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Forest Hydrology and Biogeochemistry

Synthesis of Past Research and Future Directions

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Forest Hydrology and Biogeochemistry

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Foreword

Forest hydrology as a field has evolved greatly since the first paired watershed study was published by Bates (1921) in the *Journal of Forestry*. Bates described his work as the "first serious effort to obtain, under experimental conditions, a quantitative expression of forest influences on snow modeling, streamflow (and thus, by implication, evaporation) and erosion." Since then, many paired watershed studies have been published – with an explosion of such work in the late 1950s and through the 1960s during the First International Hydrological Decade. Despite the appearance of several textbooks in the past decades, the last major benchmarking effort was Sopper and Lull's (1967) edited conference proceedings from the International Symposium on Forest Hydrology, held at Penn State University, USA, in 1965. This was the first and last major synthesis and integration effort for the field in over four decades. Since Sopper and Lull, much has changed in forest hydrology: new instruments, some new theory, new disciplinary additions to forest linkages; most notably biogeochemistry.

Forest Hydrology and Biogeochemistry: *Synthesis of Past Research and Future Directions* is a long anticipated, important addition to the field of forest hydrology. It is, by far, the most comprehensive assemblage of the field to date and written by many of the top researchers in their field. The book reveals for the first time since Sopper and Lull, the current state of the art and where the field is headed – with its many new techniques developed since then (isotopes, fluorescence spectroscopy, remote sensing, numerical models, digital elevation models, etc.) and added issues (fire, insect outbreaks, biogeochemistry, etc.). Levia, Carlyle-Moses, and Tanaka have done a spectacular job of assembling a strong array of authors and chapters. As an associate professor of ecohydrology, Del Levia has a background in water transfers through the forest canopy and biogeochemical transformations in forest systems in American forested watersheds with extensive international experience as well. Darryl Carlyle-Moses is an associate professor of geography with experience in Canadian and Mexican forest systems, focused mostly on water transfers through the forest canopy. Tadashi Tanaka is professor of hydrology at University of Tsukuba in Japan with a long and distinguished career in forest hydrology, from groundwater studies to tracer studies and water flux measurements in headwater catchments. The geographical teaming of editors is an important element to the work, where the addition of the Japanese perspective (to the more dominant European and North American and Australian perspectives) with many chapters penned by Japanese forest hydrologists adding greatly to the breadth of approaches and examples. Attention to editorial detail is clear; from careful assembly of all the key component areas to an awareness of the benchmark papers in the field and need to include them (even when they fall outside the non-English speaking literature).

Distillation of a large and varied disparate discipline like forest hydrology and biogeochemistry is challenging. The book's organization effectively parses out the many aspects of the field in six useful parts. The first part outlines the historical roots of forest hydrology and biogeochemistry, with special reference to the Hubbard Brook watershed – arguably "Mecca" for the field and the foundation we all now follow in watershed-based coupled hydrobiogeochemical studies. The authors of that chapter are emblematic of the authorship of much of the book, pairing one of the founding fathers of field with one of the most promising young professors in the field. Sampling and novel approaches follow this background setup, with definitive chapters covering the latest in terms of spatial and temporal monitoring. Forest hydrology and biogeochemistry by ecoregion is a part that follows. The ecoregion component is a clever move in the assembly of the material for the book, providing a view into real-world landscapes and how uniqueness of place drives coupled hydrobiogeochemical processes. The editors have gathered authors from Canada, USA, Australia, China, Japan, and over a dozen countries in Europe to produce this range of ecoregion breadth. The three last parts of the book are "hydrologic and biogeochemical fluxes from the canopy to the phreatic surface," "the effects of time, stressors and humans," and finally, "knowledge gaps and research opportunities." Many of the hottest topics in relation to fire, insects, climate change, landuse change are addressed in a thoughtful and stimulating way.

Forest Hydrology and Biogeochemistry: *Synthesis of Past Research and Future Directions* is a celebration of a field. Like Bates' work, it is a serious effort to synthesize quantitative expressions of forest influences on water quantity (and now also water quality). The research pioneers who contributed to Sopper and Lull's major synthesis would be mesmerized by what now is possible and what is defined in this volume in terms of new research directions and opportunities. Reading it will give graduate students and researchers alike, a sense of direction and optimism for this field for many years to come.

