



森林

林

余新晓 张志强 陈丽华 谢宝元 王礼先 等 著
Forest Ecological Hydrology

生态

水文

中国林业出版社

森林生态水文

Forest Ecological Hydrology

余新晓 张志强 陈丽华 谢宝元 王礼先 等著

中国林业出版社



本书主要著者

(以姓氏笔画为序)

于志民 牛健植 王小平 王礼先
甘 敬 刘世海 余新晓 李文宇
吴东国 张志强 陈丽华 武 军
范志平 秦富仓 秦永胜 谢宝元

学术秘书:牛健植 秦富仓

图书在版编目(CIP)数据

森林生态水文/余新晓等著. —北京:中国林业出版社,2004.11

ISBN 7-5038-3849-3

I. 森… II. 余… III. 森林—生态系统—水文学—研究 IV. S715

中国版本图书馆 CIP 数据核字(2004)第 087440 号

森林生态水文

出 版:中国林业出版社 (100009 北京西城区刘海胡同7号)

E-mail: cfphz@public.bta.net.cn

电 话: 66184477

发 行:中国林业出版社

印 刷:北京地质印刷厂

版 次:2004年11月第1版

印 次:2004年11月第1次

开 本:889mm×1194mm 1/16

印 张:16.5

字 数:455千字

印 数:1~2000册

定 价:55.00元

森林是陆地生态系统的主体,具有巨大的经济价值、文化价值和生态价值,是美好家园的创造者;水是生态系统最为活跃而又不可替代的生态因子,是人类的生命之源,是联系地球系统地圈—生物圈—大气圈的纽带,与森林关系密切;水资源和森林资源匮乏问题是人类进入 21 世纪所面临的重要资源问题之一,其产生的主要原因在于人类活动破坏了森林与水资源的生态空间。

研究森林与水相互交织的复杂关系是生态学家和水文学家千百年关注的热点,但他们都是有针对性地开展研究工作。进入 20 世纪 90 年代,生态学家和水文学家发现单纯从事本领域研究工作,有些问题解释不通,并有局限性,如生态学家们关注水文过程对生态系统功能的重要影响,但忽视了水文过程与生态系统植物群落变化与相互制约的内在联系;水文学家过去关心最多的是洪水与干旱的成因、工程水文的实际设计应用等,但随着对生态与环境问题的重视与提出,他们发现诸如流速如何影响河道内的植物生长、河川径流的情势与滨岸生态环境过程之间是如何相互作用与联系的、如何使水文学研究适应可持续的生态平衡等等也是研究的重点。生态环境保护日益引起人们的关注,人们也越来越认识到与自然生态系统协调共处对人类可持续发展的重要性,而在自然生态系统与人类的众多复杂关系中,水是最为活跃和最具决定性的因素,水资源开发利用所导致的区域水文过程变化将不可避免地对该区域生态环境体系产生影响,而区域生态环境变化,尤其是植被生态系统的变化,将势必对区域水文过程产生作用。

社会的需求和人类的进步要求开展水文循环过程的变化与其相关生态环境变化的交叉研究。非常可喜的是,余新晓同志及其合作者编写的《森林生态水文》一书,它是著者们多年研究的结晶,他们以都市水源保护林为研究对象的暖温带森林生态系统定位研究站为基地,以生态过程和生态格局的水文学机制为研究核心,以植物与水分关系为基础理论,将尺度问题贯穿于整个研究之中,以林冠层、地被物层和土壤层的水分关系为基础理论,将尺度问题贯穿于整个研究之中,针对林冠层、地被物层和土壤层的水分运动过程开展研究工作,研究对象涉及径流、侵蚀产沙、侵蚀模拟、生态用水、水质等方面内容,该书深刻揭示了生态格局和生态过程的水文学机制,为水资源可持续利用及有效管理提供了科学依据。我相信,该书的出版将会对同类地区的生态水文研究,对我国生态环境建设,起到一定的技术支持和理论指导作用。

