown by case studies described in this volume, dealing with Al, Pb, U and Hg (see Chapter 13, this volume).

1.3.8 SHORT- MEDIUM- AND LONG- TERM CHANGES

In small catchments, stream discharges can vary greatly with rapid flow increases during prolonged heavy rain or snowmelt especially in small basins with steep slopes and thin soils. Runoff generally subsides rapidly once precipitation ceases. Concomitant with these fluctuations in stream discharge, the chemical composition of stream water can vary substantially. Common observations include a sharp decline in alkalinity and pH, Si, Ca^{2+}, Mg^{2+} and Na^+ with increasing flow. By contrast, the concentrations of dissolved organic C, K^+, Fe and Al tend to increase (Cresser and Edwards, 1987; Hooper and Shoemaker, 1985; Sullivan *et al.*, 1986). These changes in streamwater chemistry during storm or snowmelt events are attributed to varying water pathways in the subsurface, involving, for example, alterations from micropore to macropore flow or changing contributions from various soil horizons (Mulder *et al.*, 1990). When hypothesizing variable flowpaths, it is implicitly assumed that each water pathway gives rise to a characteristic solution composition related to the chemical controls afforded by different soil environments (see Chapter 12, this volume).

It seems that most of the seasonal variations in streamwater chemistry are driven by climatic (e.g. evaporation, precipitation quantity and quality, temperature) and biotic factors (e.g. nutrient assimilation, mineralization, nitrification, production of organic acids, transpiration). Therefore, similar to the short-term variations, seasonal variations are largely governed by the processes taking place in the terrestrial part of the catchment.

Changes occurring over several years, decades or even centuries may be related to changes in soil chemical, biological or physical properties, or changes in forest status. Long-term monitoring programmes of chemical parameters in streamwater are required to detect such changes directly and to date, only few such data sets (up to 25 years) exist (Driscoll *et al.*, 1989; Christophersen *et al.*, 1990b). Data records have been collected in forested ecosystems in northeastern North America and northwestern Europe that are affected by acidic deposition. These multi-year data series show a general decline in the concentration of base cations in runoff waters. It is hypothesized that this decline relates to a decrease in base saturation due to prolonged leaching of base cations from the already base-poor soils that characterize these catchments.

Also observed at these sites is a downward trend in streamwater SO_4^{2-} during the last decade that coincides with a decrease in the atmospheric deposition of SO_4^{2-}. The contemporary decrease in base cations and input acidity suggests that the rates of mineral weathering in these catchments are still too low to replenish the stores of exchangeable base cations. A decrease in a soil base saturation is expected to be associated with a decline in soil pH and an increased solubility of soil-bound trace elements and Al.

Chemical evolution of surface waters occurs largely in the terrestrial environment. However, some variability may be related to processes occurring within the aquatic environment. For example, stream-channel CO_2 degassing (e.g. Reuss and Johnson, 1985, 1986) and cation exchange with streambed material (e.g. Henriksen *et al*., 1988) can significantly alter the ionic composition on at least an episodic time scale. In-lake alkalinity generation is a process that may also cause temporal variability on a seasonal scale.

To understand ongoing processes in catchments we should probably look far backwards. In the temperate zone of the Northern Hemisphere most existing catchments were deglaciated about 12 000 years ago, when a warmer climate appeared. Results from catchments in New England, USA (Ford, 1990), illustrate the importance of chemical changes in the long term, coupled with simultaneous changes in biota. Palaeoecological methods were used to test the hypothesis of natural ecosystem acidification (Ford, 1990). Chemical analyses of fractionated sediments indicated historical change in the inputs of major elements including aluminium, manganese, iron, silicon and calcium. The analyses revealed patterns of biogeochemical cycling, weathering and soil formation, which affected the historical dynamics of the terrestrial and aquatic communities resulting in enhanced pH changes.

1.4 MANIPULATION EXPERIMENTS

Very specific for small catchments are manipulation experiments enabling one to verify hypotheses derived from monitoring of undisturbed catchments. The most common way of performing these experiments is setting up paired catchment design, e.g. manipulating a catchment, for which there is a control catchment, reasonably similar in a number of physicochemical, biological and hydrological parameters. Manipulation may consist of exclusion of pollution input, addition of nutrients or toxic elements or change in land-use (deforestation or reforestation).