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Preface

A tremendous amount of work has been conducted in forest hydrology and biogeochemistry since the 1980s, yet there has been no cogent, critical, and compelling synthesis of this work on the whole, although a number of seminal journal review articles have been published on specific aspects of forest hydrology and biogeochemistry, ranging from precipitation partitioning to catchment hydrology and elemental cycling to isotope biogeochemistry (e.g., Bosch and Hewlett 1982; Parker 1983; Buttle 1994; Levia and Frost 2003; Muzylo et al. 2009). The forest hydrology and biogeochemistry volumes published to date have served a different (albeit equally valid) purpose to the current volume, serving as either a reference tool for a particular study site or as a textbook. Over the past 30 years, the Ecological Studies Series has published a number of such volumes, including *Forest Hydrology and Ecology at Coweeta* (1988), *Biogeochemistry of a Subalpine Ecosystem* (1992), and *Functioning and Management of European Beech Ecosystems* (2009). Lee (1980) is one of the last comprehensive forest hydrology texts. Recent published works have focused on climate change and stressors. These books reflect the growing body of research in forest hydrology and biogeochemistry. However, none of these texts were specifically aimed at synthesizing and evaluating research in the field to date. As such, *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions* is especially timely, relevant, and arguably necessary as periodic review and self-reflection of a discipline are integral to its progression. Thus, the aim of this international rigorously peer-reviewed volume is to critically synthesize research in forest hydrology and biogeochemistry to date, to identify areas where knowledge is weak or nonexistent, and to chart future research directions. Such a task is critical to the advancement of our discipline and a valuable community building activity. This volume is intended to be a one-stop comprehensive reference tool for researchers looking for the "latest and greatest" in forest hydrology and biogeochemistry. The book also is meant to serve as a graduate level text.

Forest Hydrology and Biogeochemistry: *Synthesis of Past Research and Future Directions* is divided into four primary parts following an introductory chapter (constituting Part I) that traces the historical roots of forest hydrology and biogeochemistry. The introductory chapter employs the Hubbard Brook Experimental Forest as a model to elucidate the merits of watershed scale hydrological and biogeochemical research. The four primary parts of the book are: sampling and methodologies utilized in forest hydrology and biogeochemistry research, forest hydrology and biogeochemistry by ecoregion, hydrological and biogeochemical processes of forests, and the effects of time, stressors, and people on forest hydrology and biogeochemistry. It is important to note that each part examines forest hydrology and biogeochemistry from different perspectives and scales. While overlap among chapters has been kept to a minimum, some overlap is inevitable. One also could argue that some overlap is beneficial given the nature of the book and the fact that most researchers will likely read select chapters of relevance to their research rather than the book in its entirety. The part on sampling and novel approaches is intended to provide researchers and students with a broad cross-section of methodological approaches used by some forest hydrologists and biogeochemists and to foster their wider use by the larger community. As such, these chapters may be used as a primer for one wishing to learn how to utilize various methods to answer questions of importance to forest hydrologists and biogeochemists. The next part adopts a holistic focus on the forest hydrology and biogeochemistry by ecoregion. Specific forest types covered include lowland tropical, montane cloud, temperate, boreal, and urban. These chapters are intended to provide researchers with a concise synthesis of past research in a given forest type and provide future research directions, emphasizing a particular forest type as a whole (i.e., from an ecosystem perspective) rather than hydrological and biogeochemical processes. The following part emphasizes processes regardless of ecoregion and forest type. These chapters begin at the interface of the atmosphere–biosphere with atmospheric deposition and follow the transport of water and elements to the subsurface via routing along roots to surface water–groundwater interactions. Thus, these chapters focus on the hydrology and biogeochemistry of the critical zone. The next part of the book examines the effects of time, people, and stressors on forest hydrology and biogeochemistry, capturing some of the newest thinking on the effects of external stressors, such as ice storms and climate change, on the functional ecology of forests. The final chapter (constituting Part VI) summarizes some of the major findings of the book and is intended to galvanize future research on topics that merit further work by identifying possible research questions and methodologies to move the disciplines of forest hydrology and biogeochemistry forward.

