SCOPE 51 - Biogeochemistry of Small Catchments

17 Small Catchment Research in the Evaluation and Development of Forest Management Practices

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17.1 INTRODUCTION

The hydrologic literature is replete with examples of the use of small catchment experiments to examine the effects of forest management practices on water resources. Examination of hydrology symposia in recent years indicates that approximately 20% of the papers deal with some aspect of land-use activities and hydrologic interactions. It is not our intent in this chapter to review this voluminous literature, but rather: (1) to provide briefly a historical background on the topic; (2) to outline some philosophical and conceptual approaches in using small catchments to evaluate forest management activities; (3) to illustrate the benefits and limitations of these approaches through select examples; and (4) to suggest topics considered to be of high priority for future research.

17.2 HISTORICAL BACKGROUND

The roots of forest hydrologic investigations are embedded in basic questions of the relationship between forests and runoff. The historical development of small catchment research in a number of countries is provided in the formative volume *International Symposium on Forest Hydrology* (Sopper and Lull, 1967), the product of a seminar held at the Pennsylvania State University in 1965. Forest hydrologic investigations have a long history and extend over more than a century. For example, two experimental watersheds were established in Czechoslovakia in 1867 in the upper reaches of the River Becva in Moravia to examine the role forests play in surface runoff (Nemec *et al.*, 1967). In later years, controversy over the hydrologic influence of forests on floods led to establishment of additional experimental watersheds (Valek, 1962). In 1902, paired experimental watersheds were established in the Emmental region of Switzerland to study the effects of deforestation and intensive use of mountain lands on flood flows and sediment transport (Keller, 1988). Subsequently, in the United States, concern about soil erosion, flood control, sustained streamflow and dwindling timber resources led to establishment of forest reserves (National Forests) from the public domain lands in the West in the early 1900s. In fact, enactment of the Weeks Act of 1911 was based on the role of forests in regulating the flow of navigable streams.

The first catchment experiment in the United States was initiated in 1909 to measure streamflow before and after removal of trees at Wagon Wheel Gap in Colorado (Bates and Henry, 1928). The need for scientific studies of factors controlling floods and erosion was accentuated by the disastrous 1927 flood in the Mississippi River Basin. Attendant controversy over the role of forests in regulating streamflow led to formal establishment of watershed management research by the USDA Forest Service. For example, the Coweeta Basin in North Carolina was selected as a site for a hydrologic laboratory in 1931. As reviewed by Douglass and Hoover (1988), the research approach at Coweeta encompassed the hydrologic cycle with studies of basic hydrologic processes on individual experimental basins to determine the principles underlying the relation of forests to the supply and distribution of water. This approach formed the template for other Forest Service watershed management programmes which followed in the period 1940-1955. The recent development of small catchment programmes in Europe has been partially reviewed by Keller (1988) and the evaluation of forest hydrology in Europe is summarized by Brechtel (1982). Many projects were implemented in the period 1960-1980 including a number of European catchments studies in connection with forest dieback, namely in Germany.

Indeed, the development of experimental watersheds as a research tool was a direct result of the need to understand the influence of forests and related management activities on water resources. Controversy about the influence of forests on floods and concern about erosion frequently provided the stimulus to develop research programmes.

17.3 CONCEPTUAL CONSIDERATIONS

A basic premise of many experimental watershed programmes is that human activities on the landscape ultimately have some influence on the water resource. It is universally possible to examine the use or misuse of land by measuring the properties of surface or subsurface waters draining forest ecosystems. Thus, alteration of the quality, quantity, or timing of water flowing from the land can be viewed as a sensitive indicator of the long-term success or failure of land management programmes (Hewlett, 1964). An equally important tenet of small catchment research is that good resource management is synonymous with good ecosystem management (Swank and Crossley, 1988a). The utility of catchments as a basic unit for examining human-induced effects on forest structure and function has been demonstrated in many regions of the world. In all cases, water is a common thread since it is the primary mechanism for transporting substances within and from forested lands.

The design of small catchment studies has emerged from a variety of forest management perspectives including approaches that: (1) demonstrate the deleterious or beneficial effects of prevailing land-use activities or the effects on water resources of different (improved) forest management technologies; (2) elucidate principles of forest hydrologic processes; and (3) meld theory development, experimental testing, modelling and subsequent application of knowledge to management. Obviously, the approach and design of catchment experiments are, or should be, based on specifically stated questions or hypotheses.

The use of small catchments to demonstrate the integrated effects of specific forest management activities on water resources is a very effective approach to address local or regional issues. The demonstration approach usually entails a sequence of "this is what we had", "this was the management activity", and "this was the result" (as measured downstream of the activity at a weir or gauging station). Such an approach can provide both a visual and a quantitative assessment of hydrologic responses to management of sufficient magnitude to either alter or support current practices and provide guidelines for managers and policy-makers. Examples include the demonstration of the effects of alternative logging methods on erosion and stream sedimentation; effects of mechanical site preparation on soil loss; changes in streamflow quantity and timing following forest cutting, species conversion, or alternative land-use practices (i.e. forest to agriculture conversions); and the impacts of pesticide or fertilizer applications on water quality. The literature is replete with examples of these practices and others which provide findings useful for forest resource planning. However, small catchment demonstrations are frequently case histories that are site-specific. Cause-and-effect relationships based on process studies within the catchment may be lacking and extrapolation to other catchments limited. Thus, a major disadvantage of catchment demonstrations is their lack of quantitative prediction and potentially high risk in extending results to other ecosystems.

Small catchment research has been quite successful in establishing hydrologic principles which are essential to interpreting the effects of management practices. Examples include elucidation of mechanisms of water movement down forest slopes; quantification of various components of evapotranspiration and effects on runoff generation; derivation of functional relationships between forest stand structure, evapotranspiration, and runoff; elucidation of the importance of the different forms of precipitation on the quantity and timing of runoff; and quantification of differences in hydrologic processes between different forest types. Enhanced understanding of principles provides a basis for predicting and interpreting hydrologic responses in relation to a variety of management prescriptions.

Perhaps the greatest management benefits to be derived from catchment experiments are from studies that link sound theoretical development with appropriate experimental testing, including process-level research conducted concurrently with the management prescription (Figure 17.1). This design encompasses the other approaches and frequently leads to the modification and/or development of models that are testable at the catchment scale. Thus, the demonstrated effects of a management practice on the water resource can be related to causative factors, providing a sound basis for the prediction and extrapolation of the magnitude of responses in other catchments. This design of catchment studies is an interdisciplinary, integrated approach and usually requires substantial resources to implement. However, it is frequently the best approach to answer complex questions about management effects on forest ecosystems.

