



United Nations  
Educational, Scientific and  
Cultural Organization



International  
Hydrological  
Programme

# Forest Management and the impact on water resources: a review of 13 countries



IHP - VIII / Technical document N° 37  
Latin America and the Caribbean

United Nations Educational, Scientific, and Cultural Organization

International Hydrological Programme

International Sediment Initiative

# Forest management and the impact on water resources: a review of 13 countries



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Published in 2017 by the United Nations Educational, Scientific and Cultural Organization, 7, place de Fontenoy, 75352 Paris 07 SP, France and UNESCO Regional Office for Sciences for Latin America and the Caribbean – UNESCO Montevideo

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ISBN 978-92-3-100216-8



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Graphic design: Leonardo Alvarez de Ron

Cover design: María Noel Pereyra

Typeset: Pablo García Chevesich

Edition: Miguel Doria, Soledad Benítez, Joaquín Jafif and Tatiana Másmela

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## Acknowledgements

The editors deeply thank all the contributing authors that submitted a chapter representing their country, for all the time and effort invested.



# Executive summary

Trees have been around for more than 370 million years, and today there are about 80 thousand species of them, occupying 3.5 billion hectares worldwide, including 250 million ha of commercial plantations. While forests can provide tremendous environmental, social, and economic benefits to nations, they also affect the hydrologic cycle in different ways. As the demand for water grows and local precipitation patterns change due to global warming, plantation forestry has encountered an increasing number of water-related conflicts worldwide.

This document provides a country-by-country summary of the current state of knowledge on the relationship between forest management and water resources. Based on available research publications, the Editor-in-Chief of this document contacted local scientists from countries where the impact of forest management on water resources is an issue, inviting them to submit a chapter. Authors were instructed to use the following structure:

## 1. Introduction

Present a brief history of the country's native forests and forest plantations, describing the past and current natural and plantation forest distribution (map, area, main species), as well as main products produced (timber, pulp, furniture, etc.). Characterize the country's water resources and main water uses, discussing the key water resource issues. Finally, describe the forest & water issues that are relevant in the country.

## 2. Literature review

Write a brief review of water-related forest management studies. Include methods (e.g. paired watershed studies, precipitation/runoff relationship, water balance, hydrological modelling, sap flow meters, etc.) and results. End with a section on best management practices utilized or recommended by the country to increase water yield and/or improve water quality.

## 3. Politics

Discuss key environmental regulations, laws, and policies related to forestry and water, and evaluate how research results have interacted with politics and *vice versa*, i.e. the creation of new regulations, either enforced by the law, or simply applied by the private sector, to improve water yield and water quality. Also, discuss the role of forest certification systems in managing water quantity and quality.

## 4. Climate change and the future of forestry & forest research

Evaluate the effects of climate change in the country, especially on water resources, describing how the area occupied by forest plantations is increasing or decreasing, and where. End this section proposing future research and management practices that should be incorporated in the management of forest plantations to improve water quality and water yield.

An excellent group from 13 nations, representing almost half the World's population, submitted chapters (Argentina, Australia, Brazil, Chile, China, Republic of Congo, India, Malaysia, Peru,



Romania, South Africa, Spain, and United States), making this document a relevant contribution to the current state of water and forestry-related issues, management, and policies worldwide.

Differences in historical forest management, climate, vegetation types and socioeconomic conditions driving the use and management of forests mean that forest hydrology research results vary from nation to nation. This makes it difficult to generalise and extrapolate between countries and regions. What seems to be of greatest importance is the combination of watershed characteristics (size, slope and soils), current and prior land uses and local climates, especially the temporal distribution of annual precipitation and temperatures.

In certain climates, for example parts of Australia, Brazil, Chile, China, India, South Africa, Spain and the USA, where natural grassland, shrublands or land previously cleared for agriculture is replaced with fast growing plantations, streamflows and groundwater recharge are often substantially reduced, potentially creating local conflicts between plantations and other water users. In South Africa and Australia, this has led to introduction of legislation to limit plantation developments in some areas. Conversely, reforestation of degraded agricultural land, especially where soils have been heavily compacted, can sometimes increase dry season streamflows by increasing infiltration rates and may also increase the soil's water holding capacity as well as improving water quality. Consequently, flood mitigation is seen as an important role of forests in some countries.

Whereas once forests were thought to bring rain, it is now well documented that at local scales of tens to tens of thousands of ha, replacement of shallow-rooted vegetation with forest usually reduces streamflow but may improve water quality. Permanent clearing of forest will increase streamflow in some regions, albeit often accompanied by reduced water quality. In the few parts of the world where fog drip is an important hydrologic input, forest clearing reduces water yield. At much larger scales, for example in the Amazon Basin in Brazil and Peru, extensive forests can cycle moisture between the land and the atmosphere so that large-scale clearing of natural forest may have detrimental effects on regional and national water cycles.

In many countries, including Brazil, Chile, China, India, Malaysia, Peru, Romania, and Spain, deforestation and soil degradation have created water quality problems, which are now being addressed, or will need to be addressed through reforestation. In China, for example, extensive areas of highly erodible soils have been reforested. However there may be a trade-off between improved water quality through soil restoration and reduced water yield, unless rainfall occurs only during winter months, as is the Chilean case.

Fire in forests can create concerns over water quality, and less commonly, water yield. In Australia, Spain and the USA, fire seasons are becoming longer and more extreme due in part to combinations of drier and warmer climate. Forest management to reduce fire risk and the associated detrimental effects of wildfire on water quality, is now an important consideration in these countries.

Based on the information provided, the countries with the closest links between forest hydrology research and policy-making are Australia, Brazil, China, South Africa, and United States. However, in most of the reminding eight countries, research and political initiatives are rapidly advancing. Importantly, most countries have invested resources and research into climate change adaptations, including its effects on forests and water interactions. In many countries there is still a clear lack of connection between research results and effective forest management policies, a topic that urgently needs to be addressed.

Generally speaking, conflicts between forests and water are increasing worldwide, and future research should focus on how to solve current and future conflicts, considering local climates. As agriculture, mining, and urbanization continue to grow, it is expected that the demands for water resources will increase, leading to more conflicts. However, demands for forest-related products will also increase. Furthermore, the establishment, conservation, and management of forests are tasks that most countries should focus on, in order to ensure healthy watersheds. In this sense, activities such as reforestation, afforestation, and land restoration represent a key factor for the future, since worldwide millions of hectares are deforested every year, with many of them becoming deserts.

Before concluding, it is worth mentioning gender mainstreaming, even though the topic has not been the focus of this work, when remarking the importance of strengthening forests' as an effort to work towards poverty reduction, biodiversity conservation and sustainable development.

Though gender analysis of forest management for water resources is country specific, generally countries have a clear differentiation between the roles of men to those of women, as typically men are in charge of harvesting and manufacturing wood products, whereas women focus more on fruit collection or similar less intense tasks.

A study released by the International Union for Conservation of Nature (IUCN) in the International Year of Forests, 2011, concludes that men and women have different yet complementary knowledge, use and management of the forests. Therefore, in order to achieve sustainable use of forest and land resources, both women and men's needs, knowledge and experience must be valued and considered. This work suggests that despite there has been progress in women's access to education employment opportunities in development countries, there is still a marked disparity in forest education, employment and career perspectives in forestry. Results indicate that women have poor access to training programmes, official-decision making process as well as property rights of forests. On the other hand, women play an important role in forest resource management and conservation due to their close dependence on forest resources for subsistence (fuelwood, fodder, herbal medicine among others) and income.

A greater focus by future research on the interaction between forest management, water management and gender issues can help to better understand their interconnection and to identify ways to strengthen the management of both resources while fostering gender equality.

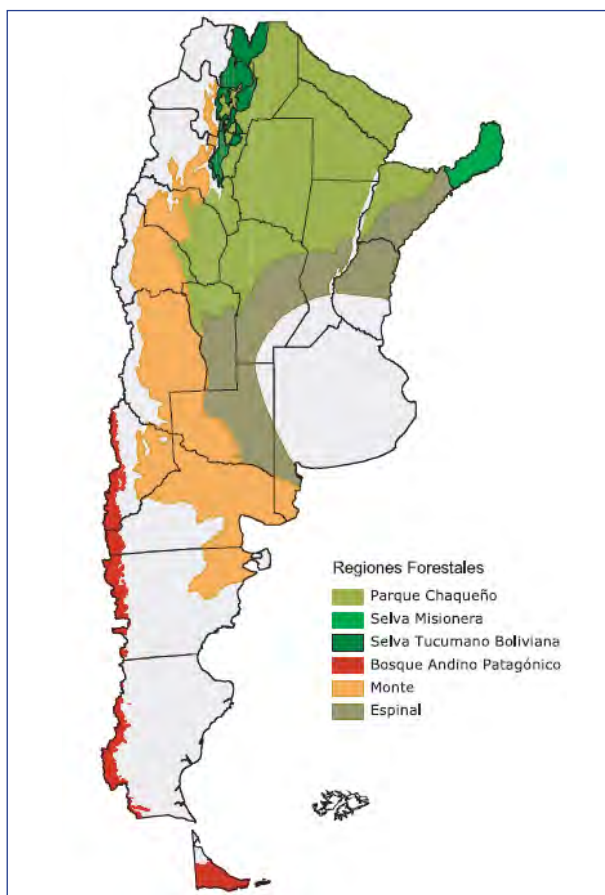
# Chapter 1. Forest Management and Water in Argentina

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## 1.1 Introduction

Argentina is the Latin American country with most arid semi-arid and dry sub-humid area, covering 75% of the country. Its large size, its variety of climatic conditions, geomorphic processes, soil, water and vegetation resources determine a great deal of ecological diversity and production systems based on the use of natural resources. These features define in Argentina large areas of native and planted forests, such as subtropical forests, xeric forests and cold temperate forests.

In this vast region, different environments of forests, shrubs and grass steppes, high deserts, wetlands, which have been subjected to different productive uses according to the different stages of colonization that the country underwent, are distinguished. Native forests in Argentina can be grouped into six forest regions as shown in Figure 1.



**Figure 1.** Forest regions of Argentina (source: Management Unit of Forest Assessment System (UMSEF) Head Office of Forestry, December 2002.). (“Parque Chaqueño”: Chaco Park Forest; “Selva Misionera”: Misiones Rainforest; “Selva Tucumano Boliviana”: Tucuman-Bolivian Rainforest; “Bosque Andino Patagónico”: Andean Patagonian Forest; “Monte”: Monte Shurblands; “Espinal”: Espinal Xeric Forest. ([http://cyt-ar.com.ar/cyt-ar/index.php/Regiones\\_forestales\\_de\\_Argentina](http://cyt-ar.com.ar/cyt-ar/index.php/Regiones_forestales_de_Argentina)).

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- 1) **Chaco Forest:** quebracho colorado santiagueño (*Schinopsis lorentzii*), quebracho blanco, algarrobo, vinal, itín, mistol, lapacho, palo blanco and palo lanza, yuchán, brea, duraznillo, palo santo, chañar, molle, urunday, guayacán, viraró, espina corona, palo piedra, palo amarillo (or ibirá-catú), tala, palmares.
- 2) **Misiones Rainforest:** Lapachos; laureles, guatambú blanco, palo rosa, cedro misionero, peteribí, yerba mate, marmelero, canafístola, timbó, guayubirá, urunday, cancharana, incienso, grapia, maría preta, rabo itá, rabo molle, azota caballo, aguaí, camboatá, carne de vaca, persiguero, el pino paraná (or araucaria), numerous mirtáceas, several bambúseas, as tacuarembó and tacuaruzú, palms as pindó.
- 3) **Tucumán-Bolivian Rainforests (“Yungas”):** tipuana tipu; the cebiles; pacará (called timbó in other regions); tarco (or rosewood); pink lapacho; biscote; picconia excelsa/palo blanco; terminalia australis/palo amarillo; White launches; (Guayaibí in other regions); laurels; horco-molle; (Or muddy stick); myrtle; cedars; Creole walnut; machine; cebiles; It pacará; Pine Hill; walnut.
- 4) **Andean Patagonian Forest:** populated mostly by conifers, Fagaceae, Myrtaceae and several species of *Nothofagus* such as pehuén; lipain, maitén, ñire, tepa, tepú, cypress Guaitecas, coihue, Coyan, lleuques, raulí, radial, lenga, Temu, the quetri or “myrtle” or the giant “patagonian larch” (lahuán) and huililahuán, copihue, notro and various evergreen shrubs such as cinnamon, blackberry, elderberry, strawberry, sarsaparilla etc.
- 5) **Monte Shrublands:** predominantly of jarillas (genus *Larrea*), pitch, pichana, retamo, tintitaco, and others that are typical jarillal.
- 6) **Espinal Xeric Forest:** «ñandubay» (*Prosopis affinis*), *Prosopis alba* and *P. Nigra* (black locust and black locust), Tala (*Celtis tala*), deciduous dry forests, shrubs and grass steppes; «Caldén» (*Prosopis caldenia*).

Today, a high percentage of these lands have significant levels of degradation and deterioration of their physical and chemical properties, generating negative environmental impacts besides agricultural activity itself.

In the early 20<sup>th</sup> century, natural forests covered a third of the Argentine territory; they were over one hundred million hectares (the areas of France and Spain together). Since then, the loss of native forest has been a constant process with pulses associated with favorable moments for agricultural expansion due to prices of agricultural products, technological changes or sociopolitical context (example of this were the years of the First World War, when Argentina was the leading producer of tannin extract).

In 1980, a period of deforestation began, helped by demand for primary products of native forests with the modernization of livestock management, increased agricultural area, and consequently the expansion of the railway system, which in summary generated a significant reduction in forest area.

The first estimate of the effective area of forest in Argentina corresponds to the National Agricultural Census of 1937. Since then, estimates show a marked decrease in forest area.

The First National Native Forest Inventory was developed under the Native Forests and Protected Areas Project (IBRD Loan 4085-AR, 1998-2005). The first survey of the surface and distribution of native forests nationwide is from 1998 (UMSEF – Head Office of Forestry - SAyDS, 2002) (Table 1).

**Table 1.** Argentine Area of Native Forest between 1937 and 2011 (ha). Source: Year 1937: National Agricultural Census; 1987: estimates (IFONA) National Forestry Institute; 1998: First National Native Forest Inventory-Project Native Forests and Protected-Secretariat of Environment and Sustainable Development Areas. Years 2002-2011: Management Unit of Forest Assessment System (UMSEF). Head Office of Forestry. Secretariat of Environment and Sustainable Development. Cabinet of Ministers.

Year 1937	Year 1987	Year 1998	Year 2002	Year 2004	Year 2006	Year 2011
37,535,308	35,180,000	33,190,442	30,073,365	29,603,147	28,727,427	27,221,721

In recent decades, Argentina has been facing a process of transformation of its native forests of important dimensions, with the aggravating circumstance that forests are primarily replaced by soybean monocultures. This type of farming practice deteriorates the site so much that it can be assumed that conversion is permanent and if the lands were abandoned, the recovery of the original native forest would not be feasible.