The editors wish to thank all authors for their tremendous work ethic in association with this book. It is clear that chapter authors rose to the occasion and prepared well thought syntheses that will help chart future research directions. The editors also would like to express their gratitude to all of the authors who served as peer reviewers. We were duly impressed with the thorough and thoughtful nature of reviewer comments that undoubtedly improved the quality of the book. The editors also acknowledge the review efforts of those scientists whom were external to the book itself who provided excellent suggestions for chapter improvement; listed alphabetically, we acknowledge W. Michael Aust, Doug Burns, Sheila Christopher-Gokkaya, Helja-Sisko Helimsaari, April James, Koichiro Kuraji, Daniel Leathers, Myron Mitchell, Aleksandra Muzylo, and Wolfgang Wanek. David Legates is recognized for editorial advice during the project. We also acknowledge Jeff McDonnell for writing the Foreword of the book and the efforts of the Series Editor, E.-D. Schulze. The editors also wish to recognize Dr. Andrea Schlitzberger of Springer's Ecological Studies Series and Project Manager Elumalai Balamurugan for their hard and efficient work on this book. The editors wish to give special thanks and recognition to Springer Geosciences Editor, Robert Doe, and his assistant, Nina Bennink, for their professionalism, timely responses, clear feedback, and generous support as this book evolved through various stages of succession (with a few disturbances along the way) to its climactic completion in the course of 22 months.

It is the sincere hope, belief, and expectation of the editors that this volume will serve as an invaluable resource to many in the forest hydrology and biogeochemistry communities for years to come. We are confident that this volume, composed of the thoughts of some of the very best and talented researchers worldwide, will be a highly cited and impactful book that will catalyze fruitful research that propels our knowledge of forest hydrology and biogeochemistry forward.

Newark, Delaware — Delphis F. Levia
Kamloops, British Columbia — Darryl E. Carlyle-Moses
Tsukuba, Japan — Tadashi Tanaka
March 2011

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Part I
Introduction

Chapter 1
Historical Roots of Forest Hydrology and Biogeochemistry

Kevin J. McGuire and Gene E. Likens

1.1 Introduction

The scientific disciplines of forest hydrology and forest biogeochemistry have contributed greatly to our understanding of the natural world even though they are relatively young disciplines. In this chapter, the historical origins, developments, and major advancements of these disciplines will be presented. The Hubbard Brook Ecosystem Study (HBES) will serve as a case study to illustrate the development, integration, and new research directions of these disciplines. Finally, this chapter on the historical roots and evolution of forest hydrology and biogeochemistry sets the stage for the remaining chapters of this volume by providing a conceptual framework in which most hydrological and biogeochemical work is conducted. Excellent reviews on forest hydrology and biogeochemistry are given by Sopper and Lull (1967), Bormann and Likens (1979), Lee (1980), Waring and Schesinger (1985), Likens and Bormann (1995), Schlesinger (1997), Ice and Stednick (2004a), de la Cretaz and Barten (2007), NRC (2008), and DeWalle (2011).

1.2 The Early Foundations of the Influence of Forests on Water

1.2.1 Pre-Twentieth Century

Kittredge (1948), Zon (1912), and Colman (1953) provide the earliest historical perspectives of "forest influences," which Kittredge describes as "including all effects resulting from the presence of forest or brush upon climate, soil water, runoff, stream flow, floods, erosion, and soil productivity." However, the earliest accounts of interactions between forests and water were probably those of Vitruvius (ca. 27–17 BCE) when he recognized that forests played an important role in evaporation. He postulated that in mountainous regions, the loss of water due to evaporation was limited because forests reduced the sun's rays from reaching the surface (Biswas 1970). About 100 years later, Pliny the Elder in *Natural History* (77–79 CE) observed,

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"it frequently happens that in spots where forests have been felled, springs of water make their appearance, the supply of which was previously expended in the nutriment of the trees...Very often too, after removing the wood which has covered an elevated spot and so served to attract and consume the rains, devastating torrents are formed by the concentration of the waters" (Bostock and Riley 1855).