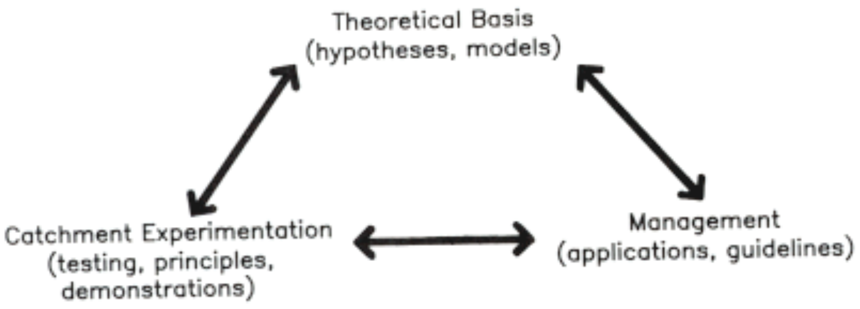

Figure 17.1 Small catchment research yields the greatest benefits when linked with a sound theoretical basis for conducting the experiment. The relevance of theoretical constructs is improved through an understanding of management needs, objectives and forest planning procedures. In turn, the results of catchment experiments are used to revise the theory and, as appropriate, to provide guidelines and improved methods for resource management.

17.4 SELECT EXAMPLES OF APPROACHES

Below we will illustrate the usefulness of small catchments in assessing the effects of various forest management activities on water and soil resources. Many examples could be cited from the literature and we have selected only a few that address the topics of water yield, timing of streamflow, water quality parameters, and nutrient cycling with a focus on soil nutrients and forest productivity.

17.4.1 WATER YIELD AND TIMING OF STREAMFLOW

17.4.1.1 General

Transpiration, interception and, hence, 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, intensity and pattern of cutting and climate of the area. Conversely, establishment of forest cover on sparsely vegetated land generally decreases water yield. These generalizations are based on a review of results from 39 catchment experiments throughout the world (Hibbert, 1967). The addition of 55 experiments to the data base (Bosch and Hewlett, 1982) support these generalizations. It was additionally inferred from the world literature that the influence of manipulated vegetation on water yield was greatest for conifers, followed by deciduous hardwood, brush and grass cover (Bosch and Hewlett, 1982). Water yield increases due to cutting or decreases due to planting are largest in high rainfall areas. However, clearcutting effects are shorter-lived than in low rainfall areas because vegetation regrowth is more rapid.

17.4.1.2 Regional examples

Swank *et al*. (1989) provide more specific, quantitative relationships between forest cover alternatives and water yield responses in a summary of effects of timber management practices on soil and water for major forest types in the United States. For example, from catchment experiments involving a variety of cutting intensities in hardwood forests of the Appalachian Highlands Physiographic region of the eastern United States, a generalized response of first-year streamflow increases after cutting is available (Figure 17.2; Douglass and Swank, 1975). First year increases are proportional to the reduction in basal area and also related to the energy available for evapotranspiration (insolation index). Thus, clearcutting a north-facing (0.22 index) hardwood stand increases streamflow about 41 cm while selection cutting in the same stand (e.g. 30% of basal area) increases flow about 8 cm. These generalized relations apply to a major portion of the moist eastern hardwood region and can be refined by considering soil depth and cutting patterns (Swank *et al.,* 1989). Streamflow increases are typically largest in the first year after cutting and decline as vegetation regrows. Streamflow returns toward baseline levels at a rate approximating a logarithmic decay curve and the average duration is commonly six to ten years (Swift and Swank, 1981).

Equations for predicting water yield responses to silvicultural prescriptions, based on these catchment results, are available for the region (Douglass and Swank, 1975) and have frequently been used as a tool in forest management planning. Their usefulness has been further tested in a multiple-use demonstration experiment at Coweeta Hydrologic Laboratory in western North Carolina (Douglass and Swank, 1976). A 144-ha catchment was selected to pilot test water, timber, wildlife and recreation objectives. Silvicultural prescriptions included thinning 39 ha of the highly productive mesic cove forest; clearcutting 77 ha of mid- and upper slopes to regenerate mixed oak forests that had previously been high- graded; and 28 ha of the highest elevation portions of the forest were preserved to protect slopes, provide wildlife cover and provide an attractive setting for a major hiking trail. The cumulative effects of these timber prescriptions on water yield were estimated using the equations previously described and values were compared with measured responses for the entire catchment (Table 17.1). In the early years following harvest, predicted changes were slightly greater than measured values; in later years, the model under- predicted water yield. Year-to-year variability in measured responses is strongly influenced by precipitation amounts and distribution, factors not accounted for in prediction equations. As the harvested forests regrew, water yield increases declined to no significant difference in year nine. For the entire response period, there was little difference between measured and predicted yield increases, with a total yield change of 67 cm. Thus, such equations derived from experimental catchments provide predictions of sufficient accuracy for most planning purposes.

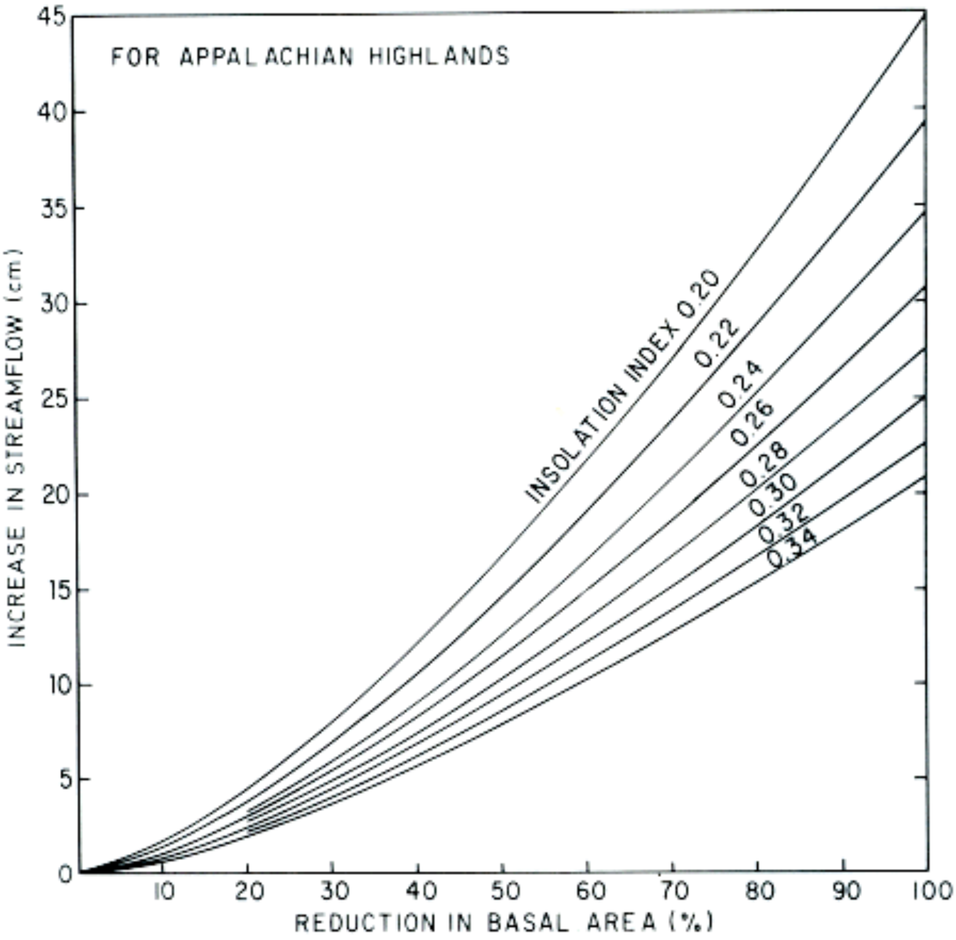

Figure 17.2 Streamflow increases in the first year after cutting a mixed hardwood forest are related to the amount of vegetation cut (expressed as basal area) and the amount of solar radiation received by the forest (expressed as insolation index). The relationships were derived from experimental catchment studies in eastern hardwood forests of the United States (from Douglass and Swank, 1975).