中国工程院院士

吴君祥

2004 年 6 月

森林生态水文从提出到现在只有 60 多年的历史,作为一门研究森林与水关系的新兴学科,具有显著的综合性、交叉性和边缘性。在 20 世纪 90 年代初期,森林生态水文研究的主要内容是森林植被与水量要素之间的相互关系,进入 21 世纪,随着社会经济的迅猛发展,人口数量激增,自然资源大量消耗,国际社会出现了资源、环境、人口和发展等重大问题,森林生态水文研究的重点也转向森林生态系统与水资源、水环境和协调人、森林与水的复杂关系,以及为解决重大生态建设工程和生产技术问题提供理论与方法。

长期以来,在科技部、国家林业局和北京市的大力支持下,作者一直致力于森林生态水文领域的研究,近年来又获得了国家自然科学基金重点基金和中德、中奥等国际科技合作项目的资助,使对森林植被与水(包括水量、水质和泥沙)关系的研究不断深入。1987 年北京林业大学和北京市林业局在北京市密云县共同建立了以都市水源保护林为研究对象的暖温带森林生态系统定位研究站,十余年来,通过长期野外观测实验、采样分析、建立模型和利用地理信息系统及与“3S”技术相结合,从径流小区、坡面径流场和小流域等不同尺度层次,系统地研究了森林植被对径流、水质和土壤侵蚀的影响,强调尺度分析和综合分析;从森林植被冠层、地被物层和林木根系分布层等不同作用层次,深入分析了森林植被林冠截留、枯枝落叶层持水、林地土壤水分运动规律、林地坡面地表径流过程和森林生态系统的水量平衡,强调过程分析和机制分析;从生物地球化学循环入手,阐明森林植被对降水化学性质的影响和主要养分元素的生物地球化学循环规律,强调功能分析和作用分析;从森林植被生态用水的角度,建立了森林植被生态用水的理论,强调生态分析和应用分析。综合长期工作的研究,将多年来的成果进行系统总结,编撰此书,期待对我国该领域的研究起推动作用,并在我国林业生态工程建设中发挥积极作用。

本书立足于国际森林生态水文学科前沿,以长期和大量的第一手实验数据为基础,系统论述了森林生态水文过程—尺度—机制—功能的基本理论。全书共分 10 章,第一章从森林植被变化对水量的影响、森林植被对流域径流形成机制的影响、森林植被控制土壤侵蚀机理研究、森林生态系统生物地球化学循环研究、森林水文模型研究进展和生态用水研究现状与发展趋势等方面论述了森林生态水文国内外研究进展;第二章通过森林林冠截留的实验分析,从森林植被冠层的水文机理和枯枝落叶层的水文机理两个方面论述了森林植被冠层与地被物层水文机制;第三章分析了森林植被对天然坡面和小流域等尺度对地表径流的影响;第四章建立了森林植被生态用水的理论,进行了生态用水的计算与分析 and 生态需水的预测与分析;第五章论述了径流小区尺度森林植被对土壤侵蚀产沙的影响、天然坡面尺度森林对

土壤侵蚀产沙的影响、试验小流域尺度森林对土壤侵蚀产沙的影响和森林对土壤侵蚀影响的空间尺度效应;第六章通过试验流域地理信息数据库的建立和小流域侵蚀过程空间联系的分析,建立了试验流域土壤侵蚀模型系统,对森林小流域土壤侵蚀过程进行了模拟和检验;第七章从大气降水化学性质、森林植被降水格局、森林生态系统降水化学性质、森林土壤层透过水化学性质、浅层地下水(潜水)及河流断面水化学性质监测分析和河川径流、地下水与大气降水中化学元素特征比较等方面论述了森林植被对降水化学性质的影响;第八章分析了刺槐林、油松林和板栗林主要营养元素的生物地球化学循环,对不同森林类型主要营养元素生物地球化学循环进行了比较;第九章对森林水质影响评价进行了分析;第十章对土地利用(森林植被)变化的水文响应进行了分析。

森林生态水文许多重要理论和实践问题的研究尚在探索之中,随着研究的不断深入,必将对森林生态水文理论体系的发展和应用起到积极的推动作用。作者殷切期望本书的出版能引起有关人士对该研究领域的更大关注和支持,并希望能对从事森林生态水文及相关学科的专家学者有所裨益,共同将这一重要的科学领域推向新的发展阶段。

本书的研究资料的积累过程实际上就是作者从事森林生态水文科研和研究生教学的过程,曾先后得到关君蔚院士、沈国舫院士、蒋有绪院士、朱金兆教授、尹伟伦教授、周心澄教授和于志民教授等诸位先生的指导,在此一并表示衷心的感谢!