According to the data, some of the most affected forest regions correspond to Tucumán-Bolivian Forest and Chaco Forests. Table 2 presents deforestation data for some provinces within the period 1998- 2002, which show the continuing loss of native forest surface.

**Table 2.** Deforested area (ha) by province and forest region during the period 1998-2002  
(Source: UMSEF – Head Office of Forestry - SAyDS).

Province	Deforestation Period 1998-2002		Total
	Chaco Forest Region	Tucumán-Bolivian forest region	
Córdoba	121,107		121,107
Chaco	117,974		117,974
Salta	152,800	41,589	194,389
Santiago del Estero	306,055		306,055
Tucumán	20,865	1,306	22,171

The province of Salta and Chaco are highly affected by indiscriminate logging and deforestation. In the region called Dry Chaco (Chaco Seco), 70% of native forests were eliminated to benefit agricultural production. Another region that is particularly threatened by logging companies is the Yungas rainforest, which also includes territories of the provinces of Salta, Jujuy and Tucuman, constituting one of the richest areas of biodiversity in the Americas. In 2013 Argentina was the non-tropical country that suffered deforestation the most, as 34 ha/day were cleared.

In addition to indiscriminate logging and general deforestation, we should mention forest fires as an important agent of reduction of native forests as, for example, in the province of Cordoba, where 139,000 ha were burnt in 2003 and 138,340 in 2013 and over a million and a half trees disappeared.

We should also add that the native forests of Argentina have undergone severe degradation processes that favor biomass loss and result in impoverished forests, often compromising their ability to provide goods and services. There is clear evidence that the loss of biomass in tropical forests occurs at a higher rate than surface loss due to deforestation; however, as it is a less evident process, it does not get the attention it deserves. The magnitude of this process from the data from the First National Native Forest Inventory indicates, for example, for the region of Chaco forest that out of a total of 459 plots surveyed, only 7% kept its natural state while the remaining 93% showed signs of



human intervention due mainly to livestock, logging or agroforestry (Forest Policy: Native forests and environmental preservation. Observatory of Public Policy, November 2010, available online).

Implanted forests in Argentina contain mostly fast-growing exotic species whose wood is suitable for industrial use (to a lesser degree for the production of oils, resins and tanning). Very few are implanted to be used with windbreak or fixation of sand dunes purposes.

In 1998 the area of planted forests covered 780,396 ha, by the beginning of 2006, according to unofficial estimates, there were approximately 1,000,000 ha of planted forests.

Afforestation has been focused mainly on the introduction of exotic species previously eliminating native forests and jungles, which alters the ecology and wildlife and dramatically reduces fauna and fertility of soils, thereby facilitating their water erosion. Among implanted non-native conifers, several species of pines, especially ponderosa pine, cypress, cedar, and in colder areas, firs and redwoods, stand out.

In Argentina, exports of agricultural and forestry primary sector, together with agribusiness have traditionally been the main source of foreign exchange (35% GDP).

The Argentina Republic has a land area of nearly 2.8 million km<sup>2</sup>, equivalent to 279 million hectares, approximately 30 million of which are covered with forests (i.e. 10% of the total) and 20 million intended for farms (7% of total), so one would expect that the forest resource would have economic importance. However, the primary forest sector has fluctuated in recent decades only between 0.1% and 0.3% in GDP, whereas the derived agro forestry does not normally exceed 2% of it.

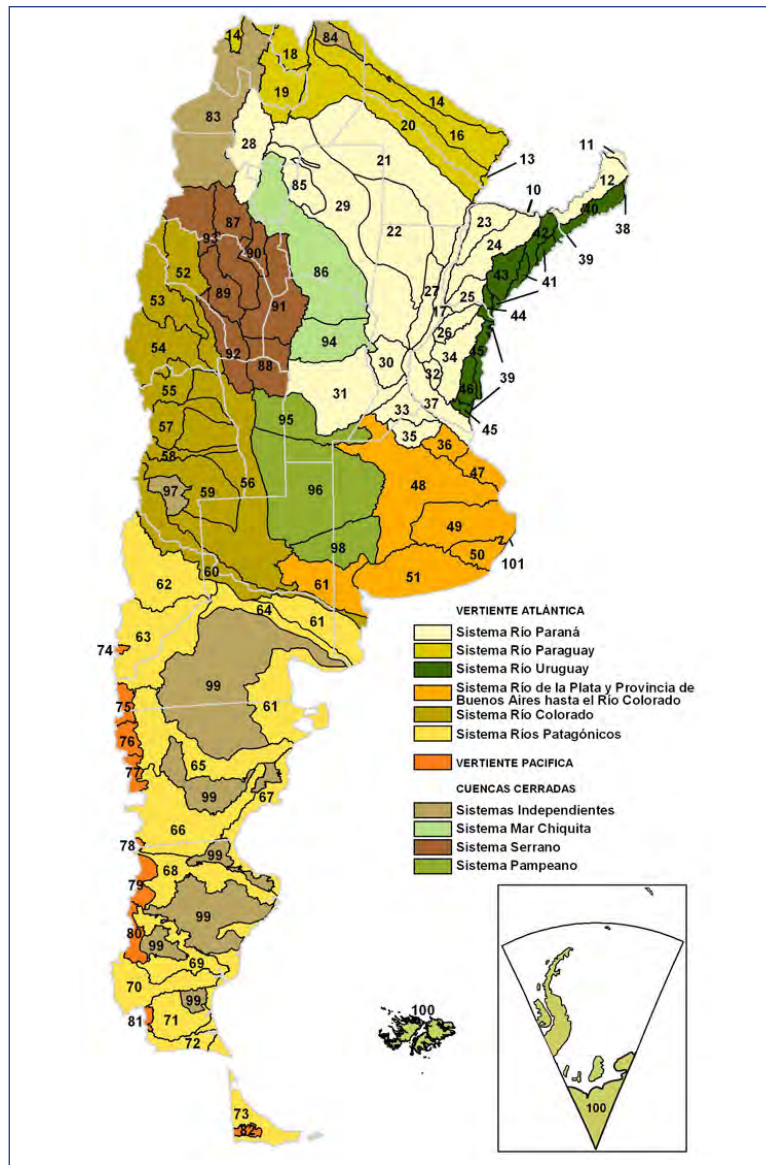
This is a striking situation since different technical estimates admit that in addition to existing surfaces covered with forests, there are about 20 million ha of ground that is suitable for commercial forestry cultivation and that does not compete with agricultural uses. And productivity of cultivated forests with exotic species is high, equaling or surpassing that of other countries with traditional forestry.

In Argentina, the exploitation of forests involves a wide range of productive activities and services, from the harvest of seeds and the production of forest seedlings and other inputs, implantation and management of the forests, to the manufacture of finished parts, furniture, housing, cellulose pastes, cardboard and papers of different quality, wood panels, chemical extracts for the industry and a large set of byproducts, and even the manufacture of machines and equipment for these various activities and related marketing and transportation services. Overall, none of the subsectors of the forestry industry has achieved the necessary development to generate strong markets of suppliers of goods and services and significantly promoted the development of related activities.

## 1.2 Literature review

In Argentina, the supply of water resources can be expressed as a mean annual flow of about 26,000 m<sup>3</sup>/s. 85% of surface water in the country corresponds to the Argentine territories of the basin of Río de la Plata, with its rivers Paraguay, Uruguay and Parana, among its main water courses, and with the highest concentration of population and productive activity. On the other side are located the arid and semi-arid regions with low rainfall basins and less than 1% of the total surface water.

In the country you can find eleven watersheds shown in Figure 2. The National Population, Households and Housing Census conducted in 2010 recorded a total of 40,117,096 inhabitants, so the annual average surface water supply per capita can be expressed as a rate of about 20,400 m<sup>3</sup> / inhabitant / year, well above the threshold of water stress of 1,000 m<sup>3</sup> / inhabitant / year. The distribution is very uneven, with about 90% of the population living in urban areas of over 10,000 inhabitants.



**Figure 2.** Watersheds of Argentina

(Source: <https://www.educ.ar/recursos/14649/los-biomas-y-la-hidrografia-en-el-territorio-argentino>)

With regard to groundwater, the latest available studies recorded that 30% of the water used corresponds to this source. Major exploitable aquifers have been surveyed in the country, with high level of knowledge in some cases, as in the provinces of San Juan and Mendoza, which heavily depend on them. Recently, Argentina, together with Brazil, Paraguay and Uruguay, implemented the “Project for Environmental Protection and Sustainable Development of the Guarani Aquifer System” located in geological formations that are found at different depths in a vast region of the Basin of Río de la Plata, considered as one of the most important freshwater reserves of the world.

In Argentina there is a growing threat to the sustainability of groundwater and surface water sources due to human alteration of land use in the tributary basin. Non-conservationist farming practices, deforestation, agrochemical use and changes in land use, particularly urbanization, disturb the water balance and quality conditions of the sources.



Examples of these phenomena are:

- The increase in the amount of suspended solids resulting from more water erosion due to deforestation, overgrazing and mismanagement of arable land, as verified in Lakes Los Molinos and San Roque in Cordoba; in the province of Misiones, in some areas of the Bermejo River Basin and other areas of the country.
- The presence of pesticides in surface courses, as has been detected in waters of the Uruguay River and the Río Negro.
- The contamination of surface reservoirs as the Embalse de Río Hondo, in Santiago del Estero, or Lakes Los Molinos and San Roque in Cordoba, due to untreated wastewater from coastal urban and industrial settlements or settlements located in the tributary basin.
- The contamination of aquifers due to disposal of sewage in septic tanks, as the case of “Puelche” in the province of Buenos Aires, or intensive industrial urban development, as in the industrial city belt bordering the Parana and Río de la Plata from Rosario to La Plata, where its tributaries in very serious state of contamination, such as the Matanza-Riachuelo and Reconquista, in the suburbs of Buenos Aires, are the most eloquent expression. Serious shortcomings in the management and disposal of urban and industrial toxic solid waste, particularly in urban peripheries, contribute to this situation.

### *Use of water resources*

- **Extractive uses:** Drinkable water and water for sanitation and irrigation stand out among other consumptive uses of water. Irrigation demands 70% of the total, followed by the municipal supply, livestock watering, and industrial use.

The country has 125 irrigation systems or areas, taking into account both public and private complementary and comprehensive irrigation. It is considered that the potential of land suitable for irrigation is about 6,300,000 hectares, of which only 2.5 million may be feasible for comprehensive irrigation. Total irrigated area is about 1.5 million hectares, while the area with irrigation infrastructure available (including in it the registered one) covers about 1.75 million hectares. While this would indicate that there is great potential for expansion, in many cases large investment is still needed to deliver the water to the areas to be incorporated.

- **Non-extractive uses:** The need to increase the availability of water resources by regulating their seasonal variability, to mitigate floods and generate electricity, boosted the construction of reservoirs and multipurpose dams since the beginning of the 20<sup>th</sup> century. Initially, the State's efforts were focused on arid and semi-arid areas, accompanying the development of irrigated areas and, subsequently, massive power generation through great binational works in rivers Parana and Uruguay. To date, the country has built important regulation capacity with more than 100 large dams in operation and dedicated mostly to multiple uses (power generation, municipal and industrial supply, irrigation, flood mitigation, navigation and recreation).

The largest hydropower potential is associated with the basins of the Plata (rivers Bermejo, Paraná and Uruguay) and with the ones that flow into the Atlantic (rivers Colorado, Negro, Chubut and Santa Cruz).

### *Fire Impacts to Quality of Reservoirs San Roque and Los Molinos.*

The following describes the situation in two reservoirs after the disappearance of native forests due to fires and deforestation.

Córdoba along with its hinterland is one of the most important cities in Argentina with a population of more than 1,400,000 inhabitants in 2010. In this city, water is supplied by the San Roque and Los Molinos reservoirs. The region is subject to strong variations in its hydrological cycles. Besides, a steady population growth experienced in recent years in the city and its hinterland has derived in conflicts for the water supply, which were protracted by droughts, floods and changes in the land use. Additionally, periodic fires in the basin seriously deteriorated both reservoirs.

A study performs to the assessment of impairment suffered annually by both lakes due to fires occurring in the Sierras de Cordoba was conducted. This study attempted to determine the increased siltation in reservoirs that supply water to the city as a result of fires. The model used to calculate the specified degradation in the basin is the Djorovic & Gavrilovic (1974). Results showed a significant decrease in the time needed to reach a full siltation of the reservoirs due to fires in the upper basin.

As a result of the natural watershed degradation, erosion and sediment deposition occur in vast land areas and mainly in the riverbeds. The obstacle of dams for sediment discharge in rivers draining upstream thereof, causes accumulation of sediment and widespread erosion in the downstream reaches. Table 3 shows the embankment of reservoirs San Roque and Los Molinos considering the effects of fire on watersheds and when different levels are reached.

Along with the solid materials degradation product of the basin, the rivers are loaded with nutrients directly related to the chemical characteristics of soils involved. Agricultural activities not regulated, overgrazing and fires, among other actions that depend on man, especially in the basin headwaters increase rates of sediment generation directly affecting the net volume of reservoirs and their water quality.

To reduce these effects, implementing land use practices in the watershed, controlling deforestation actions, and preventing and controlling unwanted fires is required.

**Table 3:** Summary of the values of reservoir embankment in San Roque and Los Molinos in both situations.

Reservoir	Construction	Original Reservoir Volume	Embankment			
			2011 (%)	50% (year)	75% (year)	100% (year)
<i>Without considering the effect of fires</i>						
SAN ROQUE	1944	201	22%	2094	2169	2244
LOS MOLINOS	1953	307	9%	2281	2445	2609
<i>Considering the effect of fires</i>						
SAN ROQUE	1944	201	29%	2061	2119	2178
LOS MOLINOS	1953	307	11%	2213	2343	2473

Regarding the storage capacity of reservoirs and for a proper planning of water resources, in what refers to the ability of regulation of the dam, conducting bathymetries that will generate some basis for required monitoring and control is needed.

Highlands use should be regulated by setting maximum cattle stocks in terms of heads per hectare leading to a rational use and avoiding overgrazing.

### 1.3 Politics

The National Constitution of Argentina (1994), Article 41, states that “The Nation promulgates rules containing the minimum protection, and the provinces those necessary to reinforce them, without altering local jurisdictions “. On this basis, it approved and promulgated the General Environment Act 25,675 (2002) and later Act 26,331 (2007) of minimum standards for the environmental protection of native forests. This law states the minimum principles of environmental protection of native forests and the environmental services they provide to society, and includes the contribution of public funds for environmental services provided by native forests. The standard promotes the enrichment, restoration, conservation, sustainable use and management of native forests in Argentina. In the different districts that have native forests, the need to adapt the legislation for sustainable use, based on what is stated in this standard, is determined.