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

Table 17.1 Comparison of predicted changes in annual water yield with measured values for Coweeta WS 28, a 144ha mixed hardwood forest with a combination of thinning, clearcutting, and no cutting

Year following harvest	Measured change (cm year^{-1})	Predicted change (cm year^{-1})

1	16 .5	18 .3
2	10 .2	13 .0
3	7 .9	9 .9
4	2 .3	7 .6
5	2 .8	6 .1
6	8 .1	4 .6
7	10 .4	3 .6
8	8 .6	2 .3
9	1 .0	1 .5
Total	67 .8	66 .9

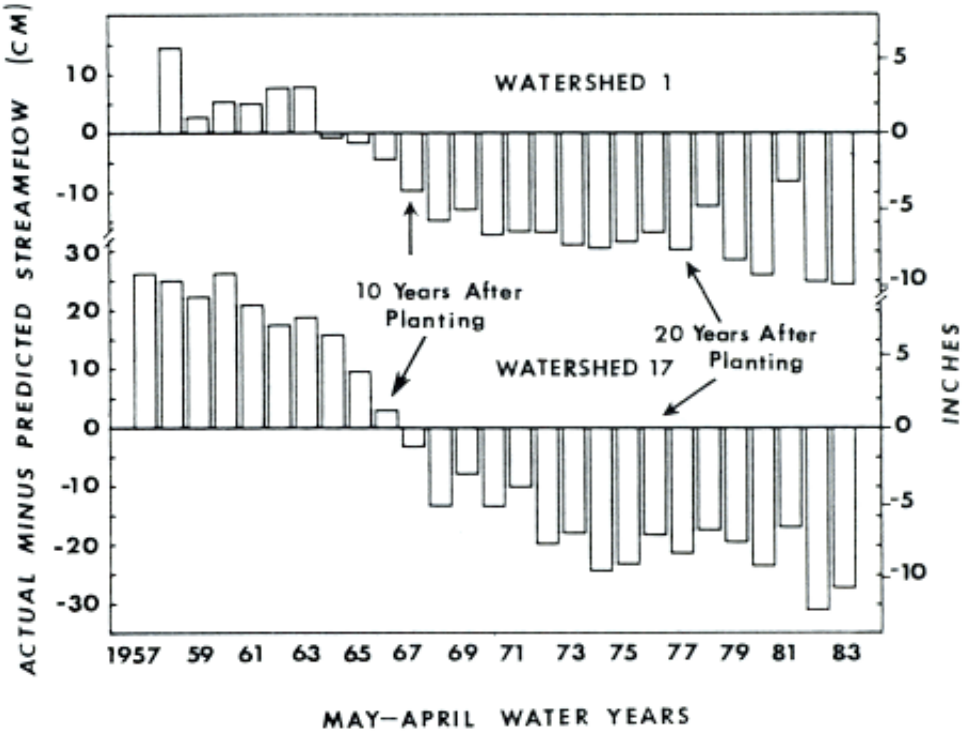

Figure 17.3 Annual changes in streamflow on two Coweeta catchments following clearcutting and conversion from mixed hardwood to white pine (from Swank *et al.,* 1988). About 10 to12 years after planting, evapotranspiration was greater from the pine than from hardwood and, hence, streamflow was less than predicted for mature hardwoods.

Appalachian Mountains reduced water yield only 10 years after planting (Swank and Douglass, 1974). By age 15, water yield reductions were about 20 cm (20%) less than expected for a hardwood forest (Figure 17.3). Reasons for greater evaporative losses from young pine than from mature hardwoods have been described in several reports (Swank and Miner, 1968; Swank and Douglass, 1974; Swift *et al.,* 1975). In another experiment, hardwoods were converted to a grass cover (Hibbert, 1969). Water yield response varied from no significant change the first year after conversion to an increase of 14 cm in the fifth year as grass production declined. Vegetation conversions and comparisons on experimental watersheds elsewhere have also shown large changes in water yield (Feller, 1981; Pearce and Rowe, 1979; Dons, 1986).

It is apparent that findings on water yield from small catchment experiments provide general guidelines for forest and water managers. In fact, in some regions where numerous experiments have been conducted over a range of conditions, 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.

17.4.1.3 Hydrologic models

Modelling provides a logical method for linking forest management catchment experiments with process-level studies. PROSPER, an evapotranspiration simulation model is one example of a hydrologic model developed from and applied to forest catchment studies. The model links atmosphere, vegetation and underlying soils through use of simultaneous equations that combine energy balance, mass transport and soil moisture dynamics (Goldstein *et al.,* 1974; Huff and Swank, 1985). The model has been used to evaluate the consequences of thinning, clearcutting, species conversions and long-term forest succession (Swift *et al.,* 1975; Troendle, 1979; Huff and Swank, 1985). Simulations of evapotranspiration in the Southern Appalachians for mature mixed hardwoods, clearcut hardwoods and white pine plantations showed large differences in timing and water use rates of the cover type (Figure 17.4). Differences in water use could be attributed to alteration of interception and transpiration (Swift *et al.,* 1975). Annual simulated drainage associated with silvicultural practices of conversion from mixed hardwoods to white pine and clearcut forest showed good agreement with measured catchment responses (Table 17.2). The model has also performed well for other forest types in different regions of North America (Vose and Swank, 1992). PROSPER and another streamflow simulator (WATBAL) were further modified to evaluate the impact of silvicultural activities on the hydrologic cycle; subsequently, these methods were incorporated in a handbook to guide best management practices for forest resources (Troendle, 1979).