本书的出版得到了国家科学技术学术著作出版基金的资助,以及国家“十五”科技攻关计划“退耕还林还草工程区水源涵养型植被建设技术与示范”和农业科技成果转化资金项目“水源保护林培育与经营管理综合配套技术”的资助,也是国家林业局首都圈森林生态站监测成果的总结。鉴于森林生态水文研究的复杂性及作者的知识和能力有限,书中难免有不妥之处,敬请读者不吝赐教。

余新晓

2004年5月于北京

Foreword

Only around sixty years has gone since the subject of Forest Ecological Hydrology put forward. As a newly developed subject focusing on studying the relationship between forest and water, forest ecological hydrology shows its apparent characteristics in terms of synthesis, borderline and cut-cross. Before 90s of the 20th century, researches were mainly on relationship between forest cover and basic factors affecting water yield. But since then, particularly after entering the 21st century, along with rapid socio-economic development and growth of population as well as large consumption of natural resources, serious problems emerged in the aspect of resource, environment, population and development all over the world. The forest ecological hydrology thus shifted its focal researches to studying the relationship between forest ecosystem and water resources, harmony between water environment and human life, forest and water, as well as developing theories and methods for implementing ecological construction program and solving technical problems in production activities.

For a long time, with the support of the Ministry of Science and technology, the State Forestry Bureau and Beijing government, the author has been continuously working on researches of forest ecological hydrology. In recent years, in-depth work is being carried out to study the relationship between forest and water (yield, quality and sediment) with additional support from the Key National Foundation for Natural Science and international technical cooperation such as Sino-German and Sino-Austrian cooperation project. In 1987, taking the urban headwaters protection forest as the study object, a warm temperate forest ecosystem research station was established in Miyun County of Beijing jointly by the Beijing Forestry University and the Beijing Forestry Bureau. Therefore, different researches have been conducted in a long-term basis at the station, i. e. systematic researches on impact of forest on runoff, water quality and soil erosion in scales of runoff plot, slope plot and watershed through field observations, sampling analysis, modeling, GIS and 3S technology, with emphasis on scale and synthetic analysis approaches; in-depth analysis of interception of forest crown and litter-layer, water flux in soil, process of overland flow of forested slope, water equilibrium of forest ecosystem, with emphasis on process and mechanism analysis approaches; researches on impact of forest on chemical characteristics of rainfall and on bio-geochemical cycle of the main nutrient elements, with emphasis on function and effect analysis approaches; developing the theory of ecologic water requirement of forest, with emphasis on ecological and applicable analysis approaches. Based on the previous work, the author tries to summarize his researches results systematically into this book edition. The author hopes this book can contribute to promoting research in this field and also can play a certain role in implementing the forest ecological construction program of our country.

This book describes the basic theory of process-scale-mechanism-function of forest ecological hydrology systematically, standing at the front of the subject of forest hydrology in the world and making use of plenty of first hand data obtained from long-term researches. The book contains ten chapters all together. In Chapter 1, reviewing the research development of forest hydrology in the world, with respect to impact of forest change on glow yield and on mechanism of watershed flow generation, mechanism of forest in soil erosion con-