In this context, the Sustainable Forest Management Plan (SMP) is one of the fundamental tools for management. According to the standard, this instrument is defined as “The document summarizing the organization, means and resources, in time and space, of the sustainable use of forest resources, timber and non-timber, in a native forest or group of native forests, for which a detailed description of forest lands in their ecological, legal, social and economic aspects should be included, and in particular, a forest inventory with a first level of detail as to allow decision-making regarding forestry to apply in each of the units of native forest and its estimated profitability “(Balducci et al, 2012).

### 1.4 Climate change and the future of forestry & forest research

Climate trends that have occurred in most of the Argentine territory in the last three or four decades are remarkable. And they are likely related to global climate change. These trends have affected natural systems and human activities, requiring rapid adaptation.

The most important are:

- Increase of annual average rainfall in parts of the country, especially in the northeast and western area peripheral to the traditional wet region.
- Increase of frequency of extreme precipitation in much of eastern and central Argentina.
- Increase of temperature in the mountainous area of Patagonia and Cuyo, with general retreat of glaciers.
- Increase of river flows and frequency of floods across the country, except in the Comahue and northern Patagonia.

Furthermore, according to the Second National Communication of Argentina to the UN Framework Convention on Climate Change, October 2007 (op.cit. 4), there has been a decline in the flow of rivers originating in the Andes in San Juan, Mendoza and Comahue. However, the Andean Regional Center of INA (INA-CRA) argues that the decrease in river flow is not verifiable by identifying trend studies, conducted in the main rivers of the province (Pochat, 2012)

#### *Commentaries*

Argentina has been through a very intense deforestation process, still occurring, driven mainly by the need to free land for agriculture (particularly for the production of grains, mainly soybean). This process has almost deprived entire provinces of its original forests (case of Córdoba, where only remnants can be seen).

Deforestation and the new land practices have had very strong impacts on water resources, both in their quantity and quality. Deforestation and, later, agriculture transform totally the environment, introducing afterwards the use of agrochemicals that have important impacts on water quality (both surface and subsurface). There is a strong need to know better these impacts and how they can be diminished.

To reduce siltation effects in reservoirs, implementing land use practices in the watershed, controlling deforestation actions and preventing and controlling unwanted fires is required.

Highlands use for grazing should be regulated by setting maximum cattle stocks in terms of heads per hectare leading to a rational use and avoiding overgrazing in order to keep the watersheds health.

Prevention of fires (and control, once they occurred) is a debt that Argentina has to its forests. Recent fire cases that have been in the global media show the need to take this aspect more seriously.

Protected Natural Areas will be an important contribution to regional sustainable development, providing the whole society with environmental services and goods in perpetuity, with real and direct benefits to local communities.

Historical experience shows that - abandoned to market rules and to economic actors' various degrees of "green" consciousness -, natural and cultural resources are under constant and progressive deterioration, which directly or indirectly becomes detrimental to the population (Rodríguez del Pozo, 2003).

It should be understood that the fight against desertification and the fight against poverty are two variants of the same objective, which encourages sustainable management of natural resources in order to promote rural development and thereby improve living conditions of dryland inhabitants.

## 1.5 References

- Balducci, Ezequiel Diego; Eliano, Pablo; Iza, Hugo Rubén; Sosa, Ignacio Alberto. 2012. Bases Para el Manejo Sostenible de los Bosques Nativos de Jujuy. 1a ed. Incotedes, ISBN 978-987-28804-0-8.
- Djorovic M, and Grivilovic (1974). Quantitative classification of torrent waterways. Institute for Forestry and Wood Industry (referido en MOPU 1985).
- Bosques Andinos (2011) Infografías. Bosques Andinos. Programa de Schweizerische Eidgenossenschaft, Confederation Suisse, Confederation Svizzera, Confederation svizra.
- FAO – LADA (2011) Publicación sobre la degradación de la tierra en Argentina para decisores políticos. La Lucha contra la Desertificación en Argentina: Degradación de la Tierra en Zonas Áridas e Identificación de Prácticas de Manejo Sustentable de Tierras [www.fao.org/nr/lada/index.php?option=com\\_docman](http://www.fao.org/nr/lada/index.php?option=com_docman).
- LADA (2008) Proyecto Evaluación de la Degradación de Tierras en Zonas Áridas. Informe final de la Ejecución de las Cartas Acuerdo N° 1 Escala local. Disponible en [www.fao.org/nr/lada](http://www.fao.org/nr/lada).
- Pochat, Victor. 2012. Recursos Hídricos - Julio de 2012 - Víctor Pochat. Ministerio de Ciencia, Tecnología e innovación productiva.
- Reyna, S.; Reyna, T.; Lábaque, M. (2014). "Fire Impacts to Quality of Reservoirs San Roque and Los Molinos" Pinnacle Environmental & Earth Science, Vol. 1 (2) 2014, Article ID pees\_146, 315-321, 2014.
- Rodríguez del Pozo (2003). Proyecto: Bosques Nativos y Áreas Protegidas. BIRF - Préstamo 4085-AR.
- UMSEF - Dirección de Bosques – SayDS. 2002. Cartografía y Superficie de Bosque Nativo de Argentina al año 1998. Publicado en diciembre de 2002.

# Chapter 2. Forest Management and Water in Australia

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## 2.1 Introduction

### *Australia's Forests*

- Total land area of 769 million ha; 125 million ha of native forest; fire prone forests dominated by *Eucalyptus* and *Acacia*.
- 1 million ha of *Eucalyptus* plantations, mainly for pulpwood; 1 million ha of *Pinus* plantation for pulp, sawn timber, veneer and composite wood products.

Australia is the driest inhabited continent with unique forest vegetation dominated by *Eucalyptus* and *Acacia*. It is also an old continent with soils often high in salts but leached of essential minerals, especially phosphorus. Low rainfall, low nutrient, sometimes saline soils and unique vegetation have had strong influences on forest hydrology in Australia.

Substantial areas of Australia's native vegetation, including forests and woodlands, have been cleared for agriculture since Europeans arrived in the late 18<sup>th</sup> and 19<sup>th</sup> century. About 22% of all Australia's woody native vegetation has been cleared since 1750, including about 30% of Australia's native eucalypt forests (Beeton *et al.* 2006). Clearing of native vegetation is now restricted or banned in most states. Australia now has 125 Mha of forest (16% of the total land area), of which most is natural forest and only 2 Mha is industrial plantation. Figure 1 shows the distribution of the main forest types within Australia. The 15 plantation regions indicated in Figure 2 are areas considered to be most suitable for plantations and where the vast majority of Australia's 2 Mha of plantations are grown. Only about 0.2% of Australia's land area has forestry plantations. This may increase over coming decades as tree planting is used to sequester carbon to offset greenhouse gas emissions.

The Australian aborigines were the 1<sup>st</sup> to manage Australia's forests, primarily by using cool fires to create open grassy understory. Anecdotal evidence suggests that when Europeans arrived some 200 years ago at least some parts of the landscape had a park-like appearance. For example it was often noted that horses could be ridden through forests and that they largely had a grassy understory (Watson 2014). The arrival of Europeans in the early eighteen hundreds quickly resulted in large-scale decimation of aboriginal population and with that ended their management. Large-scale clearing of forests began for agriculture. Many millions of hectares of forest and woodland were cleared. For a detailed anecdotal account of the transition of the landscape during Australia's early history of European settlement see Watson (2014).

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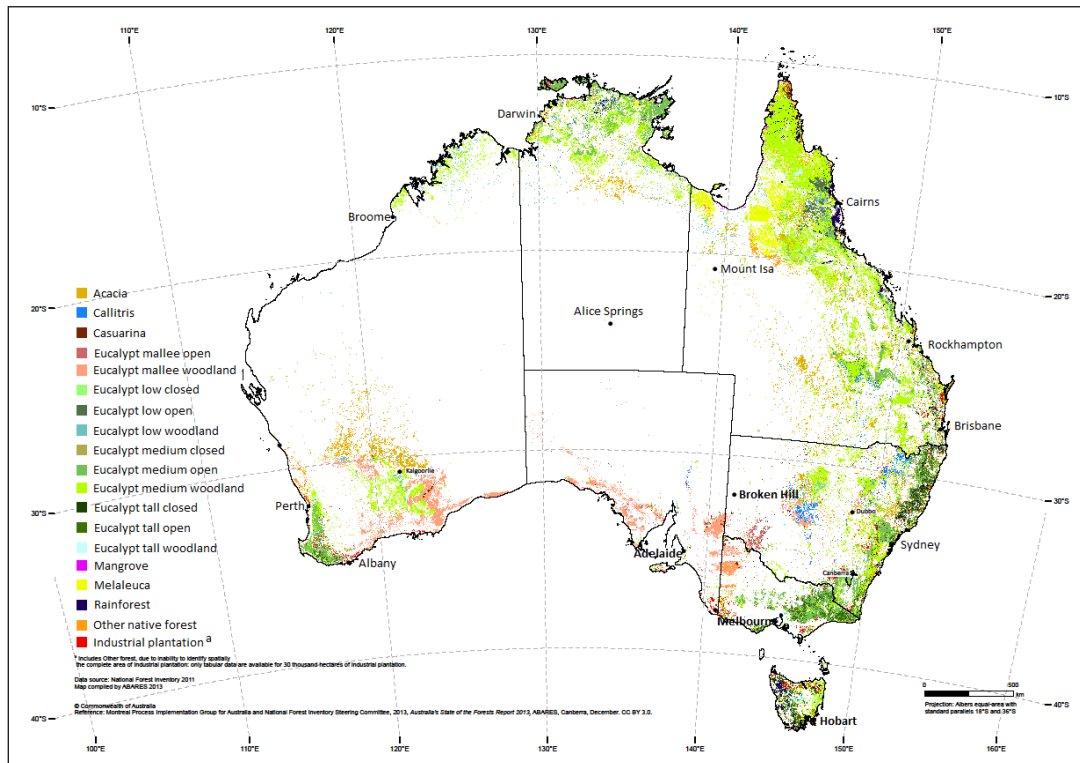


Figure 1. Distribution of Australia's forests.

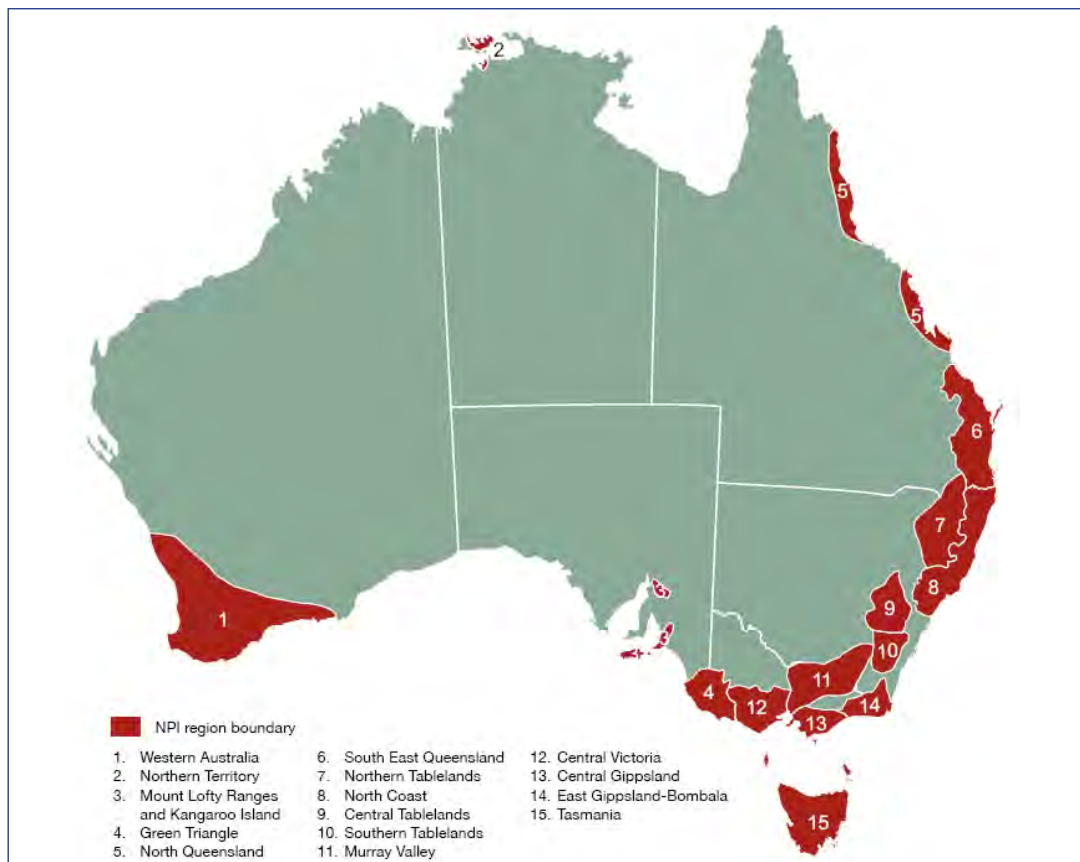


Figure 2. Australia's plantation growing regions. Source Parsons *et al.* 2006.

## *Australia's Government*

Following the arrival of British settlers after 1788, until 1900, Australia was a group of six independent British colonies, each with its own colonial government. At Federation in 1901 these colonies were united to form the Commonwealth of Australia with the establishment of the Australian Parliament. Australia now has a three tier system of government: an overarching federal government, eight separate state and territory governments and numerous local governments. Forest policy and Management is largely the responsibility of the states. However, the federal government sets overall policy directions and maintains national statistics on forests and forestry.

## *Australian forest ownership and management*

- Europeans settlers in the 19<sup>th</sup>C cleared large areas for agriculture and exploited some forests; in the 20<sup>th</sup> C state government forest services introduced sustainable native forest harvesting and multiple-use; much forest is now privately owned, the rest is mostly in parks, reserves and multiple use public forests.
- National forests polices have encouraged development of industrial plantations to replace imported wood products, with a target of 3 Mha by 2020 (unlikely to be achieved: currently 2 Mha); plantations were largely publically developed before the 1980s, but now much is in private ownership.
- Various codes of practice for native and plantation forest harvesting in most states aim to protect environmental values including surface water quality and yield.

During the 2<sup>nd</sup> half of the 19<sup>th</sup> century and early 20<sup>th</sup> century, the states established their own forest services to manage forests on public lands. Australia has a system of private and public land ownership. Most of the agricultural and urban land is privately owned but large areas of forest remain public land in national parks, state forests and other reserves. State forest and national parks services are responsible for managing these publicly owned forests.