Table 17.2 Change (cm) in annual streamflow attributes due to conversion from mature oak-hickory forest (from Swift *et al.,* 1975)

		White Pine		Clearcut	
Water year May-April	Annual precipitation	Measured streamflow	Simulated drainage	Measured streamflow	Simulated drainage
1940 /41	154.0	-	-	+36.0	-
1941/42	158.5	-	-	+41.3	-
1963/64	196.0	-	-	+38.1	-
1971/72	198.9	-20 .2	-20 .2	--	+36.5
1972/73	234.3	-18 .3	-16 .9	--	-

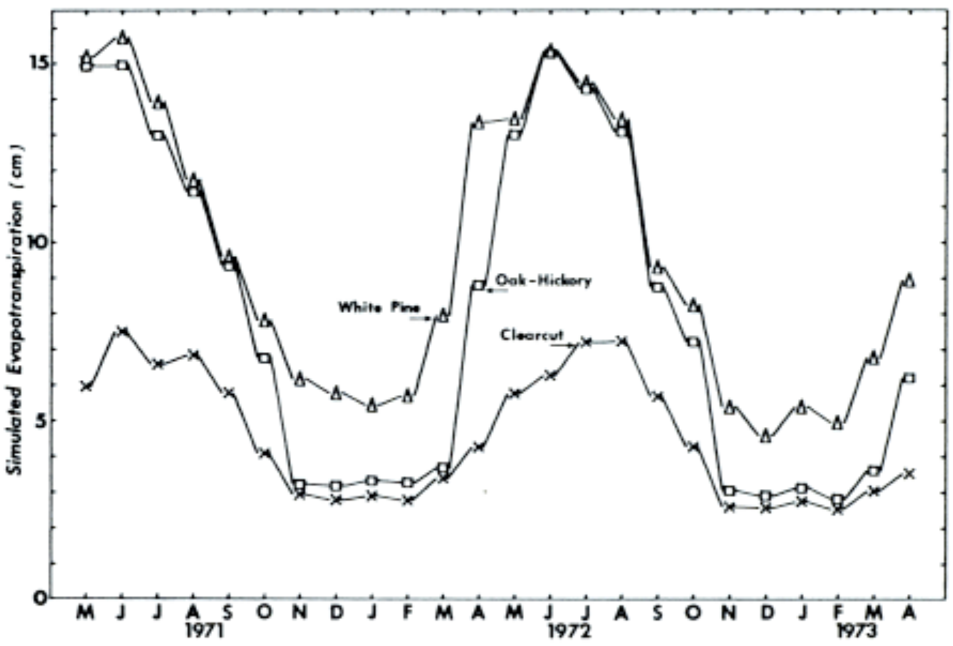

Figure 17.4 Monthly totals of simulated evapotranspiration for a 16-year-old white pine plantation, a mature oak-hickory forest, and a clearcut forest (from Swift *et al.,* 1975).

17.4.1.4 Timing of streamflow

Paired watershed experiments provide a basis for determining the effects of management practices on the intra-annual distribution of streamflow and storm hydrograph characteristics. Annual water yield increases associated with cutting (Section 17.4.1.2) are not distributed uniformly throughout the year. In areas with shallow soils and a snow cover, a large proportion of increased flow occurs in the spring and summer months in direct response to precipitation patterns and evapotranspiration reductions due to cutting. On catchments with deep soils and raindominated precipitation, flow increases are observed in the summer and autumn months and may extend into early winter (Figure 17.5).

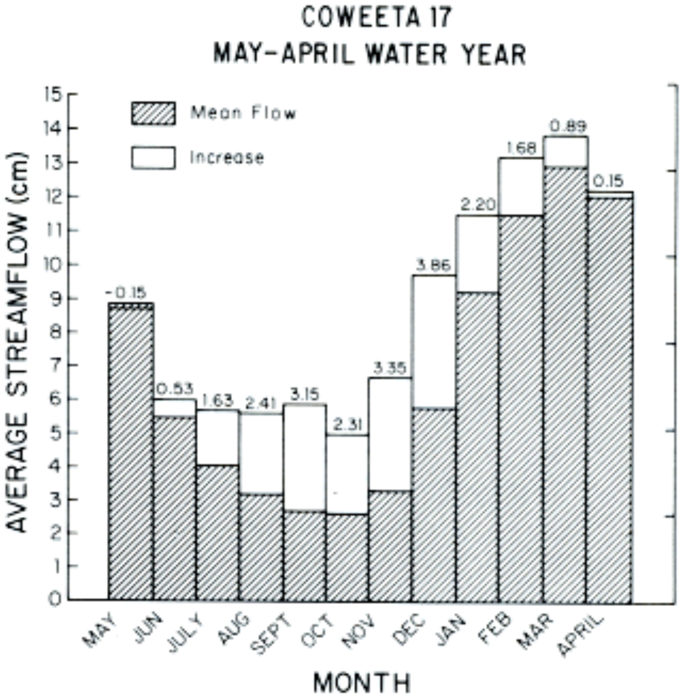

Figure 17.5 Mean monthly flow on Coweeta WS 17 prior to clearcutting and mean monthly increases during a seven-year period of annual recutting (from Swank *et al.,* 1988).

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 the 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 (Hornbeck, 1973; Verry *et al.,* 1983). 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). For example, commercial logging in the Southern Appalachians increases quickflow volumes 10 to 20% and peak flow rates 15 to 30% and there is little change in other storm hydrograph parameters (Table 17.3). Knowledge about such changes is useful in designing culvert sizes but the consequences of increases further downstream are considered to be insignificant since the proportion of a drainage basin cut within a year is usually small.

17.4.2 WATER QUALITY

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.

Table 17.3 Summary of changes in storm hydrograph parameters after clearcutting and/or commercial harvest in mixed hardwood forests at Coweeta Hydrologic Laboratory

					Mean storm Increases for selected hydrograph parameters		
Watershed number	Size (ha)	Treatment	Inclusive years after treatment	Total quickflow volume (%)	Peakflow rate (%)	Initial flow rate (%)	Recession time (%)
7	58.7	Clearcutting, cable logging, product removal and minimal road density	3	10	15	14	10
28	144.1	77 ha clearcut, 39 ha thinned, 28 ha no cutting, products removed; high road density	9,2[a]	17	30	N/A	N/A
37	43.7	Clearcut, no products removed	4	11	7	NS	NS

N/A, not available; NS, not significant.

[A] Inclusive years after treatment used for total quickflow and peakflow rates, respectively.`

Changes in these parameters vary widely depending on the properties of the baseline forest ecosystem and the type of management activity, such as harvesting and associated logging methods; site preparation methods such as use of mechanical equipment; and stand improvement between initial re-establishment and harvesting which may involve the use of fire, herbicides, or fertilizer.

17.4.2.1 Sedimentation

A major concern in harvest and regeneration practices is the impact on stream sedimentation. Roads and skid trails are the primary sources of sediment associated with silvicultural activities as documented in many catchment studies (Lull and Reinhart, 1972; Anderson *et al.*, 1976; Swift, 1988). Careful layout, construction and maintenance of roads will minimize increases in stream turbidities. The most sensitive aspect of road construction occurs at stream crossings because soil from cuts and fills has direct access to the stream. Rapid establishment of surface protection such as a grass cover is a key factor in erosion control for roads. As demonstrated in catchment studies at Coweeta, newly constructed roads lose the most soil in the short period before grass becomes established (Figure 17.6). In the example shown, about 75% of the soil eroded during the 2.5 years of observation was delivered to the stream immediately below a road crossing in the first two months. Long-term research at the catchment scale has provided practical guidelines for protecting water quality related to forest access road construction (Swift, 1988).