trol, bio-geochemical cycle of forest ecosystem, progress in modeling researches as well as research status and trend of ecological water requirement; in chapter 2, through experimental analysis of forest crown interception, describing the hydrological mechanism of forest crown and ground cover based on studies on hydrological mechanism of forest crown and litter; in chapter 3, analyzing the impact of forest on overland flow of natural slope and watershed scheme; in chapter 4, developing the theory of ecological water requirement of forest and conducting the calculation and analysis of ecological water requirement, as well as prediction of ecological water requirement; in chapter 5, discussing the impact of forest of runoff plot, natural forested slope and experimental watershed on soil erosion and sediment generation, and the spatial scale effect of forest on soil erosion; in chapter 6, establishing the soil erosion model of experimental watershed and also the modeling and verification of soil erosion process of forested watershed; in chapter 7, discussing the impact of forest on rainfall chemical characteristics based on analysis of atmospheric rainfall chemical characteristics, rainfall pattern of forest, rainfall chemical characteristics in forest ecosystem, chemical characteristics of infiltrating water of forest soil, chemical characteristics of shallow groundwater and river intersect under monitoring, comparison of chemical elements characteristics among river flow, underground water and atmospheric rainfall; in chapter 8, analyzing the bio-geochemical cycle of the main nutrient elements of Robinia pseudoacacia, pine and chestnut forest and comparison among different type of forests; in chapter 9, discussing the assessment of impact of forest on water quality; in chapter 10, analyzing the response of hydrology on land use and forest vegetation change.

No doubt, there are still many other aspects of theory and practice of forest ecological hydrology under exploring. Obviously, deepening research will play an active role in promoting the theory system development and application of forest hydrology. The author sincerely hopes that the publication of this book can attract more attention and support to this scientific subject, and also expects the book can benefit those expertise and scholars working on forest ecological hydrology and relevant fields, in order to increasingly promote the development of this significant science into a new stage.

The accumulation of the data referred to the book actually reflects the author's work on researches and education for postgraduates. During this period, the author has obtained valuable guidance from the academicians of Mr. Guan Junwei, Mr. Shen Guofang and Mr. Jiang Youxu, professors of Mr. Zhu Jinzhao, Mr. Yin Weilun, Mr. Zhou Xincheng and Mr. Yu Zhimin. Here, the author expresses his gratitude to all of them.

The publication is financed by the State Publication Foundation, "Tenth Five-Year Plan" National Key Projects in Science and Technology (Grant No. 2001BA 510 B 02 - 02) and the project of the Commercialization of Agricultural Research Findings (Grant No. 02 EFN216700779). Due to the complex of forest ecological hydrology research and the author's limitation in his knowledge and capability, the book is far from perfect, thus comments and suggestions are always welcome.

Prof. Dr. Yu Xinxiao
Beijing, May 2004

序 前 言

第一章 森林生态水文研究进展	(1)
第一节 森林植被变化对水量的影响	(2)
一、流域(系统)研究	(2)
二、过程研究	(5)
第二节 森林植被对流域径流形成机制的影响	(6)
第三节 生态用水研究现状与发展趋势	(8)
一、问题的由来	(8)
二、研究现状	(11)
三、发展趋势	(13)
第四节 森林植被控制土壤侵蚀机理研究	(13)
一、森林植被冠层的防蚀作用	(14)
二、森林植被枯落物层的防蚀作用	(14)
三、森林植被含根土壤层的防蚀作用	(15)
四、森林植被防蚀作用的生态学研究进展	(16)
五、森林植被防止土壤侵蚀临界	(17)
六、森林植被防蚀作用的模型表达	(17)
第五节 森林生态系统生物地球化学循环研究	(18)
一、林分生长量、生产力和生物量研究	(18)
二、森林生态系统养分循环的研究	(18)
三、森林生态系统对水质影响的研究	(19)
第六节 森林生态水文模型研究进展	(22)
第二章 森林植被冠层与地被物层水文机制	(24)
第一节 森林林冠截留的实验分析	(24)
一、森林降水林冠截留率	(24)
二、林内降水与林外降水的关系	(24)
三、森林林冠截留随降水量的变化关系	(26)
第二节 森林植被冠层的水文机理	(27)
一、森林林冠截留过程分析	(27)
二、林冠截留模型	(31)
三、林冠透过降水的能量特性分析	(32)