As Andréassian (2004) notes, Pliny's observations highlight the major concerns of forest cover on water and climate (namely streams and precipitation). These and other observations of forest influences led Medieval and Renaissance governments to establish protection forests (Kittredge 1948). In France, King Philippe Auguste issued a decree in 1219 "of the Waters and Forests" that recognized the close relation between water and forests in forest management (Andréassian 2004). During the mid-nineteenth century in France and Switzerland, debates on the effects of forest clearing emerged partly from recent torrent and avalanche activity that had occurred in the Alps, which formed the beginning of the scientific study on the influence of forests on water (Kittredge 1948). Andréassian (2004) describes several French watershed studies that occurred during this period (Belgrand 1854; Jeandel et al. 1862; Matthieu 1878), which are among the earliest studies to report on measurements of forest influences on hydrology and climate.

Despite the experiences in Europe, national recognition in the USA concerning the role of forests in protecting watersheds did not occur until the late nineteenth century, which essentially ushered in a wave of research on forests and water. During the mid to late nineteenth century, there was much speculation on the role that forests played in climate. The accepted wisdom was that deforestation had caused significant macroscale climate changes, especially higher temperatures and lower precipitation; however, much of that was dismissed when climatic data became available showing that only at the microsite did forests have effects on climate variation (Thompson 1980).

Interests in forest influences in the USA began when conservationists such as George P. Marsh became alarmed by the rate of forest clearing and suggested, after reviewing European findings and observations in the Alps, that forest removal had devastating effects on streamflow (Marsh 1864). The publishing of Marsh's *Man and Nature* followed by several reports on forest influences (e.g., Watson 1865; Hough 1878), eventually led to the 1891 Forest Preservation Act and 1897 Organic Act. These important pieces of legislation both described forest reserves, but the latter also provided a blueprint for their management and for the "purpose of securing favorable conditions of water flows." As Kittredge (1948) noted, the period from 1877 to 1912 might be called the "period of propaganda," when numerous writings and debates occurred concerning issues of forest influences on climate and floods. The importance of forests on flood control was generally accepted by foresters, but it had been challenged by prominent engineers such as Chittenden (1909) of the US Army Corps of Engineers and the Chief of the Weather Bureau, W.L. Moore (1910). With little scientific evidence to resolve the controversy, Raphael Zon, the Chief of Silvics with the USDA Forest Service, proposed the creation of the first experiment stations on the national forests and established the first forest and streamflow experiment at Wagon Wheel Gap, Colorado in 1909.

This study and others (e.g., in New Hampshire, see Federer 1969) helped ensure the passage of the Weeks Act in 1911 that provided "for the protection of watersheds of navigable streams" and the purchase of 9.3 million ha of land for national forests in eastern United States. The following year, Zon (1912) issued a seminal report to Congress on "Forests and water in the light of scientific investigation," which summarized evidence for the influence of forests on floods. This report would become the authoritative reference on the topic for the next several decades.

1.2.2 Early Twentieth Century: Watershed Studies

Disasters in the Alps during the early to mid-nineteenth century when forests were being cleared for pasture land prompted the Swiss to develop the first true watershed study in 1900, in the Emme Valley Emmenthal region (Engler 1919). The study was designed to evaluate the effects of forests on streamflow through comparison of the hydrological response to precipitation of two 0.6 km^2 watersheds, the Sperbelgraben (97% forested) and the Rappengraben (69% pasture and 31% forest) (Colman 1953). However, results from the Emmenthal study were largely qualitative and conclusions were suspect since the watersheds were not first compared under similar forest cover conditions (Bates and Henry 1928), i.e., the experimental design was faulty (Penman 1959; Whitehead and Robinson 1993).

In 1909, the USDA Forest Service began to plan a purposeful experiment on the Rio Grande National Forest, near Wagon Wheel Gap, Colorado with two contiguous watersheds that were similar in topography and forest cover. Observations were made on meteorological characteristics and streamflow under these similar conditions. Then, forest cover was removed from one of the watersheds and measurements continued as before, until the effects of the forest removal had been determined (Bates and Henry 1928). Wagon Wheel Gap was the first true paired-watershed study, which allowed for direct comparison of the timing and amount of streamflow and amount of erosion before and after removal of the forest. The experiment showed that forest removal increased annual water yield compared to the reference watershed, but the increase in water yield lessened over time as vegetation reestablished with essentially no effect after 7 years. This study would set the stage for the development of the paired-watershed approach (Wilm 1944; Hewlett and Pienaar 1973) all across the USA (Fig. 1.1). Although experimental watersheds have been criticized for their lack of representativeness, expense, and difficultly in interpreting results (Hewlett et al. 1969; Ward 1971; Whitehead and Robinson 1993), they have been instrumental to an understanding of forest hydrology.