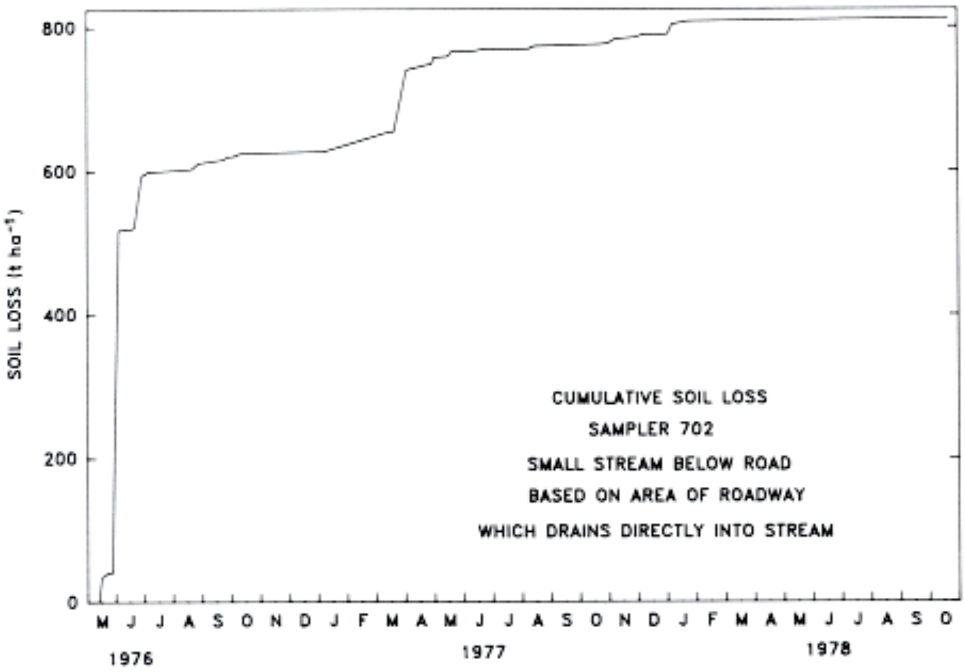

Figure 17.6 Cumulative soil loss from a forest road at a stream crossing during the first 2.5 years after start of construction (from Swift, 1988).

17.4.2.2 Stream temperature

Catchment experiments have shown that removal of the forest canopy adjacent to forest streams increases solar heating of surface waters with a consequent increase in maximum summer temperatures of 1.1 to 6.1°C in eastern United States streams (Swift and Messer, 1971; Hornbeck and Federer, 1975; Kochenderfer and Aubertin, 1975). In western United States forests, even larger stream temperature increases have been observed following harvest of streamside vegetation (Brown and Krygier, 1970). However, catchment studies have shown that adverse increases in stream temperature can be avoided by maintaining a buffer strip along streams (Brown *et al.,* 1971; Hornbeck *et al.,* 1986). As Stone *et al.* (1980) observed, elevated stream temperature is not an inevitable consequence of the harvest method but is subject to trade-off analysis in forest planning.

17.4.2.3 Dissolved nutrients

Forest management activities such as forest cutting and harvesting interrupt the natural recycling of nutrients and there is concern that nutrients released may affect downstream uses or reduce site productivity. The use of small catchments in recent decades as a tool for biogeochemical cycling studies has produced a large body of information on streamwater nutrient responses to management, particularly clearcutting. Changes in streamwater nutrient concentrations following cutting vary substantially between localities, even within a physiographic region. For example, in Central and Southern Appalachian forests, measurable increases in concentrations of NO_3^-, K^+, and other constituents have been observed following cutting but the magnitude of change is small and unimportant to downstream uses (Swank *et al.,* 1989). In contrast, clearcutting in northern hardwood forests may result in large increases in concentrations of some nutrients (Hornbeck *et al.,* 1986). Process research on catchments has identified some of the reasons for a varied ecosystem response to disturbance.

Small paired catchment experiments provide a basis to assess effects of management practices on dissolved nutrients (Figure 17.7). Dissolved nutrient concentrations should be measured before, during and after disturbance on reference and manipulated catchments. Pretreatment calibration regressions of monthly fluxes of nutrients between the reference and managed catchments can be used to estimate the magnitude of management impacts (Table 17.4). In the illustration used, concentration changes were small for most nutrients but when combined with annual increases in discharge due to cutting, there was a substantial increase in nutrient export (Figure 17.7, Table 17.4). These accelerated nutrient losses may be more critical to soil fertility than water quality as discussed below.

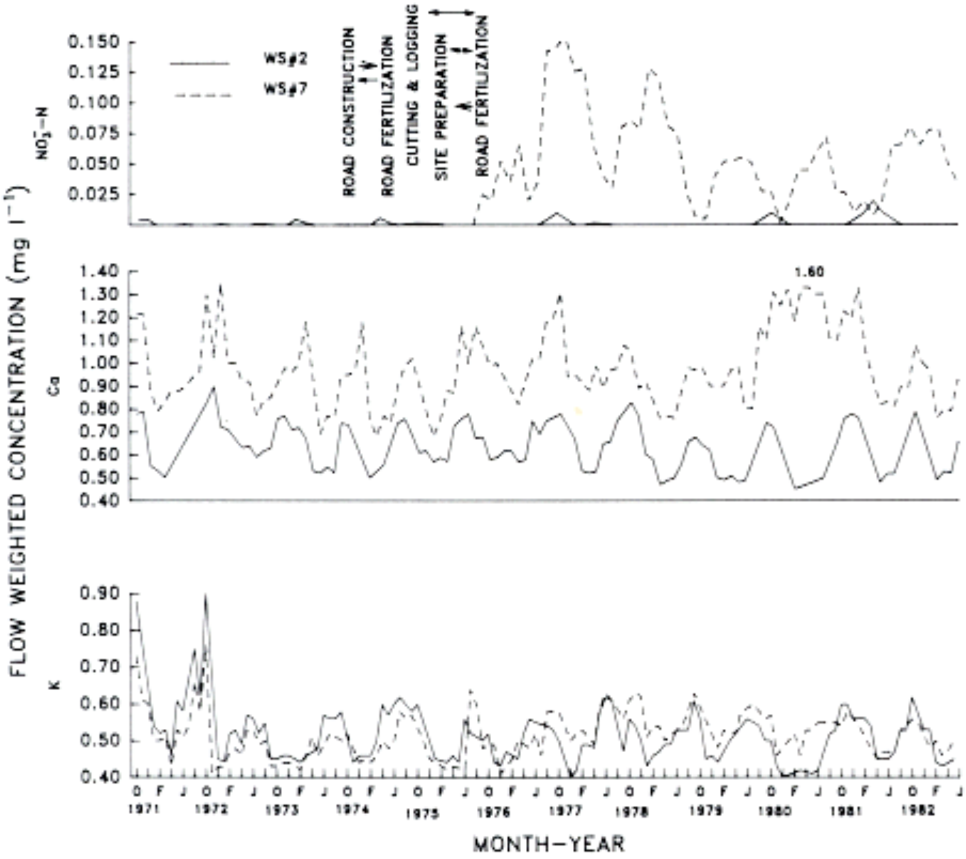

Figure 17.7 Mean monthly concentrations (flow-weighted) of K, Ca and NO_3^--N in streamwater of Coweeta WS7 during calibration (1971-76), road construction, clearcutting and logging, site preparation, and post-harvest recovery periods (Swank, 1988).