第三节 森林植被枯枝落叶层的水文机理	(33)
一、枯枝落叶层的水文生态功能	(33)
二、枯枝落叶层的蓄水减沙功能	(39)
第三章 森林对不同尺度径流的影响	(41)
第一节 天然坡面径流场森林对地表径流的影响	(41)
一、天然坡面径流场概况	(41)
二、降水特性分析	(43)
三、坡面径流过程及其形成机制分析	(45)
四、天然坡面尺度刺槐林对地表径流的影响分析	(47)
第二节 小流域尺度森林对地表径流的影响	(51)
一、试验小流域概况	(51)
二、试验小流域降水径流过程分析	(52)
三、小流域尺度刺槐林对地表径流量的影响	(54)
四、刺槐林对地表径流洪峰流量的影响	(56)
第四章 森林植被生态用水	(58)
第一节 森林植被生态用水的理论	(58)
一、生态用水的定义	(58)
二、生态用水的分类	(59)
三、生态用水计算的理论基础	(60)
第二节 生态用水的计算与分析	(65)
一、生态分区与生态用水类型	(65)
二、生态用水定额的确定	(68)
三、现状生态用水的计算	(72)
四、现状生态用水分析	(77)
第三节 生态需水的预测与分析	(80)
一、生态需水量的预测	(80)
二、生态需水分析	(82)
第五章 森林植被对侵蚀产沙的影响	(85)
第一节 径流小区尺度森林植被对土壤侵蚀产沙的影响	(85)
一、人工径流小区布设及其自然条件	(85)
二、人工径流小区产流量与产沙量	(85)
第二节 天然坡面尺度森林对土壤侵蚀产沙的影响	(89)
一、天然坡面场降水过程产沙特性分析	(90)
二、天然坡面场降水产沙量分析	(90)
第三节 试验小流域尺度森林对土壤侵蚀产沙的影响	(92)
一、对比试验流域暴雨径流过程产沙特性分析	(92)
二、森林径流的空间尺度效应分析	(94)
第四节 森林对土壤侵蚀影响的空间尺度效应	(96)
一、径流小区尺度	(97)
二、天然坡面尺度	(98)

三、试验流域尺度·····	(99)
四、森林防治土壤侵蚀临界·····	(99)
五、森林年土壤侵蚀量分析·····	(100)
第六章 GIS支持下森林流域径流与侵蚀模拟·····	(101)
第一节 试验流域地理信息数据库的建立·····	(101)
一、软硬件设备配置·····	(101)
二、空间数据库的建立·····	(101)
三、属性数据库的建立·····	(102)
第二节 小流域侵蚀过程空间联系的分析·····	(102)
一、基本分析思路·····	(102)
二、水文DEM分析·····	(102)
第三节 试验流域土壤侵蚀模型系统的建立·····	(106)
一、截留模型·····	(107)
二、枯落物糙率系数模型·····	(107)
三、径流量计算模型·····	(107)
四、土壤侵蚀模型·····	(109)
五、泥沙输移模型·····	(109)
第四节 森林小流域径流和土壤侵蚀过程模拟·····	(110)
第五节 径流和土壤侵蚀模拟结果检验·····	(111)
第七章 森林植被对降水化学性质的影响·····	(119)
第一节 大气降水化学性质·····	(119)
一、密云水库北京集水区大气降水特征·····	(119)
二、大气降水化学性质·····	(120)
第二节 森林植被降水格局·····	(123)
一、刺槐林对降水再分配特征·····	(123)
二、油松林对降水再分配特征·····	(124)
三、板栗林对降水再分配特征·····	(125)
四、不同类型森林对降水再分配特征比较·····	(125)
第三节 森林生态系统降水化学性质·····	(126)
一、刺槐林降水化学性质·····	(126)
二、油松林降水化学性质·····	(127)
三、板栗林降水化学性质·····	(128)
四、不同类型水源林降水化学性质比较·····	(129)
第四节 森林土壤层透过水化学性质·····	(132)
一、刺槐林土壤层透过水化学性质·····	(133)
二、油松林土壤层透过水化学性质·····	(135)
三、板栗林土壤层透过水化学性质·····	(135)
四、不同类型森林土壤层透过水化学性质比较·····	(136)
第五节 浅层地下水(潜水)及河流断面水化学性质监测结果·····	(138)
第六节 河川径流、地下水与大气降水中化学元素特征比较·····	(140)