The cessation of aboriginal management of the land resulted in a change to fire regimes in some parts of the country. In south-western, southern and eastern Australia removal of regular cool burns resulted in thickening of the forest understory and possibly increasing the frequency or extent of occasional very large wildfires that occur under unusually hot dry windy conditions. The first of these 'mega-fires' occurred in Victoria in 1851 when much of the state burnt. Very severe fires have re-occurred every 20 to 50 years since then. Reduction of fire risk or mitigation of fire effects is often an important part of forest management. For example, after severe fires in 2009 killed 179 people and destroyed over 2000 buildings, a royal commission recommended a substantial increase in the amount of fuel reduction burning undertaken in Victoria's forests, increasing almost fivefold the area of planned fuel reduction burning undertaken each year.

Setting up of state forest services in the 19<sup>th</sup> century and early 20<sup>th</sup> century resulted in a move away from simple forest exploitation to sustainable forest management. Plans to sustainably utilize and regenerate forest for timber production were introduced over decades as an understanding of the ecology of the native forests was developed through research and as methods for drying and sawing the dense timber from eucalypts were devised.

Multiple use management of state forests now aims to sustainably harvest timber while maintaining environmental and other socioeconomic values. One of the main concerns has been protection of soils from erosion and protection of streams from siltation and deterioration in water quality. Much of the research in Australian native forests since the 1970s has focused on how to mitigate or minimise the impacts of forest harvesting and forest fires on stream water quality. A large body of research examines how wildfires, forest roads and forest harvesting affect sediment run-off from



forest soils and on stream water physical and chemical properties. This has resulted in development of prescriptions for forest management in various areas as part of 'codes of forest practice'. These codes are administered and enforced by state forest services or departments of primary industries, environment or environmental protection agencies: forest harvesting plans are developed; exclusion zones are identified that will protect streams from disturbance; harvesting coupe size and road locations are prescribed to minimise risks to water quality; site rehabilitation is mandated to further minimise erosion and deterioration of water quality. More recently, impacts of large-scale wildfires and of planned fuel reduction burns on water quality have been the subject of some research.

As well as obtaining forest products from native forests, Australia since the late 19<sup>th</sup> century has sought to replace imported softwood timbers with locally grown plantation wood. The early 20<sup>th</sup> century saw the establishment of various arboreta designed to identify exotic species, particularly conifers, that would grow well and produce good quality timbers in Australia. In southern Australia *Pinus radiata* was identified as being a fast-growing versatile timber species and, largely since the nineteen sixties, almost 1 Mha of plantations of this species has been established in southern Australia. In drier parts of southern Australia particularly south-west Western Australia, *P. pinaster* is also grown in plantations for timber. In south-eastern and eastern Queensland about 200,000 ha of three species of tropical pines and their hybrids have been planted. Some native pines are also grown in plantations in Queensland.

Until the early 1990s there was very little planting of *Eucalyptus* in Australia for timber with most hardwood timber being harvested from native eucalypt forests. However with large Japanese pulp mills looking for new sources of high-quality pulping wood and with government policies aimed at trebling Australia's plantation area from 1 Mha to 3 Mha between 1995 and 2020, large areas of *Eucalyptus* particularly *E. globulus* and *E. nitens* were established between the early 1990s and the global financial crisis in 2008.

### *Australia's water resources*

Water in Australia is mainly used for irrigated agriculture, for some industrial processes and for urban water supplies; Scarcity of water supplies often leads to competition between water uses including the water needs of natural ecosystem. The majority of Australia's fresh water resources are located in the tropical north. However, remoteness and generally poor conditions for agriculture mean these water resources are largely unexploited. Most of the population is concentrated along the east and southern coasts where major rivers have been dammed to create large water storage reservoirs to supply Australia's main urban areas. Large engineering schemes in the decades after World War 2 diverted rivers inland to provide large stores of water for irrigated agriculture, mainly in inland New South Wales, Victoria, South Australia and Queensland. Some regional and local groundwater systems are also used extensively for irrigation.

Current forest water issues include:

- Protection of water quality with increasing wildfire and planned fuel reduction burning
- Protection of water yield after timber harvesting and wildfire in some native forests
- Managing water yield reductions after conversion of agricultural land to forestry plantations in a few regions with high concentrations of new industrial plantations

## 2.2 Literature review

- Paired catchment studies, established from the 1960s to the 1980s, have examined the effects of forest clear fell and regeneration, forest thinning, wildfires and mining and forest regeneration on catchment water quality and yield in native eucalypt forests.
- Several paired catchment studies have examined the effects of replacement of native forest or pasture with pine plantation.
- Various plot-scale studies have directly measured water use by native forests or plantations to determine the drivers of water use and how water use is affected by forest management.
- Runoff plots, sometimes using rainfall simulators, have examined effects of roads, disturbance and rainfall intensity on water quality.
- Modelling and plot-scale studies have examined use of tree planting to combat dryland and irrigation salinity and the sustainability of land-based effluent reuse.
- Analysis of long-term catchment land use, rainfall and streamflow data have determined trends in water yield and in some cases salinity, in the decades following tree planting on previously cleared land from which generalised rainfall-runoff equations for forest and non-forest land have been derived.
- A recent book by Bren (2015) provides a detailed Australian perspective on forest hydrology and catchment management, with specific examples.

The impetus to established forest hydrology research programs in Australia has often been political or based on a desire by governments to develop science-based policy and management solutions to specific socio-economic and environmental issues. From the 1940s to the 1970s, large wildfires and public debates over forest clearing, timber harvesting or mining in native forests, particularly where these were water sources for large towns or cities, prompted establishment of catchment hydrology research programs in Victoria, New South Wales and Western Australia, based mainly on paired research catchments to which various harvesting or other management treatments were applied (Vertessy *et al.* 1998, Watson *et al.* 1999, Lane and Mackay 2001, Bari and Ruprecht 2003, Bren and Hopmans 2007, Webb *et al.* 2012). At that time, state governments, who are largely responsible for managing publicly owned forest and water resources, were willing to fund large, long-term, in-house research programs to obtain the best science on which to base natural resources management decisions. More recently, such research has been outsourced to universities and Australia's national research agency (the CSIRO), often with a shorter-term focus on development or application of generalised models or study of hydrological processes at the plot-scale.

### *Water quality from forests*

Australian research on forest water quality has included both native forests and plantations. Wild fires, clear-fell timber harvesting and construction of roads for forest operations can have impacts on water quality (Cornish and Binns 1987, Hopmans *et al.* 1987, Croke *et al.* 1999, Wilson 1999, Townsend and Douglas 2000, Lane *et al.* 2006, Hopmans and Bren 2007, Sheridan *et al.* 2007, Lane *et al.* 2008, Smith *et al.* 2010, Smith *et al.* 2011). If not well managed, these can result in deterioration in water quality, risking drinking water supplies and water dependent ecosystems.

Paired catchment studies (see Section 2.2) have often included regular manual sampling of water from base-flow and automatic samplers design to collect frequent water samples during and after storm events. Water quality parameters studied include: sediment concentrations and total sediment loads, total dissolved salts, turbidity, and concentrations of mineral elements such as N, P, Na and

Cl. Various biological water quality parameters have also been measured, particularly in catchments supplying potable water to urban communities.

Findings of some of this research, particularly on how to mitigate effects of wildfires, timber harvesting and road construction, have been incorporated into state government codes of forest management practice (see Section 2.4).

Research during the 1980s and 1990s examined the beneficial effects of tree planting for controlling dryland and irrigation salinity (Stirzaker *et al.* 2002, Polglase *et al.* 2002) and for sustainable land-based disposal of sewage and other effluents (Myers *et al.* 1999). Australia's generally old soils and dry climate have resulted in gradual accumulation of salts from rainfall over millennia, mainly in regions where mean annual potential evapotranspiration exceeds mean annual rainfall, so that small concentrations of salt in rainfall are not fully leached from the soil profile and salt gradually accumulates over time. Under much of the original deep rooted native vegetation, groundwater recharge was small and salts were distributed throughout the soil profile. Clearing of vegetation for dryland agriculture, or irrigation of agricultural land in semi-arid regions, has increased groundwater recharge in many areas, causing water tables to rise, which concentrates salts near or on the soil surface. A dry climate and soils low in nutrients, particularly P, make some soils suitable for land-based effluent reuse.

### *Water yield from natural Eucalyptus forests*

Research on water yield from Australia's native forests has been strongly influenced by large wildfires in Victoria in 1939. Substantial streamflow declines in the three decades following these fires in the forests supplying water to Australia's 2<sup>nd</sup>-largest city, Melbourne (Langford, 1976) led to establishment of the first and most comprehensive long-term catchment hydrology research program in Australia. These moist *Eucalyptus regnans* and *E. delegatensis* (ash-type) forests grow in high rainfall (MAP 1200-2800 mm year<sup>-1</sup>) mountainous regions in southern and eastern Victoria and Tasmania, usually on deep, fertile, well drained soils. Conversion from relatively old, senescing forests (150-300 years old) to dense regrowth of the same species, caused by wildfire or clearcutting, results in declines in water yield of up to 50% over the next 20 to 30 years (Langford 1976, Kuczera 1985, Watson *et al.* 1999, Watson *et al.* 2001, Bren *et al.* 2010), due mainly to changes in transpiration (Dunn and Connor 1993, Vertessy *et al.* 2001, Buckley *et al.* 2012) and interception (Haydon *et al.* 1996). Kuczera (1985, 1987) characterised the regional forest age vs yield curve (commonly referred to as the Kuczera curve) for forests in Melbourne's water supply catchments.

Much subsequent debate and forest hydrology research in these and other eucalypt forests has focussed on whether this response to disturbance is typical of native eucalypt forests. Roberts *et al.* (2001) observed reductions in stand sapwood area and transpiration with forest age in *E. sieberi* forest regenerated from seedlings after fire or timber harvesting, suggesting there may also be an age related change in water yield from other eucalypt forests that regenerate primarily from seedlings after complete removal of the eucalypt overstorey. A long-term study in eight paired research catchments at Karuah, New South Wales, initially indicated a long-term response of streamflow to forest age in high rainfall (MAP 1400-1700 mm year<sup>-1</sup>), warmer moist *Eucalyptus* forests, possibly similar in magnitude to that observed in Victoria's ash-type eucalypt forests (Cornish 1993, Cornish and Vertessy 2001). However, after analysing a longer period of post-treatment streamflow records from the Karuah catchments, Webb *et al.* (2012) concluded that while an ash-type water yield response can occur in other forest types, "...it appears to be the exception rather than the rule".

Less dramatic disturbances such as selective thinning, patch cutting and regeneration or strip thinning in 40 to 50 year old regrowth forest resulted in water yield increases of ~20%, persisting for 10 to 20 years (Jayasuriya *et al.* 1993, Watson *et al.* 2001, Hawthorn *et al.* 2013). After analysing up to 45 years of rainfall, streamflow and forest inventory data from the Victorian paired research catchments, Benyon *et al.* (2015) concluded that overstorey sapwood area, estimated from stocking density and basal area, has the strongest correlation with annual evapotranspiration (ET) and streamflow from

these forests, explaining almost 90% of the variation in mean annual ET. Jaskierniak *et al.* (2015) developed and tested methods to map spatial variation in stocking density and basal area using LiDAR. These can be used to map forest water use to identify low and high water yielding areas within large catchments.

In drier (MAP 900 – 1400 mm year<sup>-1</sup>), more fire tolerant mixed eucalypt forests that cover large areas of south-eastern Australia, a smaller number of paired catchment studies and plot scale measurements of ET indicate water yield responses to fire or selective logging are less dramatic than in the ash-type eucalypts (Lane and Mackay 2001, Gharun *et al.* 2013, Nolan *et al.* 2014, Nolan *et al.* 2015). Wildfire in these forests usually kills only a small proportion of the overstorey, while most trees recover by sprouting from epic buds under the bark. After an initial reduction, ET either recovers to the pre-fire state or marginally exceeds this for at least a few years. In most cases forest water use will return to pre-fire levels within 8 to 12 years but if large areas of the catchment burn at only moderate severity, enabling both quick recovery of the overstorey and development of dense patches of seedlings, a more persistent, although relatively small increase in ET above pre-fire level may occur (Nolan *et al.* 2015).

Paired catchment studies of the effects of native eucalypt forest harvesting and management and on effects of deforestation on water yield have been undertaken in Western Australia since the 1970s. In total, 27 experimental catchments in five catchment groups with mean rainfall ranging from 600 to 1200 mm year<sup>-1</sup> in south-west Western Australia have examined effects on water yield of native forest harvesting and regeneration, forest thinning, bauxite mining and reforestation and clearing for agriculture (Schofield 2003). Permanent clearing of forests for pasture increased streamflows by ~200-300 mm year<sup>-1</sup>, which has often been associated with development of dryland salinity. Clearing of native forest for bauxite mining, followed by forest regeneration, increased water yields by 8% initially before a slow recovery to pre-mining levels after 12 years. Forest thinning in higher rainfall areas increases water yield by ~100-200 mm year<sup>-1</sup>, returning to pre-thinning levels in 12-15 years (Bari and Ruprecht 2003).

### *Water yield from planted forests*

Only a few paired catchment studies in Australia have examined effects on water yield of conversion between native forest, plantations and pasture (Ruprecht and Schofield 1989, Bari and Ruprecht 2003, Bren *et al.* 2006, Bren and Hopmans 2007). More of the recent research in Australia on plantation water use has focused on analysis of long-term rainfall-runoff relationships or flow duration curves (Holmes and Sinclair 1986, Vertessy and Bessard 1999, Lane *et al.* 2005, Zhang *et al.* 2011, Brown *et al.* 2013), the use of empirical models (Zhang *et al.* 2001, Bren *et al.* 2006, Bren and Hopmans 2007, Greenwood *et al.* 2011), process-based models (Beverly *et al.* 2005, Marcar *et al.* 2010) and plot scale measurements (Benyon *et al.* 2006) to determine changes in streamflow and groundwater recharge and discharge following deforestation (permanent removal of forest) or afforestation (planting of forests on previously natural grassland or cleared agricultural land).

These studies have produced results in broad agreement with studies elsewhere in the world: that permanent forest removal increases streamflow, while afforestation of grassland or cleared agricultural land reduces streamflows and groundwater recharge. In some circumstances, for example where annual potential ET substantially exceeds annual rainfall and where groundwater in an aquifer of high transmissivity is accessible to tree roots, plantation annual ET can exceed annual rainfall and plantations can be a net groundwater user (Benyon *et al.* 2006). The magnitude of responses of individual catchments and groundwater systems are variable, depending on rainfall, forest type and condition and catchment and groundwater characteristics. Using process-based models validated against long-term streamflow observations in several catchments, Marcar *et al.* (2010) demonstrated that the effects of partial afforestation of a catchment can be strongly influenced by the location of the plantations within the catchment and therefore that it is possible to choose locations for new plantations that minimise their water yield impacts.



### *Best water management practices*

Tasmania was the first state to introduce a mandatory code of forest practice (Forest Practices Act 1985) which applies to forestry activities in all public and private forest (see Forest Practices Board Tasmania, 2000). This 120-page document provides guidelines and standards for protection of environmental values including water quality and flow during and after forest harvesting operations. It includes definitions of streamside reserves and guidelines for management of these in native forests and plantations and specifies maximum limits for forest harvesting in water supply catchments per year.