17.4.3 ELEMENT CYCLING

In any ecosystem, elemental inputs through atmospheric deposition and human activity (e.g. fertilization) must balance hydrologic outputs and changes in internal stores. The construction of element "budgets" has been the focus of numerous investigations (Chapter 8). Aggrading forest ecosystems are often characterized by relatively low elemental inputs and relatively high rates of biomass uptake (e.g. Likens *et al.,* 1977; Monk and Day, 1988; Johnson and Todd, 1990). Thus, any forest management activity altering existing element balances may adversely affect the regenerative capacity of forest stands.

Of all management activities, logging is perhaps the most disruptive to element cycles. In many forests, stores of nutrient elements in forest biomass are substantial in comparison to the available pool in the soil. Removal of biomass by logging can therefore represent a major loss of nutrients from the ecosystem.

Table 17.4 Annual changes in streamflow and solute export following clearcutting and logging on Coweeta Watershed 7

Time since treatment (May-		Increases or decreases[a] in solute export (kg ha^{-1})								
	Flow	NO-N	NH-N	PO	K	Na	Ca	Mg	SO	Cl

April water year)	(cm)	NO_3-N	NH_4-N	PO_4	K	Na	Ca	Mg	SO_4	Cl
First 4 months	0.5	0.01	<0.01	0.04	0.43	0.42	0.24	0.26	1.17	0.68
First full year	27.3	0.26	0.03	0.12	1.98	1.37	2.60	0.96	0.81	1.13
Year 2	23.8	1.12	<0.01	0.03	1.95	2.22	2.51	1.15	-0.24	1.62
Year 3	13.1	1.27	0.05	0.06	2.40	2.68	3.16	1.42	1.16	2.08
Year 4	8.6	0.25	0.15	0.06	0.80	1.07	1.63	0.46	0.93	0.59
Year 5	8.0	0.28	0.01	0.02	0.52	0.13	1.19	0.18	0.11	0.10

*Increase or decrease based on monthly calibration regressions.

The small watershed method has proved to be a useful tool for studying the effects of logging and other forest management activities on element dynamics in forests (see reviews by Mann *et al.,* 1988; Vitousek and Mellilo, 1979; Swank and Crossley, 1988b). The use of small watersheds offers the researcher a defined area in which intensive measurements of biomass and soil element pools can be confidently related to input-output budgets. By monitoring changes in element budgets, the small watershed method can be used to determine the effects of management practices on nutrient flows and capital, the mechanisms by which nutrient stores are reorganized following large-scale disturbance and long-term estimates of nutrient depletion rates.

17.4.3.1 Case study: Hubbard Brook

Results from an intensive study at the Hubbard Brook Experimental Forest (HBEF), in central New Hampshire, USA, provide a good example of the utility of the small-watershed approach. Prior to whole-tree clearcutting, watershed 5 (W5) at the HBEF was dominated by hardwood forest vegetation. Various pools of N, Ca, K and Mg in biomass and soil prior to clearcutting are given in Table 17.5. The whole-tree harvest removed 88% of the above- ground biomass. The harvested biomass accounted for 6.1 %, 180%, 141% and 116% of the soil pools of available N, Ca, K and Mg, respectively.

Post-harvest streamwater solute concentrations from W5 (Figure 17.8; Lawrence *et al.,* 1987) showed patterns similar to previous deforestation experiments at the HBEF (Likens *et al.,* 1970; Hornbeck *et al.,* 1986; Martin *et al.,* 1986). The effluxes of solutes in W5 streamwater following whole-tree clearcutting are not yet available. Thus, estimates for hydrologic losses following cutting are based on results of similar clearcut watersheds in the region (Martin *et al.,* 1986). Alteration of ecosystem processes that cause the observed trends in stream chemistry have been intensively studied. It is believed that increased sulphate adsorption in the mineral soil, and accelerated nitrification in the forest floor cause the observed trends in stream chemistry (Vitousek and Melillo, 1979; Martin *et al.,* 1986; Mann *et al.,* 1988; Nodvin *et al.,* 1988).

Table 17.5 Nutrient content (kg ha^{-1}) of biomass and soils on W5 of the Hubbard Brook Experimental Forest and nutrient removal in whole-tree harvesting. Based on data on forest floor and soil N from Huntington and Ryan (1990), on forest floor and soil Ca, K, Mg from Johnson *et al*. (1991) and unpublished data of T.G. Siccama, Yale School of Forestry

	N	Ca	K	Mg
Above-ground biomass	506	656	245	58
Below-ground biomass[a]	261	173	100	21
Forest floor total	1340	128	61	17
Mineral soil[b]	5900	193	92	27
Removed in harvest	445	578	216	51
Uncut	20	26	10	2
Residual biomass (slash)	40	53	20	5

[a] Estimated using ratio of above-ground : below-ground biomass content from Likens *et al*. (1977).

[b] Mineral soil N is total N. Mineral soil Ca, K and Mg are exchangeable.