第八章 森林植被主要养分元素的生物地球化学循环	(142)
第一节 刺槐林主要营养元素的生物地球化学循环	(142)
一、刺槐林标准地基本情况	(142)
二、刺槐林林分生长状况分析	(142)
三、刺槐林生物量测定分析	(143)
四、刺槐林主要养分元素的生物地球循环特征	(145)
第二节 油松林主要养分元素的生物地球化学循环	(149)
一、油松林生长状况调查	(150)
二、油松林主要养分元素生物地球化学循环特征	(155)
第三节 板栗林主要养分元素的生物地球化学循环	(160)
一、板栗林标准地布设	(160)
二、板栗林生物量测定	(160)
三、板栗林各器官养分元素含量测定	(161)
四、板栗林主要养分元素的生物地球化学循环特征	(161)
第四节 不同森林类型主要营养元素生物地球化学循环比较	(164)
一、不同森林类型养分贮存量比较	(164)
二、不同森林主要营养元素的生物地球化学循环比较	(167)
第九章 森林植被对水质的影响分析	(169)
第一节 森林植被对降水水质的影响	(169)
一、大气降水水质特征分析	(169)
二、森林植被内降水水质分析	(169)
第二节 森林植被对径流水质的影响分析	(172)
一、森林植被对地表径流水质的影响分析	(172)
二、森林植被壤中流水质分析	(173)
三、森林植被对地下水水质的影响分析	(184)
第三节 森林植被对水质的影响评价	(187)
一、水质评价分析方法	(187)
二、森林植被对径流水质的影响评价	(190)
三、森林植被对密云水库水体的水质影响评价	(196)
第十章 土地利用(森林植被)变化的水文响应	(199)
第一节 SWAT 模型原理	(199)
一、SWAT 模型简介	(199)
二、SWAT 组成	(200)
三、SWAT 的产流模型	(202)
四、产沙模型	(203)
五、养分转移模型	(203)
六、SWAT 的运行机制	(205)
七、AVSWAT-2000 介绍	(206)
第二节 土地利用(森林植被)的变化分析	(208)
一、土地利用(森林植被)的特点	(208)

二、土地利用(森林植被)的变化特点	(210)
第三节 SWAT 模型运行过程	(211)
一、模型数据的输入	(211)
二、模型输出	(216)
第四节 土地利用(森林植被)水文响应分析.....	(217)
一、以 1991 年土地利用为数据的模拟分析.....	(217)
二、以 2001 年土地利用为数据的模拟分析.....	(220)
三、二期模拟结果的比较分析	(223)
第五节 土地利用(森林植被)水文响应预测.....	(226)
一、不同水平年降水的水文响应预测	(226)
二、变化土地利用条件下的水文响应预测	(227)
参考文献	(229)

Preface

Foreword

1 Research development in forest hydrology	(1)
1.1 Impact of forest cover change on flow yield	(2)
1.1.1 Watershed / system study	(2)
1.1.2 Process study	(5)
1.2 Impact of forest cover on mechanism of watershed flow formation	(6)
1.3 The present situation and trend of the researches on ecological water requirement	(8)
1.3.1 Background	(8)
1.3.2 Present situation	(11)
1.3.3 Trend	(13)
1.4 Studies on forest cover in soil erosion control	(13)
1.4.1 Effect of forest canopy in soil erosion control	(14)
1.4.2 Effect of forest litter-layer in soil erosion control	(14)
1.4.3 Effect of forest root-bearing soil in erosion control	(15)
1.4.4 Progress in the ecology researches of forest's effect in erosion control	(16)
1.4.5 Threshold of forest cover in soil erosion control	(17)
1.4.6 Modeling forest cover effect in soil erosion control	(17)
1.5 Studies on bio-geochemical cycle of forest ecosystem	(18)
1.5.1 Studies on forest stand's growth, productivity and biomass	(18)
1.5.2 Studies on nutrient cycle of forest ecosystem	(18)
1.5.3 Studies on impact of forest ecosystem on water quality	(19)
1.6 Progress in the researches of forest hydrological modeling	(22)
2 Hydrological mechanism of forest canopy and ground cover	(24)
2.1 Experimental analysis of forest canopy interception	(24)
2.1.1 Forest canopy interception rate	(24)
2.1.2 Relationship between rainfall within and outside of forest	(24)
2.1.3 Relationship between forest canopy interception and rainfall intensity	(26)
2.2 Hydrological mechanism of forest canopy	(27)
2.2.1 Analysis of interception process of forest canopy	(27)