Victoria introduced a similar 'Code of Forest practices for Timber Production' in 1989 (The State of Victoria Department of Environment and Primary Industries, 2014). This 80 page document aims to "deliver sound environmental performance when planning for and conducting commercial timber harvesting operations" by detailing the mandatory regulatory principles and instructions which apply to all harvesting and associated roading operations on both public and private land in native and planted forests. Its six guiding principles include conservation of soil and water assets within forests and maintenance and improvement of river health, by protecting waterways and aquatic riparian habitats from disturbance and minimising water pollution by avoiding harvesting activities in sensitive areas such as steep slopes. It details specific mandatory actions required for all forest management and operational planning, protection of environmental values, for roading, timber harvesting and forest regeneration operations. It also lists other legislation and government policies relevant to protection and management of forests.

Other Australian states and territories each have their own version of a forest management code, practice or guidelines. In 1995, in co-operation with Australia's state and territory governments, Australia's commonwealth government prepared a statement of national principles to be applied to management of forestry plantations (see <http://www.agriculture.gov.au/forestry/australias-forests/plantation-farm-forestry/principles>). The two principles relevant to water quality and quantity are very general, stating: "Water quality (physical, chemical, or biological) should be protected by measures controlling change resulting from plantation activities" and "Water yield should be managed as required by careful planning of operations".

In 2012, Australia's national scientific and research agency, the CSIRO, reviewed all of Australia's codes of forest practice as applied to plantation forestry and how well these addressed the national principles (individual assessments can be downloaded at <http://www.agriculture.gov.au/forestry/australias-forests/plantation-farm-forestry/principles>). These reports also detailed the relevant laws governing protection of water quality and yield in each state.

Guidelines have also been developed for using tree planting to combat dry-land and irrigation salinity (Stirzaker *et al.* 2002, Polglase *et al.* 2002) and for land-based disposal of wastewater (Myers *et al.* 1999).

## **2.3 Politics**

The politics around forestry in Australia has often focussed on timber harvesting in native forests, resulting in development of state codes of forest practice (section 2.4) and regional forest agreements. However, since the late 1990s, there has also been debate in some regions over the effects of new plantations on water resources.

Because Australia is a dry continent and much of the agriculture relies heavily on irrigation, water allocation has politically been a very controversial topic in Australia for many decades. Until the 1990s, water allocation for irrigation in the various states was largely uncontrolled with no accurate water accounting. Consequently in some surface and groundwater systems, more water was allocated for irrigation than was actually available, or in others water supplies were rapidly approaching full allocation. Water in Australia can be privately owned as an entitlement separate

from land titles. In some river systems or groundwater systems, water entitlements can be bought and sold on an open water market. Since the 1990s, state and federal governments have sought to introduce accurate water accounts and to regulate water usage through water licensing and trading systems to ensure water usage is sustainable and produces the greatest net socioeconomic and environmental benefits. This resulted in all states and federal government agreeing to a national water policy in 2004, called the National Water Initiative (see [http://www.nwc.gov.au/\\_\\_data/assets/pdf\\_file/0008/24749/Intergovernmental-Agreement-on-a-national-water-initiative.pdf](http://www.nwc.gov.au/__data/assets/pdf_file/0008/24749/Intergovernmental-Agreement-on-a-national-water-initiative.pdf)). This aims to ensure sustainable use of scarce water resources, with water going to the most productive uses, once the needs of the environment have been met. Three paragraphs in this document identify the need to account for activities that reduce water supplies but which are not currently accounted for. New forestry plantations are specifically mentioned as one such activity that may require management or regulation in areas where the available water is currently over allocated or close to full allocation.

Greenwood (2013) provides a comprehensive overview of the development of Australian policy on impacts of industrial plantations on water resources.

## 2.4 Climate change and the future of forestry & forest research

Recent and current ‘hot research topics’ include: tree planting to manage dry land salinity caused by previous clearing of native vegetation for agriculture; impacts on water yield of afforestation of previously cleared land; determining and managing environmental water requirements of floodplain forest and woodland ecosystems along highly regulated rivers; understanding impacts of wildfires and planned burning on water quality in native forests; understanding threats to the health of native vegetation caused by global warming and increasing severity of droughts.

Emerging issues include the impact of groundwater pumping for coal seam gas extraction on groundwater dependent vegetation including forests and the hydrological effects of large-scale afforestation for carbon sequestration to offset greenhouse gas emissions.

## 2.5 References

- Bari MA, Ruprecht JK, 2003. Water yield response to land use change in south–west Western Australia, Department of Environment, Salinity and Land Use Impacts Series Report No. SLUI 31.
- Beeton RJS, Buckley KI, Jones G J, Morgan D, Reichelt RE, Trewin D, 2006. *Australia State of the Environment 2006*. Independent report to the Australian Government Minister for the Environment and Heritage, Department of the Environment and Heritage, Canberra, 141pp.
- Benyon RG, Theiveyanathan S, Doody TM, 2006. Impacts of tree plantations on groundwater in south-eastern Australia. *Australian Journal of Botany* 54, 181-192.
- Benyon RG, Lane PNJ, Jaskierniak D, Kuczera G, Haydon SR, 2015. Use of a forest sapwood area index to explain long-term variability in mean annual evapotranspiration and streamflow in moist eucalypt forests. *Water Resources Research* in press.
- Beverly C, Bari M, Christy B, Hocking A, Smettem K, 2005. Predicted salinity impacts from land use change: comparison between rapid assessment approaches and a detailed modelling framework. *Australia Journal of Experimental Agriculture* 45, 1453-1469.
- Bren L, Lane P, McGuire D, 2006. An empirical, comparative model of changes in annual water yield associated with pine plantations in southern Australia. *Australian Forestry* 69, 275-284.
- Bren L, Hopmans P, 2007. Paired catchments observations on the water yield of mature eucalypt and immature radiata pine plantations in Victoria, Australia. *Journal of Hydrology* 336, 416-429.
- Bren L, Lane P, Hepworth G, 2010. Longer-term water use of native eucalyptus forest after logging and regeneration: The Coranderrk experiment. *Journal of Hydrology* 384, 52-64.
- Bren L, 2015. *Forest Hydrology and Catchment Management: An Australian Perspective*. DOI 10.1007/978-94-017-9337-7. Springer, London, 276 pp.

- Brown AE, Western AW, McMahon TW, Zhang L, 2013. Impact of forest cover changes on annual streamflow and flow duration curves. *Journal of Hydrology* 483, 39-50.
- Buckley TN, Turnbull TL, Pfautsch S, Gharun M, Adams MA, 2012. Differences in water use between mature and post-fire regrowth stands of subalpine *Eucalyptus delegatensis* R. Baker. *Forest Ecology and Management* 270, 1-10.
- Cornish, P.M., Binns, D. 1987. Streamwater quality following logging and wildfire in a dry sclerophyll forest in southeastern Australia. *Forest Ecology and Management* 22, 1-28.
- Cornish PM, 1993. The effects of logging and forest regeneration on water yields in a moist eucalypt forest in New South Wales, Australia. *Journal of Hydrology* 150, 301-322.
- Cornish PM, Vertessy RA, 2001. Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest. *Journal of Hydrology* 242, 43-63.
- Croke J, Hairsine P, Fogarty P, 1999. Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia. *Hydrological Processes* 13, 2705- 2720.
- Dunn GM, Connor DJ, 1993. An analysis of sap flow in mountain ash (*Eucalyptus regnans*) forests of different age. *Tree Physiology* 13, 321-336.
- Forest Practices Board, 2000. Forest Practices Code, Forest Practices Board, Hobart, Tasmania, 125 pp.
- Gharun M, Turnbull TL, Adams MA, 2013. Stand water use status in relation to fire in a mixed species eucalypt forest. *Forest Ecology and Management* 304, 162-170.
- Greenwood AJB, Benyon RG, Lane PNJ, 2011. A method for assessing the hydrological impact of afforestation using regional mean annual data and empirical rainfall-runoff curves. *Journal of Hydrology* 411, 49-65.
- Greenwood AJB, 2013. The first stages of Australian forest water regulation: National reform and regional implementation. *Environmental Science & Policy* 29, 124-136.
- Hawthorn SND, Lane PNJ, Bren LJ, Sims NC, 2013. The long term effects of thinning treatments on vegetation structure and water yield. *Forest Ecology and Management* 310, 983-993.
- Haydon SR, Benyon RG, Lewis R, 1996. Variation in sapwood area and throughfall with forest age in mountain ash (*Eucalyptus regnans* F. Muell.). *Journal of Hydrology* 187, 351-366.
- Holmes JW, Sinclair JA, 1986. Water yield from some afforested catchments in Victoria. Hydrology and Water Resources Symposium, Griffith University, Brisbane, 25-27 November 1986. The Institution of Engineers, Australia.
- Hopmans P, Flinn DW, Farrell PW, 1987. Nutrient dynamics of forested catchments in southeastern Australia and changes in water quality and nutrient exports following clearing. *Forest Ecology and Management* 20, 209-231.
- Hopmans P, Bren LJ, 2007. Long-term changes in water quality and solute exports in headwater streams of intensively managed radiata pine and natural eucalypt forest catchments in south-eastern Australia. *Forest Ecology and Management* 253, 244-261.
- Jaskierniak D, Kuczera G, Benyon R, Wallace L, 2015. Using Tree Detection Algorithms to Predict Stand Sapwood Area, Basal Area and Stocking Density in *Eucalyptus regnans* Forest. *Remote Sensing* 7, 7298-7323.
- Jayasuriya MDA, Dunn G, Benyon R, O'Shaughnessy PJ, 1993. Some factors affecting water yield from mountain ash (*Eucalyptus regnans*) dominated forests in south-east Australia. *Journal of Hydrology* 150, 345-367.
- Kuczera G, 1985. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. Melbourne Metropolitan Board of Works, Report No. MMBW-W-0014, Melbourne Metropolitan Board of Works, Melbourne.
- Kuczera G, 1987. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. *Journal of Hydrology* 94, 215-236.
- Lane PNJ, Mackay SM, 2001. Streamflow response of mixed-species eucalypt forests to patch cutting and thinning treatments. *Forest Ecology and Management* 143, 131-142.
- Lane PNJ, Best AE, Hickel K, Zhang L, 2005. The response of flow duration curves to afforestation. *Journal of Hydrology* 310, 253-265.
- Lane PNJ, Sheridan GJ, Noske PJ, 2006. Changes in sediment loads and discharge from small mountain catchments following wildfire in south eastern Australia. *Journal of Hydrology* 331, 495-510.
- Lane PNJ, Sheridan GJ, Noske PJ, Sherwin CB, 2008. Phosphorous and nitrogen exports from SE Australian forests following wildfire. *Journal of Hydrology* 361, 186-198.



- Langford KJ, 1976. Change in yield of water following a bushfire in a forest of *Eucalyptus regnans*. *Journal of Hydrology* 29, 87-114.
- Marcar N, Theiveyanathan T, Roxburgh S, Gilfedder M, Littleboy M, Christy B, Barlow K, Almeida A, Crawford D and Benyon R, 2010. Methodology to assess site-specific impacts of plantations on catchment water yields. CSIRO: Water for a Healthy Country National Research Flagship.
- Myers BJ, Bond W J, Benyon R G, Falkiner RA, Polglase PJ, Smith C J, Snow VO, Theiveyanathan S, 1999. Sustainable effluent-irrigated plantations: an Australian guideline. CSIRO, Canberra, 286p.
- Nolan RH, Lane PNJ, Benyon RG, Bradstock RA, Mitchell PJ, 2014. Changes in evapotranspiration following wildfire in resprouting eucalypt forests. *Ecohydrology* 7, 1363–1377.
- Nolan RH, Lane PNJ, Benyon RG, Bradstock RA, Mitchell PJ, 2015. Trends in evapotranspiration and streamflow following wildfire in resprouting eucalypt forests. *Journal of Hydrology* 524, 614-624.
- Parsons M, Gavran M, Davidson J, 2006. *Australia's Plantations 2006*. Australian Government, Department of Agriculture, Fisheries and Forestry, Canberra, 60 pp.
- Polglase PJ, Theiveyanathan S, Benyon RG, Falkiner RA, 2002. Irrigation management and groundwater uptake in young tree plantations growing over high watertables. RIRDC Publication No 02/146, RIRDC, Canberra, 54 p.
- Roberts S, Vertessy R, Grayson R, 2001. Transpiration from *Eucalyptus sieberi* (L. Johnson) forests of different age. *Forest Ecology and Management* 143, 153-161.
- Ruprecht JK, Schofield NJ, 1989. Analysis of streamflow generation following deforestation in southwest Western Australia. *Journal of Hydrology* 105, 1-17.
- Sheridan GJ, Lane PNJ, Noske PJ, 2007. Quantification of hillslope runoff and erosion processes before and after wildfire in a wet *Eucalyptus* forest. *Journal of Hydrology* 343, 12-28.
- Smith H, Sheridan G, Lane P, Bren L, 2010. Best management practice guidelines for mitigating impacts on erosion and water quality from post-fire salvage harvesting of plantation forests. Technical Report 207, CRC for Forestry, Hobart, 48 pp.
- Smith HG, Sheridan GJ, Lane PNJ, Nyman P, Haydon S, 2011. Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology* 396, 170-192.
- Stirzaker R, Vertessy R, Sarre R (editors) 2002. *Trees, Water and Salt: An Australian guide to using trees for healthy catchments and productive farms*. RIRDC, Canberra, 159 p.
- The State of Victoria Department of Environment and Primary Industries, 2014. Code of Practice for Timber Production 2014. Department of Environment and Primary Industries, Victoria, 80 pp.
- Townsend SA, Douglas MM, 2000. The effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savannah (northern Australia). *Journal of Hydrology* 229, 118–137.
- Vertessy RA, Watson FGR, O'Sullivan SO, Davis S, Benyon R, 1998. Predicting water yield from mountain ash forest catchments. Industry Report No. 98/4. Cooperative Research Centre for Catchment Hydrology, Melbourne, 38 pp.
- Vertessy RA, Bessard Y, 1999. Anticipating the negative hydrologic effects of plantation expansion: Results from a GIS-based analysis on the Murrumbidgee Basin. Cooperative Research Centre for Catchment Hydrology, Report 99/6, Canberra.
- Vertessy RA, Watson FGR, O'Sullivan SK, 2001. Factors determining relations between stand age and catchment water balance in mountain ash forests. *Forest Ecology and Management* 143, 13-26.
- Watson FGR, Vertessy RA, McMahon TA, Rhodes B, Watson I, 1999. The hydrologic impacts of forestry on the Maroondah catchments. Report No. 99/1. Cooperative Research Centre for Catchment Hydrology. Monash University, Victoria, Australia, 80 pp.
- Watson F, Vertessy R, McMahon T, Rhodes B, Watson I, 2001. Improved methods to assess water yield changes from paired-catchment studies: application to the Maroondah catchments. *Forest Ecology and Management* 143, 189-204.
- Watson D, 2014. *The Bush: travels in the heart of Australia*. Penguin Books, Australia, 427pp.
- Webb AA, Kathuria A, Turner L, 2012. Longer-term changes in streamflow following logging and mixed species eucalypt forest regeneration: The Karuah experiment. *Journal of Hydrology* 464-465, 412-422.