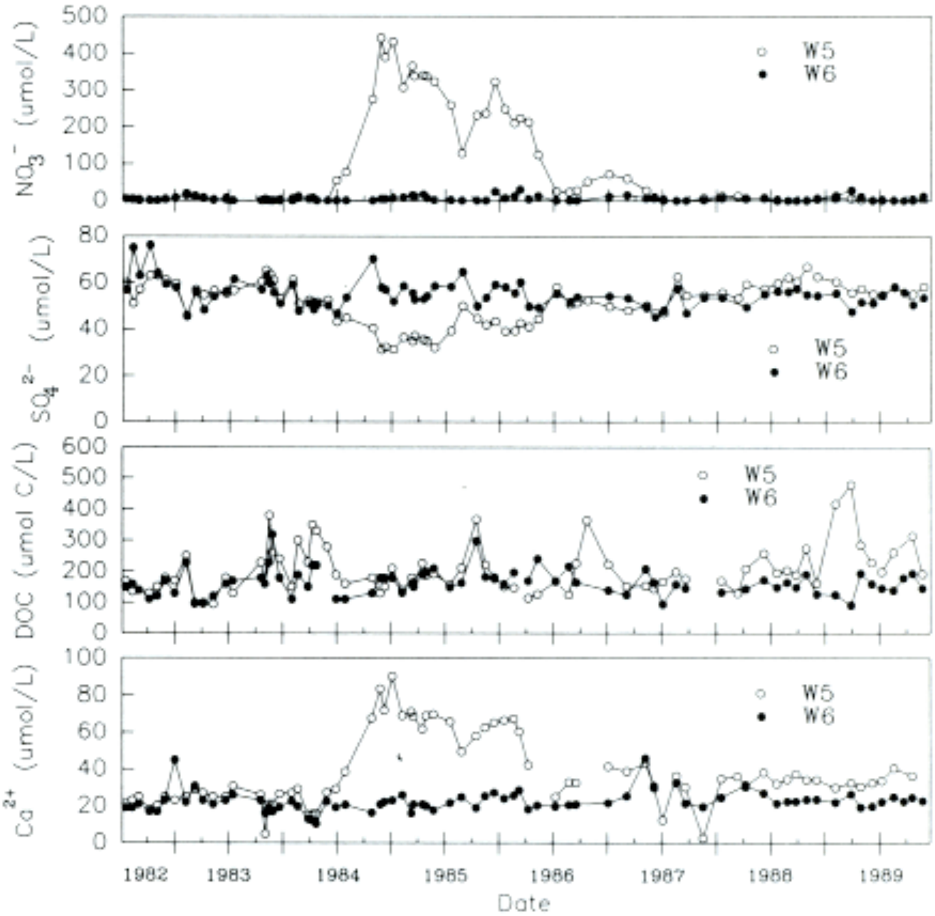

Figure 17.8 Stream-water chemistry trends at the outlets of a clearcut watershed (W5) and a reference watershed (W6) at the Hubbard Brook Experimental Forest, New Hampshire.

Table 17.6 Exchangeable cation pools ($kmol_c\ ha^{-1}$) before and after whole-tree harvesting on W5 at the Hubbard Brook Experimental Forest (after Johnson *et al*., 1991)

	Forest floor		Mineral soil		Whole solum	
Element	Before	After	Before	After	Before	After
Al	1 .8	7 .7	159 .0	160 .0	161 .0	167 .0
Ca	3 .7	3 .7	9 .6	12 .0	13 .0	16 .0
K	0 .7	0 .7	2 .2	2 .4	2 .7	3 .1
Mg	0 .4	0 .5	2 .4	3 .6	2 .8	4 .1
H	3 .0	2 .6	19 .0	13 .0	22 .0	16 .0
CEC	9 .6	15 .0	192 .0	191 .0	202 .0	206 .0

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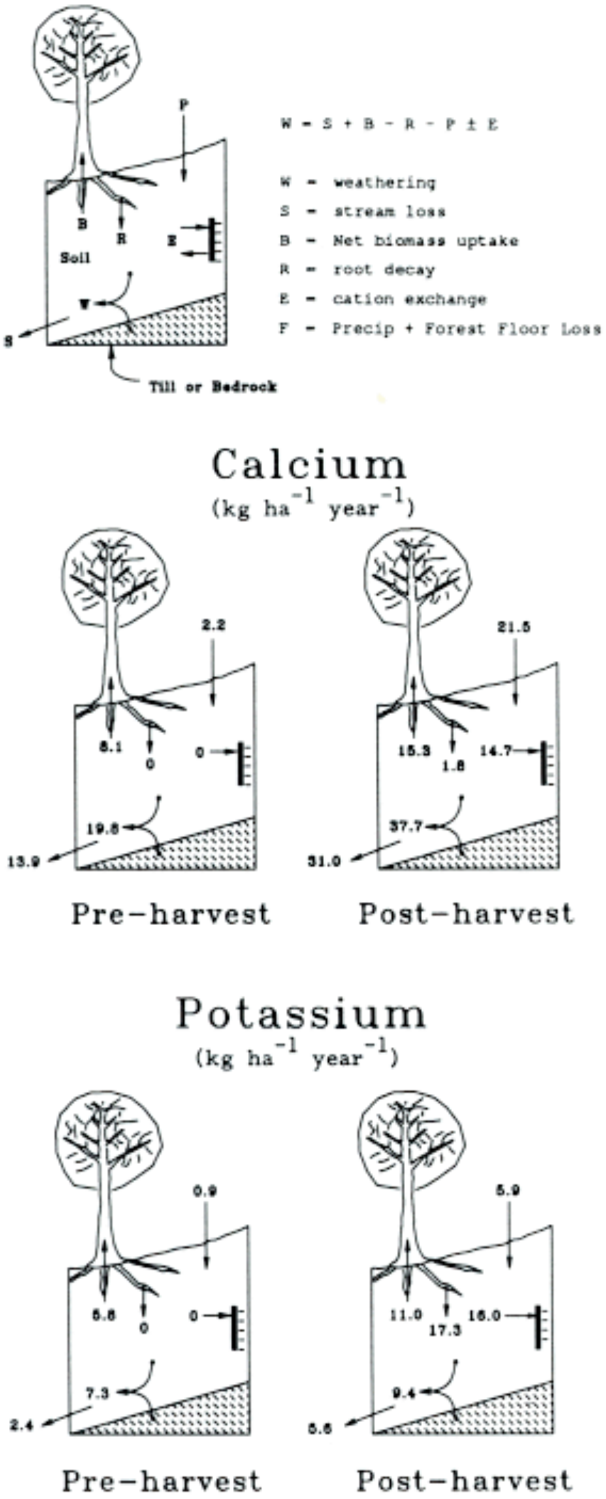

Figure 17.9 Changes in the budgets of Ca and K in three years following whole-tree clearcutting at the Hubbard Brook Experimental Forest.

There was no significant change in the cation exchange capacity (unbuffered NH_4Cl extraction) of W5 soils three years after clearcutting (Table 17.6). Exchangeable Ca and K pools increased significantly, while the exchangeable H pool decreased. Increases in exchangeable Ca and K concentrations were most dramatic (up to 100%) in the spodic horizons (Bh and Bs1; Johnson *et al.*, 1991).

The release of Ca and K from decomposing roots was remarkably rapid following clearcutting. In the first two years 3% of the Ca and 63% of the K in root biomass was released. When calculated on an area basis, the input of Ca and K to the soil solution from root decay averaged 1.8 kg ha^{-1} $year^{-1}$ and 17.3 kg ha^{-1} $year^{-1}$ for Ca and K, respectively (Fahey *et al.*, 1988).

The changes in the Ca and K budgets of W5 in the three years following harvesting are shown in Figure 17.9. These element balances lead to several important conclusions regarding the biogeochemical reorganization of forest ecosystems shortly after large-scale disturbance. First, the increased efflux of dissolved cations in streamwater following clearcutting could not be explained by leaching of exchangeable cations. Indeed, increased retention of exchangeable nutrient cations in the Bh and Bs1 horizons appears to be an important mechanism by which site fertility is maintained.

Second, the decomposition of roots was an important factor in the reorganization of nutrients on W5 following logging. Root decay was a significant source of basic cations to the soil solution and stream water. This often overlooked source may partially explain increased export of basic cations at many sites.

After accounting for plant uptake and forest floor mineralization, there remain unexplained losses of Ca and K. It is possible that release of these basic cations by chemical weathering increased following logging. Indeed, soil conditions following logging-in particular, increased soil moisture and acidity-would seem to favour this hypothesis. A more complete discussion of this pattern is presented in Chapter 14.

17.4.3.2 Factors influencing element export and depletion

A number of edaphic factors and the choice of a management strategy influence the rate of export of nutrients and other substances following logging. The relative importance of any individual factor varies from site to site. Below, we summarize these factors using selected examples from watershed studies, where possible.