2.2.2	Modeling of forest canopy interception	(31)
2.2.3	Analysis of characteristics of throughfall energy inside forest canopy	(32)
2.3	Hydrological mechanism of forest litter-layer	(33)
2.3.1	Hydrological-ecological function of forest litter-layer	(33)
2.3.2	Forest litter-layer function in water interception and sediment reduction	(39)
3	Impact of forest on runoff in different scale	(41)
3.1	Impact of forest on overland flow in natural slope runoff plot	(41)
3.1.1	General situation of the natural slope runoff plot	(41)
3.1.2	Analysis of characteristics of the rainfall during the experiment	(43)
3.1.3	Process of slope overland flow and mechanism of flow formation	(45)
3.1.4	Impact of Robinia pseudoacacia forest on overland flow in natural slope scale	(47)
3.2	Impact of forest on overland flow in watershed scale	(51)
3.2.1	General situation of the experimental watershed	(51)
3.2.2	Process analysis of rainfall and flow in the experimental watershed	(52)
3.2.3	Impact of Robinia pseudoacacia forest on overland flow in watershed scale	(54)
3.2.4	Impact of Robinia pseudoacacia forest on overland peak flow yield	(56)
4	Ecological water requirement of forest	(58)
4.1	Theory of the ecological water requirement of forest	(58)
4.1.1	Definition of ecological water requirement	(58)
4.1.2	Classification of ecological water requirement	(59)
4.1.3	Theoretical basis of calculation of ecological water requirement	(60)
4.2	Calculation and analysis of ecological water requirement	(65)
4.2.1	Ecological zoning and types of ecological water requirement	(65)
4.2.2	Determination of ecological water requirement quota	(68)
4.2.3	Calculation of present ecological water requirement	(72)
4.2.4	Analysis of present ecological water requirement	(77)
4.3	Prediction and analysis of ecological water requirement	(80)
4.3.1	Prediction of ecological water requirement	(80)
4.3.2	Analysis of ecological water requirement	(82)
5	Impact of forest on erosion and sediment generation	(85)
5.1	Impact of forest on erosion and sediment generation in runoff plot scale	(85)
5.1.1	Designing of artificial runoff plot and natural condition	(85)
5.1.2	Runoff and sediment generation in artificial runoff plot	(85)
5.2	Impact of forest on soil erosion and sediment generation in natural slope scale	(89)
5.2.1	Characteristics of rainfall process and sediment generation in natural slope plot	(90)
5.2.2	Analysis of rainfall and sediment generation in natural slope plot	(90)
5.3	Impact of forest on soil erosion and sediment generation in watershed scale	(92)
5.3.1	Characteristics of sediment generation in a stormflow process in experimental watershed	(92)