The RAIN Project in Norway (Wright and Henriksen, 1990) was set up to determine whether widespread acidification of freshwaters in southernmost Norway is reversible, e.g. whether lakes and streams will become neutral and fish will reappear following a decline in atmospheric pollution, or, whether soils were damaged by decades of acid input to such an extent, that acidic waters have little chance of returning to their pre-industrial chemistry. Similar objectives but also taking into account problems of forest growth led to initiating of the ROOF experiment in the 6000 m^2 catchment G1 at Gårdsjön Lake on the West coast of Sweden (Dise and Wright, 1992), starting in 1991 and the Danish Klosterhede Project, where a 1200 m^2 roof was constructed beneath the canopies of a spruce stand in 1988 (Rasmussen,1991).

In western Norway non-polluted precipitation falling into a catchment at Sogndal was artificially acidified while in southernmost Norway at Risdalsheia acid rain was excluded from two catchments by means of an extensive roof (KIM-860 m^2, EGIL-400 m^2 and both catchments were artificially watered (Wright and Henriksen, 1990). In western Norway acidification of precipitation resulted in acidification of runoff and an apparent increase in the net output of calcium and magnesium. In southernmost Norway an exclusion of acidic precipitation and its replacement with the same amount of 'pre-industrial' rainwater resulted in the release of organic acids and sulphate. The decline in strong-acid anion concentrations was compensated by a decrease in base concentrations and an increase in alkalinity. The net sulphate loss in the first 3.5 years of the manipulation was about 45% of the pool of readily available sulphate in the soil before commencing the treatment (Wright and Henriksen, 1990). At present, these roofed catchments are subject to another kind of manipulation: the roof will be converted into a greenhouse, and temperature and CO_2 concentration will be raised to examine potential impact of global warming on vulnerable ecosystems (Jenkins *et al*., 1992).

Sulphur was experimentally added to two forested catchments of Lake Gärdsjön in Sweden (Hultberg *et al.,* 1990). The same sulphur load, 200 kg S ha^{-1}, had different impacts on runoff chemistry, depending on the form of the added sulphur. Neutral sodium sulphate treatment generated rapid outflow of sulphate and sodium; 95% of added sulphate and sodium left the catchment within three years after the manipulation and concentrations of all affected elements (S, Na, H$^+$, Al, Mg, Ca) returned to their pre-treatment levels. Elemental sulphur affected the system in a gradual but more fundamental way. A build-up of streamflow sulphate concentrations started only in the second year after treatment and it still continues. The same holds true for stream acidification, and increased leaching of Al, Mg and Ca. Soil reserves of Mg were markedly depleted and even shallow groundwater acidified.

Experimental additions of chemicals are more often performed on the scale of plots, e.g. EXMAN (EXperimental MANipulation of forest ecosystems in Europe), a project studying additions of fertilizers to forests in five European countries (Rasmussen, 1990, 1991). A similar project named NITREX is focused on nitrogen addition or exclusion, to test the hypothesis of nitrogen saturation of European forests; two NITREX sites are small catchments (Dise and Wright, 1992).

A number of small catchment studies deal with the impacts of deforestation or reforestation. The Hubbard Brook catchment W2 was deforested in 1965 in order to evaluate changes in element flux and water budget (Likens *et al.*, 1970) and catchment W5 was commercially clearcut in order to test hypotheses derived from W2 deforestation (Fuller *et al.*, 1987). Repeated cutting experiments at Coweeta have demonstrated an increase in streamflow following the clearcut. The main increases occurred through the vegetation season as a consequence of reduced evapotranspiration (Swank *et al.*, 1988).

1.5 ENVIRONMENTAL PROBLEMS STUDIED IN SMALL CATCHMENTS

Many environmental questions and problems of husbandry of natural resources were studied in small catchments. This is documented in the second half of this volume, i.e. in Chapters 9, 10, 11, 12, 13, 14, 15, 16, and 17. The results contributed considerably to better management and small catchment research often elucidated causal relationships.

Very detailed studies of atmospheric deposition of acidic or acidifying substances were performed in small catchments. These contributed substantially to present knowledge of this process. Acidification of soils and surface waters and accompanying effects like leaching of nutrients, enhanced rock weathering or aluminum mobilization are further important adverse processes elucidated by studying small catchments.