# Chapter 3. Forest Management and Water in Brazil

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## 3.1 Introduction

From the point of view of the relationship between forest and water in Brazil, it is interesting to start with a brief analysis of the country's native biomes and the associated water resources. As can be seen in Figure 1, the largest Brazilian biome is the Amazon, followed by the Cerrado and the Atlantic Forest (IBGE, 2004).

The Amazon biome encompasses an area of 4,196,943 km<sup>2</sup>, the largest continuous remnant of tropical forest in the world, associated with the Amazon River basin. Besides its importance in terms of the largest fresh water reservoir (Tundisi, 2014), it is also currently recognized that the Amazon forests play a major influence in the atmospheric circulation and rainfall generation, not only locally, but also to other regions of the country, especially the southeast (Makarieva et al., 2014).

The Cerrado biome covers an area estimated as 2,036,448 km<sup>2</sup>, equivalent of about 25% of the Brazilian territory, covered with woody savanna vegetation and located in the central part of the country. This biome has also a paramount importance in terms of water resources, for it is the home of the headwaters of very important river basins: São Francisco, Paraná, Tocantins and Parnaíba, which are the main water source for hydroelectricity generation in the country (Oliveira et al., 2014).

The Atlantic Forest biome covers an area of about 1,110,182 km<sup>2</sup> and is located along the eastern coast, the most developed and populous part of Brazil. Over 67% of the Brazilian population lives in this biome. Because of this, it has suffered an historic process of deforestation and human occupation since the discovery of the country back in the year 1500, and it is estimated that the present remnants of this biome correspond to about 17% of its original cover (Calmon et al., 2011), from which only 8% can be classified as closed, native forests. The Atlantic Forest biome is composed by distinct forest physiognomies, which has resulted in a significant biological diversity. Its importance in terms of water values derives from the fact that it protects the water sources for the supply of many cities and a huge population (MMA, 2007).

The other three Brazilian biomes are comparatively smaller in area. The Caatinga biome corresponds to a vegetation cover of stepped savanna, which is entirely located in the national territory, with an area of 844,453 km<sup>2</sup>, occupying the northeastern, semi-arid part of the country. The Pampas biome comprises the grasslands of the southern part of the State of Rio Grande do Sul, in the southernmost part of the country, with an area of 176,496 km<sup>2</sup>. And the smallest biome is the Pantanal, a floodplain with an area of 150,355 km<sup>2</sup> in the southwest part of the country.

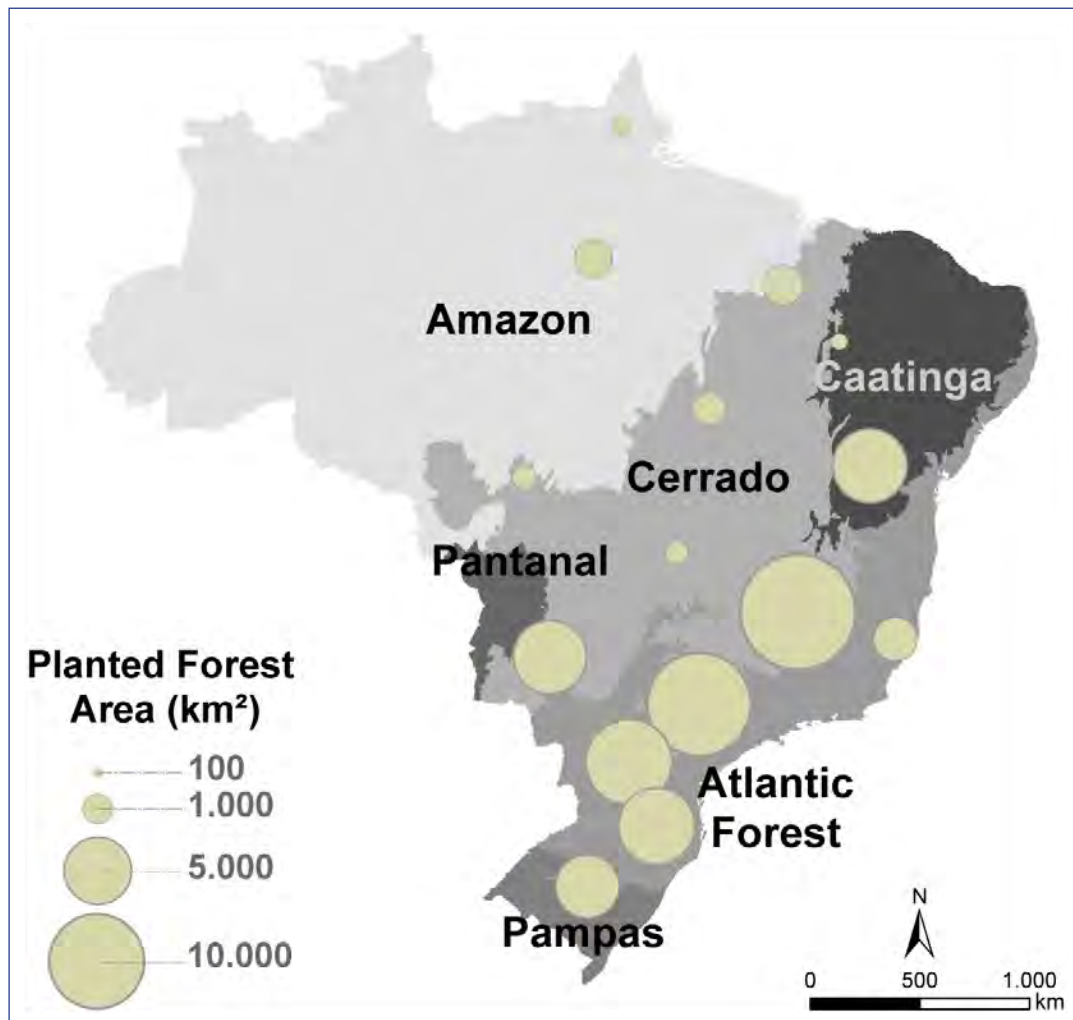
Surface water availability in the country is entirely dependent on the regularity of the precipitation regime and on storage conditions of the catchments, which, in turn, is very much related with the forest cover. Historically, however, the development of the country, in terms of agricultural expansion and urbanization, was accompanied by a widespread process of deforestation of the native forest ecosystems, the most critical of which was the one observed in the Atlantic Forest biome, but also, in smaller proportion, in the Amazon. As a result, this deforestation process may have influenced the evapotranspiration patterns locally (Gordon et al., 2011), but for sure it was responsible for the surface degradation of a huge amount of catchments in many places, with all consequences in terms of alteration of the catchment hydrological stability, soil erosion, soil compaction, water

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quality degradation and decrease in water storage capacity (Bruijnzeel, 2004). Therefore, a most critical need, now, is the restoration of forest cover, at least in terms of reclamation of hydrologically sensitive areas, riparian areas at the scale of the small catchments and aquifer recharge areas. It has been estimated, for example, that the deficit of riparian forests in the State of São Paulo alone amounts to approximately 1.4 million hectares (IPEF, 2014).



**Figure 1.** Brazilian biomes and location of planted forests (modified from IBGE, 2004).

Therefore, in terms of the relation of natural forest management and water resources in the country, it can be summarized that in the Amazon there is a surplus of water and deforestation is expected to influence river flow regime in the long run, although there is still no scientific evidence for this effect. In the Atlantic region, remaining forests still play an important regulation function but this role is limited as a result of their conditions, position in the landscape and proportion in relation to the catchment area. Nevertheless, the expectation of most people in the country is that the restoration of native forests, in general, is very much important for the conservation of water resources. Similarly, water resources problems are always attributed to deforestation. Surprisingly, many other human alteration of the landscape, which also affects water resources, does not always raise preoccupation.

Forest plantations, on the other hand, have always been considered as detrimental to water resources by the people, in general, very much in the same way as it occurs in other parts of the world. The total area of forest plantations in Brazil amounts to more than 66,500 km<sup>2</sup>, 76% with eucalypt and 24% with pine species (ABRAF, 2013), the majority being located in the southeast, south and central

regions of Brazil. However, the expansion of forest plantation areas can now be seen in other, non-traditional, parts of the country (Figure 1).

Wood production of eucalypt plantations, which was around 25 cubic meter per hectare per year in the early phase of the introduction of the species in the country, is presently around 45 cubic meter per hectare per year, although values as high as 60 cubic meter per hectare per year can usually be achieved, as a result of the gradual improvement of silviculture technology, species selection and genetic improvements (Gonçalves et al., 2013). On the other hand, such high productivity is usually achieved on a rotation length of around 6 to 7 years. For the supply of short fiber raw material for the pulp industry, these conditions are indeed competitive.

Since the introduction of the species in the country about one hundred years ago, eucalypt plantations have become a very familiar element in the landscape of the rural Brazil, providing presently around 70 million cubic meters of wood that supply an ever increasing demand for multiple applications, including wood for energy, charcoal, furniture, panels, fiber boards and for the steel industry and civil construction (ABRAF, 2013).

However, in spite of the unquestionable economic and social value of the species for the country, forest plantations, mainly eucalypt plantations, are still viewed with criticism by many people, non-governmental organization (NGOs), environmentalists, social organizations and also scholars, instigated by ancient popular opinions, beliefs and ideological disputes. It is interesting to remember, however, that this worldwide controversy is not related to eucalypt plantation only, but to forests in general. That is, the relation between forest and water is still unresolved (Andréassian, 2004). In the early phase of the forest plantations development in Brazil, as a result of a government incentive programs, much of what is known today in terms of forest hydrology, catchment water balance, landscape ecology, tree physiology and ecosystem services had not been taken into account neither in the process of licensing of the proposed afforestation projects by the government environmental agencies, nor, most importantly, in terms of the implementation of sustainable management strategies. It was common and allowed, for example, to cut remnants of natural forests for reforestation with plantations, which is today not only prohibited but considered outrageous. On the other hand, in many cases there was no preoccupation at all with the protection of hydrologically sensitive areas of the catchments along the plantation landscape, which still can be seen in old plantations in some parts of the country. As given in the current Brazilian Forest Code, these areas are considered as “permanent preservation areas” and must be protected and set aside from production purposes. This strategy also contributes to biodiversity conservation within the plantation stands (Hartley, 2002). Therefore, part of this criticism in the country may also be related with this unplanned beginning of plantation forestry.

Clearly, it thus appears that the controversy is not just of technical nature, but involves many other aspects other than the simple question of how much water do eucalypt plantations use, or whether they dry up the soil or not. It has to be tackled as a complex environmental problem, the solution of which does require the scrutiny of science, but must also take into account all the uncertainties involved in the relationship between the use of the natural resources and the related environmental impacts, mainly in terms of maintaining the ecosystems services and also including the social and cultural trade-offs involved in the transformation of the landscape and the expansion of the area of forest plantations.

This new environmental perception began to gain momentum in the country at the end of the 1980's and forest companies began to review their plantation management strategies. Most of them soon created an “environmental department” in their administrative structure. The market-oriented scheme of Forest Certification undoubtedly gave a substantial contribution for the insertion of environmental and water preoccupation in the management strategies. And then the philosophical concepts of sustainable development and sustainable forest management emanated from the UNCED Conference in Rio de Janeiro in 1992, practically consolidated, at least conceptually, the need for this paradigmatic change.

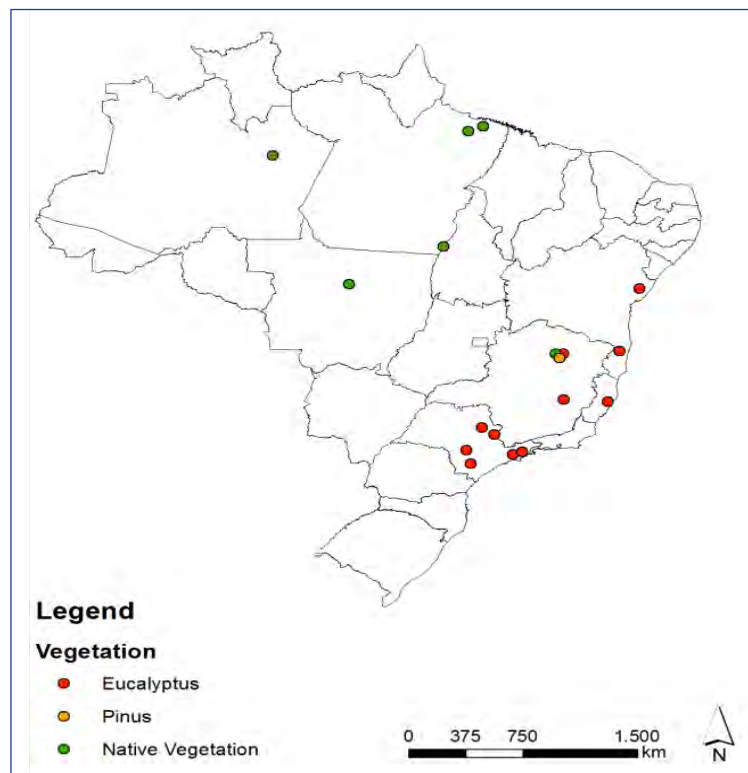
In summary, it can undoubtedly be said that the Brazilian forest plantation sector improved substantially from the point of view of the environment. But it can also be said that there is still space for further improvements in this regards, mainly in terms of hydrology and the challenge of balancing the main economic objective of forest production with the incorporation of water values in the management strategies, as will be discussed further in this chapter.

### 3.2 Literature review

In spite of the large territory of the country, and also taking into account the diversity of forest biomes, the preoccupation with the relationship between forest and water, in terms of research programs and public policies, is still scarce in Brazil, mainly as related to the effects of native forests management and the effects on water.

On the other hand, the Brazilian scientific literature related to forest plantations and water is more abundant and a review of the majority of such studies can already give a consistent perspective of the relationship between forest plantation and water, at least in terms of the magnitude of the potential effects on catchment water balance in different parts of the country (Lima et al., 2012b).