In 1936, the Omnibus Flood Control Act gave the USDA Forest Service responsibility for flood-control surveys of forested watersheds to determine measures required for retarding runoff and preventing soil erosion and sedimentation (Hornbeck and Kochenderfer 2004). Increased flooding (e.g., Mississippi River in 1927) and concerns over the role of forest harvesting in the next two decades, spawned new USDA Forest Service watershed research at the San Dimas

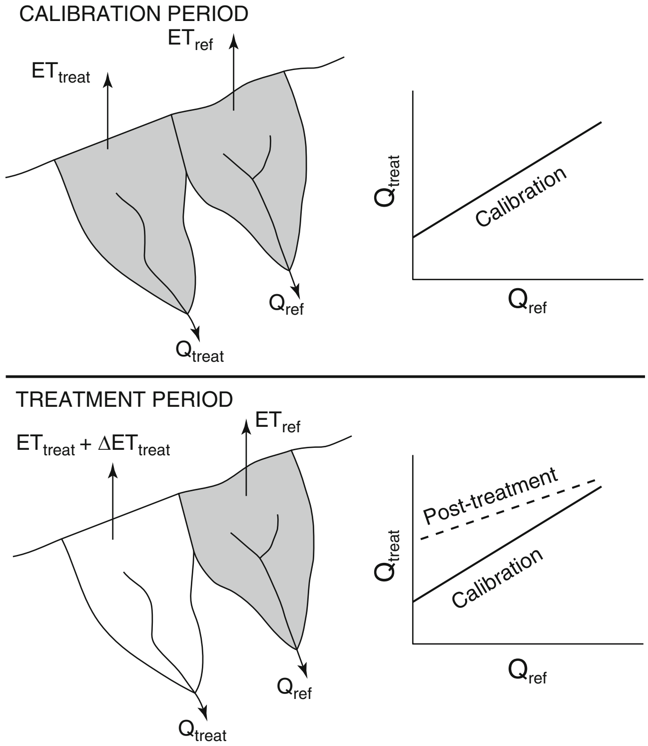

Fig. 1.1 An example of the paired-watershed approach to determine the effect of forest removal on evapotranspiration and water yield (adapted from Hewlett 1982). One watershed is manipulated (treatment, *no* shading) after an initial calibration period of where meteorological and hydrological variables observed to establish a relationship between the two watersheds. Using regression analysis or another statistical approach, differences between the treatment and reference can be established

Experimental Forest in southern California and the Coweeta Hydrologic Laboratory in western North Carolina. Although watershed studies were developed throughout the world, most were located in the USA and included some of the most noteworthy early contributions to forest hydrology (McCulloch and Robinson 1993).

1.2.3 Recognition of a New Discipline: Forest Hydrology

In his book on “forest influences,” Kittredge (1948) may be one of the first to use the term “forest hydrology” to describe a new discipline focused on water-related phenomena that are influenced by forest cover. New curricula at universities were developing to provide professional foresters with hydrologic training to deal with watershed management problems (Wilm 1957). In the decades following, there was a proliferation of forest hydrology research and the establishment of numerous experimental watersheds. Many of these experimental watersheds are now well known (e.g., Fernow, Hubbard Brook, H.J. Andrews); however, of the 150 experimental watersheds that existed by the 1960s in the USA (Anderson et al. 1976), many have since been discontinued. The discipline of forest hydrology was well established by 1965 when the *International Symposium on Forest Hydrology* was held at the Pennsylvania State University (Sopper and Lull 1967). This symposium captured the discipline in reports of findings from studies on the influences of forest cover on water yield, peakflows, and sediment from all over the world. Proceedings from this symposium are one of the most important collections of papers in forest hydrology (Courtney 1981), and at the time, sparked renewed interest in forest hydrology, launching more process-oriented research on how water cycles within forests. Water quality, however, was not given much consideration at the symposium, with the exception of matters related to sediment (McCulloch and Robinson 1993).