5.3.2	Analysis of effect of spatial scale of forest runoff	(94)
5.4	Spatial scale effect of forest on soil erosion	(96)
5.4.1	Scale of runoff plot	(97)
5.4.2	Scale of natural slope	(98)
5.4.3	Scale of watershed	(99)
5.4.4	Threshold of forest in erosion control	(99)
5.4.5	Analysis of annual soil erosion in forest	(100)
6	GIS-based simulation of runoff and erosion in forested watershed	(101)
6.1	Establishment of geographic information data of experimental watershed	(101)
6.1.1	Setup of software and hardware	(101)
6.1.2	Establishment of spatial data	(101)
6.1.3	Establishment of attribute data	(102)
6.2	Analysis of spatial relation of erosion process in watershed	(102)
6.2.1	Basic analysis approach	(102)
6.2.2	Hydrologic DEM analysis	(102)
6.3	Establishment of soil erosion model in experimental watershed	(106)
6.3.1	Interception model	(107)
6.3.2	Roughness coefficient model of litters	(107)
6.3.3	Calculation model of runoff	(107)
6.3.4	Soil erosion model	(109)
6.3.5	Sediment transport model	(109)
6.4	Simulation of runoff and soil erosion process in forest watershed	(110)
6.5	Verification of the simulated results of runoff and soil erosion	(111)
7	Impact of forest cover on chemical characteristics of rainfall	(119)
7.1	Chemical characteristics of atmospheric rainfall	(119)
7.1.1	Atmospheric rainfall characteristics in the Beijing catchment of Miyun reservoir	(119)
7.1.2	Chemical characteristics of atmospheric rainfall	(120)
7.2	Rainfall pattern in forest	(123)
7.2.1	Characteristics of rainfall redistribution affected by Robinia pseudoacacia forest	(123)
7.2.2	Characteristics of rainfall redistribution affected by pine forest	(124)
7.2.3	Characteristics of rainfall redistribution affected by chestnut forest	(125)
7.2.4	Comparison of characteristics of rainfall redistribution affected by different type of forest	(125)
7.3	Chemical characteristics of rainfall in forest ecosystem	(126)
7.3.1	Chemical characteristics of rainfall in Robinia pseudoacacia forest	(126)
7.3.2	Chemical characteristics of rainfall in pine forest	(127)
7.3.3	Chemical characteristics of rainfall in chestnut forest	(128)
7.3.4	Comparison of chemical characteristics of rainfall in different type of headwaters forest	(129)

7.4	Chemical characteristics of infiltrating water of forested soil layer	(132)
7.4.1	Chemical characteristics of infiltrating water of Robinia pseudoacacia forested soil layer	(133)
7.4.2	Chemical characteristics of infiltrating water of pine forested soil layer	(135)
7.4.3	Chemical characteristics of infiltrating wates of chestnut forested soil layer	(135)
7.4.4	Comparison of chemical characteristics of infiltrating water of different type of forested soil layer	(136)
7.5	Monitoring results of chemical characteristics of shallow underground water and cross-section water of river	(138)
7.6	Comparison of characteristics of chemical elements of river flow, underground water and atmospheric rainfall	(140)
8	Bio-geochemical cycle of the main nutrient elements of forest	(142)
8.1	Bio-geochemical cycle of the main nutrient elements of Robinia pseudoacacia forest	(142)
8.1.1	Basic situation of the standard land of Robinia pseudoacacia forest	(142)
8.1.2	Analysis of growth of Robinia pseudoacacia forest stand	(142)
8.1.3	Analysis of measurement of biomass of Robinia pseudoacacia forest	(143)
8.1.4	Characteristics of bio-geochemical cycle of the main nutrient elements of Robinia pseudoacacia forest	(145)
8.2	Bio-geochemical cycle of the main nutrient elements of pine forest	(149)
8.2.1	Investigation of the growth of pine forest	(150)
8.2.2	Bio-geochemical cycle of the main nutrient elements of pine forest	(155)
8.3	Bio-geochemical cycle of the main nutrient elements of chestnut forest	(160)
8.3.1	Design of the standard land of chestnut forest	(160)
8.3.2	Measurement of the biomass of chestnut forest	(160)
8.3.3	Measurement of the main nutrient elements of various chestnut organs	(161)
8.3.4	Bio-geochemical cycle of the main nutrient elements of chestnut forest	(161)
8.4	Comparison of bio-geochemical cycle of the main nutrient elements of different forests	(164)
8.4.1	Comparison of nutrient stock of different type of forests	(164)
8.4.2	Comparison of bio-geochemical cycle of the main nutrient elements of different forests	(167)
9	Analysis of the impact of forest on water quality	(169)
9.1	The influence to rainfall quality of forest	(169)
9.1.1	Analysis of characteristics of rainfall quality	(169)
9.1.2	Analysis of characteristics of rainfall quality within forest	(169)
9.2	Impact of forest on runoff water quality	(172)
9.2.1	Impact of forest on overland flow water quality	(172)
9.2.2	Impact of forest on interflow water quality	(173)