As indicated in Figure 2, the studies related to forest plantations and water were developed mainly in the regions with the largest concentrations of forest plantations (Lima et al., 1990; Vital et al., 1999; Soares & Almeida, 2001; Almeida et al., 2007; Cabral et al., 2010; Facco et al., 2012; Lima et al., 2012a; Lima et al., 2012b; Trevisan et al., 2012; Almeida et al., 2013; Ferraz et al., 2013), whilst the fewer studies related to native forests and water were done in the northern region of the Amazon and in the central part of the country (Holscher et al., 1997; Shuttleworth, 1988; Sommer et al., 2002; Borma et al., 2009; Vourlitis et al., 2015). This is indeed a preoccupation when one considers the potential surface degradation that can result from unplanned deforestation in the Amazon, or the current policy for the transformation of the Cerrado biome for agricultural expansion, in spite of the major water importance of this biome (Oliveira et al., 2014).



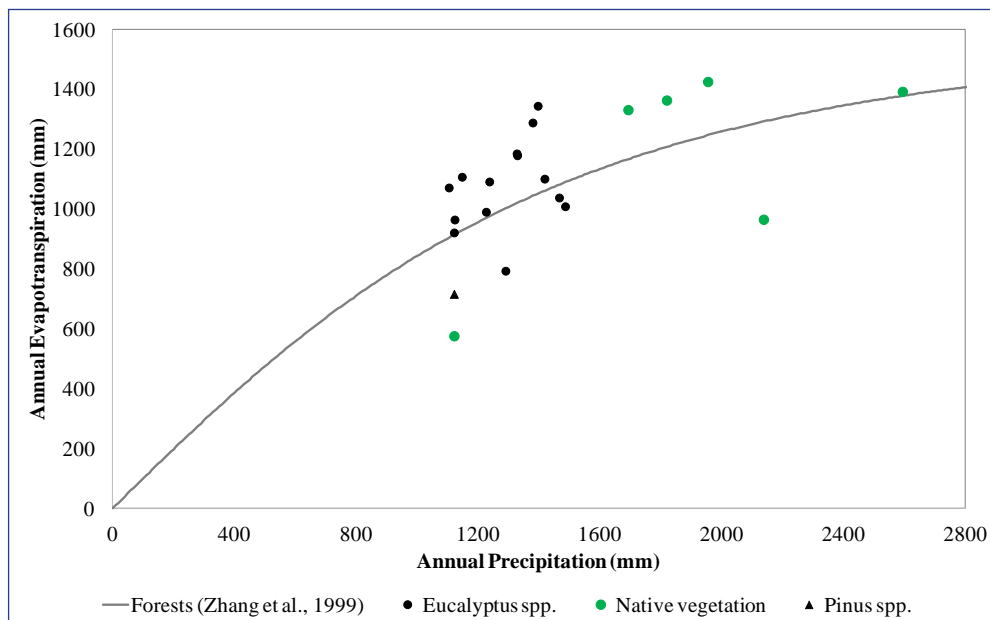
**Figure 2.** Localization of the research studies of forests and water in Brazil, in terms of forest plantations with eucalyptus and pine and also of native vegetation.



For the comparative evaluation of the research results related to forest and water, in terms of forest plantations and native forests, the average annual values of precipitation and evapotranspiration were calculated based on the annual values mentioned in the reviewed studies. These average annual values were plotted against the so called “Zhang Curve” (see Figure 3), which was derived based on the analysis of over 250 experimental catchments worldwide (Zhang et al., 2001). Forest plantations in Brazil are located in regions with average annual precipitation varying from 1100 to 1500 mm, while the average annual evapotranspiration varies from 800 to 1400 mm. As for the few studies with native forests, the average annual precipitation varies from 1600 to 2600 mm, whilst the annual evapotranspiration varies from 900 to 1500 mm.

It can also be seen in Figure 3 that the majority of the annual evapotranspiration values of the forest plantation studies fall above the Zhang curve. However, the model proposed by Zhang et al. (2001) was not developed for forest plantations, but mostly for mature native forests (Bren, 2015). This detail may explain why the values of average annual evapotranspiration of eucalypt forest plantations in Brazil stay above the Zhang curve, for these values were obtained with fast-growing, highly productive commercial plantations, which are usually managed on a rotation length of 6 to 7 years. Undoubtedly, these conditions are related to correspondingly increases in water consumption.

Based on Figure 3, it is expected that fast growing, highly productive forest plantations, managed at a short rotation length of 6 to 7 years, will present higher annual evapotranspiration, as compared with mature native forest. Rosoman (1994) called attention to this effect, referring to it as the “plantation effect”. In practical terms, this means that the potential impact of this higher water consumption is very much dependent on soil conditions and on the climatic water availability of the region (Lima et al., 2012b). In humid climates, where water surplus is higher, this increment in water consumption may not be noted. However, the impact will be more severe in regions of naturally lower climatic water surplus.



**Figure 3.** Values of average annual evapotranspiration and precipitation obtained in the studies in Brazil and the Zhang curve.

On the other hand, this evidence also suggest, in practical terms, that a major research challenge is related to the search of forest plantation management strategies that contribute to the elimination, or decrease of the potential impact of this high water consumption (Lima et al., 2012a; Ferraz et al., 2013).

Using current scientific information, some effective actions could be considered at the macro and meso scales, seeking to improve forest plantation planning in order to avoid water impacts and increase water conservation.

The most important attribute observed at macro scale is the regional climate, mainly the aspects of water availability, considering the total annual precipitation, potential evapotranspiration and also the soil water balance along the year. Other important aspect at this scale refers to physical attributes of landscape like geology and relief, indicating potential water behavior regarding infiltration, runoff and problems related to erosion, soil water retention and nutrient losses (Hewlett & Hibbert, 1967).

At the meso scale, the most important aspect is the spatial and temporal planning of land use at the catchment, including protected areas proportion and location, road design, clear-cut planning. Some examples of actions at the macro and meso scales are shown below.

**Macroscale actions** – the regional hydrological zoning based on total annual precipitation and potential evapotranspiration, as proposed by Calder (2007), would allow to identify regions more vulnerable to higher water consumption by forest plantations, where it is expected environmental and social impacts by a significant reduction of water flow in the streams (Farley et al., 2005). In this case, those areas could be submitted to specific actions at meso and micro scale in order to compensate for the low water availability, and increase the “blue water” flow at managed areas (Falkenmark & Folke, 2002), thus avoiding conflicts. The hydrological response is another important aspect that could be assessed by discharge/precipitation ratio, or specific indices such as the Flashness Index (Baker et al., 2004). This regional characterization is based mainly on soil and terrain attributes and allows the land classification considering water behavior that is very useful to guide forest management in order to reduce environmental impacts. For example, regions with characteristically high hydrological response areas are more prone to the occurrence of extreme events of droughts and floods, and also erosive processes.

**Mesoscale actions** – one of the most important actions at this scale is the definition of forest plantation proportion at landscape level. According to regional environmental law and the existence of conservation areas, forest plantations in Brazil occupy a proportion varying between 10% and 40% of a given property area. The proportion of protected areas could be increased in regions of naturally low water availability, not only by creation of reserves, but also by the alternative schemes of forest management, such as increasing the rotation length, which would contribute to diminish the plantation effect (Rosoman, 1994). In the same way, the mosaic management of clear-cut presents high potential of diminishing water consumption impacts, since it consider a mix of stands with different ages (and water consumption), thus avoiding the occurrence of huge clear-cut areas. The spatial structure of plantation areas in relation to streams and runoff channels also could be a management tool seeking to attenuate impacts and excessive water consumption, shifting plantations from areas with higher soil water content that have important water yield function at the catchment scale, as hydrologically sensitive areas (Agnew et al. 2006). The identification of these areas could indeed help local land-use planning. Also, the road design could be modified considering the surface water dynamics at the landscape level, deactivating roads from more sensitive areas, reducing density and also redesigning some roads in order to avoid stream sedimentation (Ferraz et al., 2007).

### 3.3 Politics

Brazil has a comprehensive environmental law system, which has become stronger after the promulgation of the ‘new’, 1988 Constitution.



From the point of view of the relation between forests and water, two laws deserve comments: the Forest Code<sup>6</sup> and the National Policy of Water Resources<sup>7</sup>. The Forest Code requires that all rural properties, be it public or private, should maintain a percentage of native vegetation, which varies from 20 to 80% of the property area, depending on the country region. Part of this percentage must be located on the so called “permanent preservation areas”, which have been established for the purpose of soil and water conservation. These areas are located mainly along water courses, and also around springs and headwater areas, as well as around natural water bodies, lakes and reservoirs, as established during the licensing process.

On the other hand, the National Policy of Water Resources established a decentralized administration by river basin, aiming to conciliate the environment and the water conservation. Each river basin must have a Committee and an Agency, which are responsible for, respectively, the elaboration of the River Basin Planning, and for the implementation of such plan. The funding for these actions derives from the charges for water use.

Therefore, Brazil is well endowed with environmental laws, but the ineffective enforcement of these laws difficult the real achievement of their environmental objectives.

On the other hand, another example of public policy in this respect is the recent, new legal tool, referred to as Environmental and Rural Register, by which the owners of all rural properties must declare whether their land use is or is not in accordance with the Forest Code. In case it is not, there will be a term, ranging from 5 to 20 years for the restoration of the forest cover in areas that should be protected. This Register is done on a geographic information system and all information are nested on an imagery with a resolution varying from 1:25,000 to 1: 50,000, depending on the region. It is expected that this new tool will enforce forest conservation.

Another example of a powerful tool, not only related to law enforcement, but also to the social and environmental administration of forest companies, is the Forest Certification. A recent survey made by Imaflores (Institute of Agricultural and Forest Management and Certification), one of the Brazilian Certification Institutions, compared the requirements of the Forest Code with the Forest Certification requirements among certified and non-certified forest companies, and the results are summarized in Table 1 (Pinto et al., 2014).

**Table 1.** Impacts of the Forest Stewardship Council Certification on the conservation of native vegetation in forest plantation areas in the South of Brazil (Pinto et al., 2014).

Practice	Law requirement	Percentage of forest companies that use the practice	
		Certified Group	Control Group
Control Plan of invasive species	No	100%	33%
Fauna and Flora Studies	No	71%	29%
Planting of native species	Yes	71%	50%
Monitoring of environmental legislation	No	100%	29%
Environmental licensing	Yes	86%	14%
Legal Reserve Registering	Yes	100%	57%
% of native forest	Yes	42%	34%
Conversion of native forests to plantations	No	100%	57%

<sup>6</sup> Law 9433, of 8 January 1997

<sup>7</sup> Law 12651, of 25 May 2012

### 3.4 Climate change and the future of forests & forest research

Although causation of global warming and climatic extreme events is still a matter of debate in the scientific community (Parmesan and Yohe, 2003), it seems apparent that climate extremes are becoming more common. Given the profound changes announced by the IPCC reports, climate is changing at all scales (Lawrence and Vandecar, 2014). For example, at the macroscale, circulation patterns that govern the climate of huge regions such as the Amazon basin and the southeast are likely to change. Climatic events are predicted to be more frequent and also intense (Timmermann et al., 1999). This picture is translated into the broader generalization of IPCC reports, that is, the increasing frequency of extreme events (Easterling et al., 2000) that include not only floods but also severe droughts as was experienced in Brazil in 2014. As a matter of fact, in this referred year, the southeast region experienced one of the most severe droughts in the history of the records while, at the same time, some rivers of the Amazon basin (e.g. Negro River) reached one of the highest flood stages.

With this in mind, an important topic that should be the focus of research is related to deforestation in the Amazon basin and its effects on climate since the last one influences economic activity in many sectors including forestry. Climatic interactions (teleconnections) between macroregions in Brazil, that is, the north region (Amazon basin) and the southeast, showed that the former provides a substantial amount of water vapor that, ultimately, generates rain at the latter (Fearnside, 2004). With increasing deforestation in the Amazon, climate patterns in the southeast are likely to change (Lawrence and Vandecar, 2014). Thus, understanding changes in circulation patterns at the macroscale seems to be a clear focus of research that may collaborate in predicting a better zoning of forest plantations and water management actions in case deforestation patterns and greenhouse emissions are not halted. In addition, at the local scale, research on the forest ecosystem behavior of different ecosystem under drought scenarios such as the “Seca Floresta Project” in the Amazon (Brando et al., 2008) must continue to document the consequences of a dryer climate in the Amazon and other biomes in the medium to long-term.

At this point, in a changing climate, a new agro climatic zoning should be carried out indicating the ‘new’ regions more suitable for forest plantations under many climate scenarios (e.g. Garcia et al., 2014). With these zoning maps, the already documented and predicted expansion of forest plantations in the country (Kröger, 2012; Campos, 2013; Rezende et al., 2013) could be, for example, established in degraded pastures sites that abound in Brazil (Dias-Filho et al., 2014), where sufficient annual rainfall is available. This would lead to an increase in carbon storage above ground and, thus, would contribute to tackle climate change through carbon biological sequestration with low impacts on water resources. Currently, eucalypt plantations are predicted mainly towards the areas of Cerrado and Atlantic Forest (Campos, 2013), where climate is seasonal. This could lead to more conflicts relating to forest plantations, water and people in the tropics.

At the catchment scale, besides the development of more water efficient cultivars, emphasis must also be given to the development and implementation of best management practices that improve soil water infiltration which, if exceed evapotranspiration (likely to occur in wet years), would lead to higher dry season flow (Bruijnzeel, 2004; Ogden et al., 2013). This, in turn, is related to many important ecosystem services for downstream users, such as water supply, energy generation (hydropower) and aquatic species conservation. Such practices include harvesting with machinery of low impact on soil physical properties as well as increasing soil organic matter content. Furthermore, best management practices should not be restricted to the forest plantations areas, but should focus on the provisioning of ecosystem services at whole landscape level (Foley et al., 2005). Well-conserved and diverse native riparian buffers, for example, could provide predators for many insects that could damage forest plantations. Thus, these riparian ecosystems would lead to an increase in resilience of forest plantations at this higher hierarchical level. Lastly, long-term studies monitoring hydrological variables within small catchments as well as simulation studies with these dataset should be stimulated. This would increase the records and, thus, increase our observation and prediction skills to understand streamflow responses to climate change (Strauch et al., 2015).

Finally, increases on the knowledge of hydrological ecosystem functioning as well as ecosystem restoration in many biomes such as Pantanal, Cerrado, Amazon and Atlantic Forest should be also included as future actions of research. In this sense, restoration practices should not be restricted to the restoration action *per se*, but they should focus on the development of different ecological strategies more suitable to each of these biologically and physically diverse biomes, that, as noted earlier in this chapter, have very important functions on regulating the hydrological cycle in the whole country.

### 3.5 Acknowledgements

The advance in the knowledge of the relation of forest plantations and water in Brazil is being acquired with the accumulated results of a cooperative program of hydrologic monitoring of forest plantation management in 16 experimental catchments located in several parts of the country, coordinated by the Forest Hydrology Laboratory of the University of São Paulo and IPEF – Institute of Forest Research and Studies ([www.ipef.br/promab](http://www.ipef.br/promab)).

Thanks are also due to Carla Cristina Cassiano e Aline Aparecida Fransozi, for the elaboration of the maps.