Management strategy

The interval of time between harvests ("rotation time") is a critical factor influencing the sustainability of forest cutting practices. Previous catchment studies have shown that in many systems removal of nutrients in biomass by logging is the most important mechanism of nutrient depletion (Clayton and Kennedy, 1985; Johnson *et al.*, 1988; Mann *et al.*, 1988; Federer *et al.*, 1989).

Mann *et al*. (1988) and Federer *et al*. (1989) showed that loss of nutrients by leaching was minor in comparison to removal in biomass, with the possible exception of Ca and K. A few watershed studies in the western USA confirm these conclusions (Clayton and Kennedy, 1985; Martin and Harr, 1989). Johnson *et al*. (1988) summarized results from several clearcut watershed and plot studies in the eastern USA. They found that exchangeable base cation supplies in the solum were not correlated with nutrient export in harvested biomass, but were strongly correlated with hydrologic losses of base cations. These results suggest that depletion of base cations in the solum due to logging should result in reduced streamwater losses, but continued plant uptake.

The extent of wood fibre utilization can have a profound influence on nutrient depletion. Much research in this area has centred on the differences between "whole-tree" and "sawlog" or "stem-only" harvesting. Whole-tree harvesting should have a more adverse impact on forest nutrient cycling because of the greater biomass export relative to stem-only cutting. Johnson *et al*. (1982) contrasted whole-tree and stem-only harvesting in several watersheds in eastern Tennessee, USA. They found that export of biomass and nutrients during logging was 2.6 to 3.3 times greater under whole-tree harvesting than under stem-only. Several other studies have shown similar results (e.g. Weetman and Webber, 1972; Freedman *et al.,* 1986; Hendrickson *et al.,* 1989). Mann *et al.* (1988) found no large differences in hydrologic export of nutrients between whole-tree harvested sites and stem-only harvested sites. However, they reported that biomass regrowth on whole-tree harvested sites was slower than on stem-only clearcuts, although the reasons are unclear. It appears that the major difference between the two methods is in nutrient export in biomass. This difference may be critical in areas with relatively small soil pools.

The long-term nature and complexity of predicting the consequences of different harvest intensities on soil nutrients and forest productivity requires the integration of empirical research and modelling in the context of a general theory. Experimental catchments provide a tool for such assessments as illustrated by Swank and Waide (1980). They coupled extensive nitrogen cycling data with specific process-level research on forested catchments to evaluate changes in soil nitrogen associated with different levels of wood fibre utilization and varying rotation ages. Examples of empirical and theoretical models for assessing the future consequences of management practices on productivity were reviewed by Yarie (1990).

Vegetation and parent material effects

Vegetation plays a role in nutrient depletion before and after logging. Some tree species, especially conifers, have low biomass nutrient contents. Logging of these species will have less effect on nutrient cycles than removal of other, more nutrient-rich species.

Vegetation dynamics following logging also are important to long-term productivity. Regrowing vegetation affects element export in two ways. First, the timing and magnitude of post-harvest water yield increases are controlled by regrowing vegetation as discussed earlier. As transpiration increases with re-establishment of a forest canopy following logging, discharge decreases. Sites characterized by rapid regrowth or long growing seasons should show lower losses of dissolved nutrients than sites where revegetation is slow. Second, regrowing vegetation assimilates nutrients in biomass, keeping them in the ecosystem. Several studies have shown that early successional species often have high nutrient concentrations (e.g. Marks and Bormann, 1972; Boring *et al.,* 1981). As these species are outgrown by climax species, their nutrients are recycled, largely remaining in the ecosystem.

Parent material influences long-term productivity through weathering, which is the major source of soluble nutrient cations in many systems. Through reactions between the soil solution and the exchange complex, nutrient cations released by weathering can serve to replenish depleted exchangeable cations. Weathering considerations are discussed in Chapters 4 and 5.

The potential importance of weathering as a nutrient replacement process can be illustrated by an example. Federer *et al.* (1989) predicted that 62% of total Ca in a hardwood forest in Connecticut, USA, would be depleted after three 40-year rotations. If weathering rates at this site are slow, it is possible that the ability of the soil minerals to supply Ca will not match exports after only one or two rotations. This may result in depletion of the exchangeable Ca pool and adverse effects on vegetation, even though a substantial total pool remains. A few recent studies offer some hope that independent weathering estimates will soon be obtainable (Sverdrup and Warfvinge, 1988; Aberg *et al.,* 1989).

17.4.3.3 Tropical vs. temperate systems

A major underlying theme of this volume has been the need for more small watershed studies in tropical and subtropical environments. Contrasting the effects of forest management on element cycles in tropical and temperate systems is difficult because of the sparsity of data from tropical watersheds. However, Allen (1985) summarized data from 26 studies of forest clearing effects on soil properties in the tropics and the USA. Results indicate that depletion of N and exchangeable Ca, Mg and K was up to 50%

greater on soils developed in highly weathered parent materials in the tropics than in similar soils in temperate regions or tropical soils developed in younger parent materials. A comparison of soil chemistry in uncut areas showed that soils in older parent materials in the tropics had lower concentrations of N and exchangeable base cations than tropical soils in general (Allen, 1985).

Allen's (1985) data are consistent with depletion patterns outlined above. If export in cut biomass is independent of soil pools, depletion of nutrients should be more dramatic in areas with small soil pools prior to harvesting, such as the older tropical soils. Allen 's data lead to the tentative hypothesis that differences exist between the responses of temperate and tropical forests to cutting, and that some tropical forests are more sensitive to cutting than temperate forests. However, as Allen (1985) points out, there is a great deal of variability in the response to cutting within the tropics (and temperate systems as well). In order to adequately estimate nutrient depletion rates in the tropics, data on hydrologic outputs from logged tropical watersheds are needed. The sustainability of forestry practices in the tropics depends on the degree to which losses from the soil are retained in the ecosystem. The establishment of diverse small watershed studies in the tropics is an acute need at the present time.

17.5 RESEARCH NEEDS AND OPPORTUNITIES

Small catchment research will continue to provide a primary method for assessing the effects of forest management practices on the water resource. Principles and guidelines for improved management are a major benefit of catchment-oriented experimentation. To utilize more fully the results from catchment studies, there is a need to organize and conduct more research from an integrated, interdisciplinary ecosystem approach that is based on theoretical considerations. Understanding of cause-and-effect relationships derived from such an approach can be formulated into models that provide a basis for scaling up and extrapolating results from small catchments to larger units of landscapes.

There are many opportunities to use small catchment research to address major environmental issues. The long-term records for baseline forest ecosystems at hydrologic stations provide a solid, unique basis for examining changes in forest health and water quality from the perspectives of primary pollutants and climate change. There are also opportunities to expand the small catchment research approach to assess other land-use activities such as sewage sludge disposal on forest lands and intensive recreational use.

Additionally, there is a need to establish catchment research programmes in a variety of forest ecosystems. Historically, most small catchment experimentation has been conducted in temperate forests and there is a paucity of parallel understanding for other major biomes such as tropical forests.

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