1.2.4 The Influence of Forests on Floods and Water Yield: A Summary of Paired-Watershed Results

Initially, experimental watersheds and the paired-watershed approach were primarily used to evaluate the effects of forest management practices on the timing and magnitude of streamflow and sediment load. Many of these studies were used to develop best management practices that are still in use today (e.g., Kochenderfer 1970). The subject of forest management and its influence on flooding has been a recurring scientific, social, and political theme since the mid-nineteenth century (e.g., Eisenbies et al. 2007). Experiments beginning with Wagon Wheel Gap showed that with 100% forest removal, impacts on flooding appear to be minor if soil disturbance is minimized. Generally, complete forest removal increases peakflow and stormflow volume, although results are highly variable and depend on the severity of soil disturbance, storm size, antecedent moisture condition, and precipitation type (Bates and Henry 1928; Hewlett and Hibbert 1961; Lull and Reinhart 1967; Harr and McCorison 1979; Troendle and King 1985). Given that many scientific and legal arguments regarding forests and flooding continue today (e.g., Mortimer and Visser 2004; Alila et al. 2009), we have much to learn from historical studies and could benefit from objectively re-evaluating historical datasets (DeWalle 2003; Ice and Stednick 2004b).

Following initial concerns of flooding and forest cover change, interest began to develop in manipulating forest cover to augment water yields from forested watersheds (Ponce 1983). Thus, the paired-watershed experiments were used to address a different set of questions such as: could streamflow be increased during dry periods? Or could snowpacks be managed to increase streamflow during the summer months? Changes in forest composition, structure, or density that reduce evapotranspiration rates generally increase water yield from watersheds. Paired-watershed studies showed that annual water yield can increase between 15 and 500 mm with forest removal, although these changes are often short lived (a few years) and depend on climate, soil characteristics, and percentage and type of vegetation removal (Hibbert 1967; Patric and Reinhart 1971; Bosch and Hewlett 1982; Douglass 1983; Hornbeck et al. 1993; Stednick 1996; Brown et al. 2005). The greatest streamflow increases occurred in watersheds with the highest annual precipitation (Bosch and Hewlett 1982), particularly when precipitation was highest during the growing season. Augmenting water yields generally requires that forests cover a significant portion of the watershed, mean annual precipitation exceeds 400 mm, soil depth is greater than about 1 m, and when managed, forest cover is reduced by more than 20% (Chang 2006). At some sites where regrowth species composition differed from that which was present prior to harvesting (e.g., hardwoods to conifer, mature species replaced by early successional species, or forest conversion to grassland), streamflow did not return to pretreatment levels and adjusted to differences in interception (e.g., Swank and Miner 1968) or transpiration losses (e.g., Hornbeck et al. 1997) of the newly established vegetation.

In snow-dominated regions, forest cover alterations can also increase water yield and affect the timing of snowmelt runoff. In a series of experiments at the Fraser Experimental Forest in Colorado (Wilm and Dunford 1948; Hoover and Leaf 1967; Troendle and King 1985), researchers demonstrated that depending on the amount and pattern of forest cutting, water yield could be increased from the net effect of reduced canopy interception loss and losses due to increased evaporation/sublimation (DeWalle and Rango 2008). Changes in the timing and magnitude of peak streamflow will depend on the cutting patterns (slope aspect, size) and the synchronization of melt from cut and uncut areas in a watershed (Troendle 1983).

1.2.5 Process Research in Forest Hydrology

The *International Symposium on Forest Hydrology* in 1965 was the first forum where researchers from experimental watersheds from all over the world came together, exchanged viewpoints, and presented significant results on forest-soil-water relationships and forest watershed behavior. Another objective of this symposium was "to determine the status of research in forest hydrology in order to provide a bench mark which might serve as a point of departure for anticipated research during the [International] Hydrologic[al] Decade" (IAHS 1966). Discussion by prominent hydrologists (e.g., Penman) at the *International Symposium* urged for a more processed-based understanding of hydrological results from watershed experiments (Sopper and Lull 1967). The International Hydrological Decade (IHD) helped expand the scope of research to emphasize the study of hydrologic processes (e.g., streamflow generation processes and evaporation/interception research). In addition, many new "representative" and "experimental" basins were instrumented and monitored as part of the IHD or selected from well-established, existing research watersheds (Toebes and Ouryvaev 1970).

One major outcome of this period was the explosion of research on streamflow generation and hillslope processes as evidenced by the content of the seminal book on