Different types of land-use have profound effects on biogeochemical metabolism as a crucial factor of landscape ecological stability. The study of runoff parameters is essential in this context. Small catchment research helps to determine conditions for sustainable agriculture based on the stability of biogeochemical cycles, retention of water, nutrients and dissolved substances, and erosion minimization.

Extensive programmes of comprehensive environmental monitoring are being conducted in small catchments in Europe and North America. Small catchment networks were established as an indispensable tool in detection and quantification of long-term environmental changes. The analyses of long time series of measurements within small catchments already proved that with knowledge of the biogeochemical processes it is possible to understand the mechanisms and to distinguish between anthropogenic and natural causes of observed changes.

Small catchments can be used as excellent educational tools. Not only do many disciplines from hydrology to atmospheric chemistry to botany to geology participate in small catchment studies, but also

students may learn more through an integrative approach, working in a team, about environmental problems.. Provided that the site is not disturbed by visitors, this is a good opportunity to disseminate ecological education to the public.

1.6 CONSIDERATIONS FOR THE FUTURE

It is envisaged that small catchment research will develop rapidly in the future. Small catchments are excellent sites for long-term ecological research in a very broad sense. We also strongly recommend and envision the establishment of a global network of small catchment sites for multiple purposes of environmental research and monitoring. It has been already suggested that UNESCO's Biosphere Reserves should be used as monitoring sites (Herrmann, 1990). In the context of ECE Integrated Monitoring Programme, studies in small catchments are used for determining and predicting the state of ecosystems in a long-term perspective, specifically with respect to spatial and time variations of air pollutants (Nihlgård and Pylvänäinen, 1992).

Small catchment research is relevant in relation to the study of global change (Eddy, 1992) and we hope that some connection will be established with ICSU's International Geosphere-Biosphere Programme (IGBP).

Several factors should be stressed:

1. The "geo-bio" connection. Small catchment studies pinpoint the importance of integration of scientific disciplines. Especially important is the synthesis of disciplines dealing with living and non-living components of the biosphere.

2. Monitoring of expected climatic change. Investigators are already preparing methods for assessing possible effects of climatic change.

3. The local-global link. Small catchment research may contribute to the establishment of the vital link between local findings and global synthesis. We stress two important factors. First, methods used in the catchments and their results are becoming widely standardized, their quality is usually good and so the data can be compared. Second, the precise, accurate and complete description of ecosystems within a small catchment may serve as an ideal "reference" for an evaluation and scaling of satellite or other remote sensing methods.

4. There are many specific recommendations for future research given in this book. Here we will try to stress only the most important ones:

  a. Long-term continuation of measurements in existing representative or experimental small catchments.
  b. Intensifying studies in hydrology, hydrochemistry, atmospheric deposition research, biology and other "small catchment disciplines" and enhancing data quality of all collected data.
  c. Development of conceptual and mathematical models.
  d. More extensive use of inter-site comparison, nested and paired catchments.
  e. Chemical and physical experiments and manipulations especially aiming to provide information on responses to perturbations.
  f. Intensifying research on biogeochemistry of minor elements, especially heavy metals, and organics.
  g. Focusing on the observation of events and their effects, and on long-term changes.

h. Refining measurement protocols to fully utilize the potential of experimental and representative small catchments as tools for comprehensive, reliable and relatively inexpensive integrated environmental monitoring tools.
i. Developing methods to link results of small catchment studies to large-scale units (regionalization).
j. Expanding the small catchment network, especially to the tropics and developing countries, aiming to establish a truly global network covering regions representative of different biomes and areas under anthropogenic stresses.

1.7 SUGGESTED READING

The classical work from the field of small catchment research is the summary volume of Likens *et al.* (1977) summarizing the first 15 years of research at Hubbard Brook, NH, USA.

Among the more recent works, in prominent place are volumes of Andersson and Olsson (1985) and Swank and Crossley (1988a). European experience is summarized and extensive bibliography is included in the volume of Hornung *et al.* (1990).

Papers devoted to a small catchment research appear in a number of journals- the highest rate of their occurrence is known for *Water, Air and Soil Pollution, Journal of Hydrology and Water Resources Research*.

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