### 3.6 References

- ABRAF (Associação Brasileira de Produtores de Florestas Plantadas). Anuário estatístico da ABRAF 2013, ano base 2012. Associação Brasileira de Produtores de Florestas Plantadas, Brasília, 2013, 148p.
- Agnew L.J.; Lyon, S.; Gérard-Marchant, P.; Collins, V.B.; Lembo, A.J.; Steenhuis, T.S.; Walter, M.T. Identifying hydrologically sensitive areas: Bridging the gap between science and application. *Journal of Environmental Management*, 78, p. 63–76, 2006.
- Almeida, A.Q.; Ribeiro, A.; Leite, F.P. Modelagem do balanço hídrico em microbacia cultivada com plantio comercial de *Eucalyptus grandis* X *urophylla* no leste de Minas Gerais, Brasil. *Revista Árvore*, Viçosa-MG, v.37, n.3, p.547-556, 2013.
- Almeida, A.C.; Soares, J.V.; Landsberg, J.J.; Rezende, G.D. Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. *Forest Ecology and Management*, 251, p.10–21, 2007.
- Andréassian, N. Water and forests: from historical controversy to scientific debate. *Journal of Hydrology*, 291, p. 1-27, 2004.
- Baker, D.B. ; Richards, R.P. ; Loftus, T.T. ; Krame, J.W. A new flashiness index: characteristics and applications to Midwestern rivers and streams. *Journal of the American Water Resources Association*, American Water Resources Association, Middleburg, v. 40, n. 2, p 503-522, 2004.
- Borma, L.S.; Rocha, H.R.; Cabral, O.M.; Von Randow, c.; Collicchio, E.; Kurzatkowski, D.; Brugger, P.J.; Freitas, H.; Tannus, R.; Oliveura, L.; Rennó, C.D. Atmosphere and hydrological controls of the evapotranspiration over a floodplain forest in the Bananal Island region, Amazonia. *Journal of Geophysical Research*, V. 114, p. 01-12, 2009.
- Bren, L. *Forest Hydrology and Catchment Management, An Australian Perspective*. Springer Netherlands, 268 p., 2015.
- Brando, P.M.; Nepstad, D.C.; Davidson, E.A.; Trumbore, S.E.; Ray, D.; Camargo, P. Drought effects on litterfall, wood production, and belowground carbon cycling in an Amazon forest: results of a throughfall reduction experiment. *Philosophical Transactions of the Royal Society B Biological Sciences*, v.364, n.1498, p.1839-1848, 2008.
- Bruijnzeel, L.A. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment*, v.104, n.1., p.185-228, 2004.
- Cabral, O.M.R.; Rocha, H.R.; Gash, J.H.C.; Ligo, M.A.V.; Freitas, H.C.; Tatsch, J.D. The energy and water balance of a *Eucalyptus* plantation in southeast Brazil. *Journal of Hydrology*, 388, p. 208-216, 2010.
- Calder, I.R. Forests and water: ensuring forest benefits outweigh water costs. *Forest Ecology and Management*, 251, p. 110-120, 2007.

Calmon, M.; Brancalion, P.H.; Paese, A.; Aronson, J.; Castro, P.; Silva, S.C.; Rodrigues, R.R. Emerging threats and opportunities for large-scale ecological restoration in the Atlantic Forest of Brazil. *Restoration Ecology*, 19 (2), p.154-158, 2011.

Campos, A.R. Modelagem territorial de cenário da expansão das plantações de eucalipto no Brasil. Belo Horizonte: Universidade Federal de Minas Gerais, 2013. 49p. (Master Dissertation).

Dias-Filho, M.B. Diagnóstico das pastagens no Brasil. Belém – PA: EMBRAPA Amazônia Oriental, 36p., 2014.

Easterling, D.R.; Meehl, G.A.; Parmesan, C.; Changnon, S.A.; Karl, T.R.; Mearns, O.L. Climate extremes: observations, modeling, and impact. *Science*, v.289, n.5487, p.2068-2074, 2000.

Facco, A.G. et al. Técnicas de geoinformação para estimativa do balanço hídrico em eucalipto. *Pesquisa Agropecuária Brasileira*, Brasília, v.47, n.9, p.1243-1250, set. 2012.

Falkenmark, M.; Folke, C. The ethics of sócio-hydrological catchment management: towards hydrosolidarity. *Hydrology & Earth System Sciences*, 6 (1), p.1-9, 2002.

Farley K.A.; Jobbagy E.G.; Jackson R.B. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology*, 11, p.1565-1576, 2005.

Fearnside, P.M. A água de São Paulo e a floresta amazônica. *Ciência Hoje*, 34, n.203, p.63-65, 2004.

Ferraz, S.F.B.; Marson, J.C.; Fontana, C.R.; Lima, W.P. Uso de indicadores hidrológicos para classificação de trechos de estradas florestais quanto ao escoamento superficial. *Scientia Forestalis*, n. 75, p. 39-49, 2007.

Ferraz, S.F.B.; Lim, W.P.; Rodrigues, C.B. Managing Forest plantation landscapes for water conservation. *Forest Ecology and Management*, 301, p.58–66, 2013.

Foley, J.A., Defries, R. Asner, G.P., Barford, C., Bonan, Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A.,

Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K. Global consequences of land use. *Science*, v.5734, p.570-574, 2005.

Garcia, L.G.; Ferraz, S.F.B.; Alvarez, C.A.; Ferraz, K.M.P.M.B.; Higa, R.C.L. Modelagem de aptidão climática de *Eucalyptus grandis* frente aos cenários de mudança climática. *Scientia Forestalis*, v.42, n.104, 81-87, 2014.

Gonçalves, J.L.M.; Alvares, C.A.; Higa, A.R.; Silva, L.D.; Alfenas, A.C.; Stahl, J.; Ferraz, S.F.B.; Lima, W.P.; Brancalion, P.H.S.; Hubner, A.; Bouillet, J.P.D. Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. *Forest Ecology and Management*, 301, p. 6–27, 2013.

Gordon, L.J.; Finlayson, C.M.; Falkenmark, M. Managing water in agriculture for food production and other ecosystem services. *Agricultural Water Management*, 97, p.512-519, 2011.

Hartley, M.J. Rationale and methods for conserving biodiversity in plantation forests. *Forest Ecology and Management*, 155: 81-95, 2002.

Hewlett, J.D.; Hibbert, A.R. Factors affecting the response of small watersheds to precipitation in humid areas. In Sopper, W.E. and Lull, H.W., editors, *Forest hydrology*, New York: Pergamon Press, p. 275–90, 1967

Holscher, D.; Sá, T.D.A.; Bastos, T.X.; Denich, M., Folster, H. Evaporation from young secondary vegetation in eastern Amazonia. *Journal of Hydrology*, 193, p.293–305, 1997.

IBGE (Instituto Brasileiro de Geografia e Estatística). Mapa de Biomas do Brasil. 2004.

IPEF. Relatório de Consultoria, Contrato UGL/PDRS/BIRD. 2014.

Kröger, M. The expansion of industrial tree plantations and dispossession in Brazil. *Development and Change*, v.43, n.4, p.947-973, 2012.

Lawrence, D.; Vandecar, K. Effects of tropical deforestation on climate and agriculture. *Nature Climate Change*, v.5, p.27-36, 2014.

Lima, W.P.; Zakia, M.J.B.; Libardi, P.L.; Souza Filho, A.P. Comparative evapotranspiration of Eucalyptus, Pine and natural cerrado vegetation measured by the soil water balance method. *IPEF International*, 1, p.5-11, 1990.

Lima, W.P.; Laprovitera, R.; Ferraz, S.F.B.; Rodrigues, C.B.; Silva, M.M. Forest Plantations and Water Consumption: A Strategy for Hydrosolidarity. *International Journal of Forestry Research*, Volume 2012a, 8 pages.

Lima, W.P.; Ferraz, S.F.B.; Rodrigues, C.B.; Voigtlaender, M. Assessing the hydrological of forest plantations in Brazil. In: Boon, P.J.; Raven, P.J. *River Conservation and Management*. Wiley-Blackwell, 20p., 2012b.

- MMA (Ministério do Meio Ambiente). Mapa de cobertura vegetal dos biomas brasileiros. Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira - PROBIO.18p.2007.Available: <http://www.mma.gov.br/publicacoes/biomas/category/112-geral>
- Makarieva, A.M.; Gorshkov, V.G.; Sheil, D.; Nobre, A.D.; Bunyard, P.; Li, B.L. Why does air passage over forest yield more rain? Examining the coupling between rainfall, pressure, and atmospheric moisture content. *Journal of Hydrometeorology*, 15, p. 411–426, 2014.
- Ogden, F.L.; Crouch, T.D.; Stallard, R.F.; Hall, J.S. Effects of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama. *Water Resources Research*, 49, p.8443-8462, 2013.
- Oliveira, P.T.S.; Nearing, M.A.; Moran, M.S.; Goodrich, D.C.; Wendland, E.; Gupta, H.V. Trends in water balance components across the Brazilian Cerrado. *Water Resources Research*, 50 (9): 7100-7114, 2014.
- Parmesan, C.; Yohe, G. A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, v.421, p.37-42, 2003.
- Rezende, J.B.; Pereira, J.R.; Botelho, D.O. Expansão da cultura de eucalipto nos municípios mineiros e gestão territorial. *CERNE*, v.19, n.1, p.1-7, 2013.
- Rosoman, G. The Plantation Effect. Greenpeace New Zealand, Auckland. 48p., 1994.
- Shuttleworth, W. J. Evaporation from Amazonian Rainforest. *Proceedings of the Royal Society of London. Series B, Biological Sciences*, 233 (1272), p.321-346, 1988,
- Soares, J.V.; Almeida, A.C. Modeling the water balance and soil water fluxes in a fast growing Eucalyptus plantation in Brazil. *Journal of Hydrology*, 253, p.130-147, 2001.
- Sommer, A. et al. Transpiration and canopy conductance of secondary vegetation in the eastern Amazon. *Agricultural and Forest Meteorology*, 112, p. 103-121, 2002.
- Strauch, A.M., MacKenzie, R.A., Giardina, C.P., Bruland, G.L. Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological model. *Journal of Hydrology*, v.523, p.160-169, 2015.
- Timmermann, A.; Oberhuber, J.; Bacher, A.; Esch, M.; Latif, M.; Roeckner, E. Increased El Niño frequency in a climate model forced by future greenhouse warming. *Nature*, 308, p. 694-697, 1999.
- Trevisan, R.; Salemi, L.F.; Groppo, J.D.; Silva, R.W.C.; Martinelli, L.A.; Dinâmica da água em uma microbacia com cobertura florestal de eucalipto localizada na Serra do Mar no Vale do Paraíba do Sul. *Revista Brasileira de Recursos Hídricos*, 17 (4), p.207-216, 2012.
- Tundisi, J.G. Recursos Hídricos no Brasil: Problemas, Desafios e Estratégias para o Futuro. *Academia Brasileira de Ciências*, 92p., 2014.
- Vital, A.R.T.; Lima, W.P.; Camargo, F.R.A. Efeitos do corte raso de plantação de *Eucalyptus* sobre o balanço hídrico, a qualidade da água e as perdas de solo e de nutrientes em uma microbacia no Vale do Paraíba, SP. *Scientia Forestalis*, 55, p.5-16, 1999.
- Vourlitis, G.L.; Nogueira, J.S.; Lobo, F.A.; Pinto JR., O.B. Variations in evapotranspiration and climate for an Amazonian semi-deciduous forest over seasonal, annual, and El Niño cycles. *International Journal Biometeorological*, 59, p. 217–230, 2015.
- Zhang L.; Dawes W.R.; Walker G.R. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*, 37, p.701-708, 2001.



## Chapter 4. Forest Management and Water in Chile

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### 4.1 Introduction

Chile is geographically known for its shape, a narrow (average 150 km) and long (more than 4,000 km) strip from latitudes 18° to 56° S, facing the Pacific Ocean to the west, the world's driest desert in the northern Atacama Region, Mediterranean scrub and open forests at mid-latitudes, cold rainforests in the south, and Patagonian steppe in the extreme south-east. The natural limits of Chile greatly isolate it and prevent invasions from other forests in the continent. For these reasons, Chilean forests, including Mediterranean forests (32°-38°30'S) and Temperate Rainforest (38°30' to 56°S), can be considered as a biogeographical island (Donoso 1993, Armesto et al. 1995, Armesto et al. 1998, Feisenger, 1998, INFOR 2013, CONAF 2014).

Just like most countries around the world, the majority of Chile's territory was widely covered by forests several centuries ago. Deforestation started with pre-Hispanic populations, to continue in higher rates with the arrival of European Settlers. Thus, by the end of the twentieth century, more than 19 million hectares in Chile were deforested and under some degree of erosion and desertification. Thus, by the end of the twentieth century, more than 19 million hectares in Chile were deforested and are actually under some degree of erosion and desertification. In terms of native forest types, the most widely distributed types are listed in Table 1. However, other relevant species are *Prosopis* ssp. in the north and "Palma Chilena" (*Jubaea chilensis*) in the central parts of the country, respectively. Since late 1970s, the creation of Government incentives to plant trees triggered the expansion of man-made forests established with exotic fast growing species which are the base of the Chilean forest economy. The rapid annual growth rate on trees planted in Chile represents a competitive advantage due to a shorter rotation age, compared to the same species growing elsewhere in the world, leading to the appearance of a large forest industry in the country.

Today, more than 16 million hectares of the Chilean territory are covered by either plantation (2.5 million hectares) or native (13.5 million hectares) forests (Figure 1). Forest plantations in Chile are dominated by *Pinus radiata* (D. Don) and *Eucalyptus* spp., which account for 2.3 million ha (INFOR 2013), an area increasing in average by thousands of hectares every year (CONAF 2014).

The forest industry is the second largest exporting sector in Chile, being the mining industry the first. However, forestry-related industry is the main producer of renewable prime material in the country, manufacturing a wide variety of wood products, mostly from commercial pine and eucalyptus plantations. Forest industries comprise a diverse group of large, median and small companies that produce cellulose, lumber, wood panels, furniture, and construction materials, among others.

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**Table 1.** Distribution of the main Chilean native and endemic forest species (Donoso 1981 and Society of American Foresters)

Forest type	Latitudinal range (S Lat.)	Precipitation range (mm/yr)	Area (x1,000 ha)
Evergreen	38°30' - 47°	2,000 - 5,000	4,350
Lenga	36°50' - 56°	1,000 - 3,000	3,400
Coihue de Magallanes	47° - 55°30'	2,000 - 7,500	1,801
Roble-Raulí-Coihue	36°30' - 40°30'	1,500 - 3,000	1,370
Ciprés de las Guaitecas	40° - 54°	2,500 - 7,500	972
Coihue-Raulí-Tepa	37° - 40°30'	1,500 - 4,000	457
Sclerophyllus	32° - 38°	300-1,000	343
Alerce	39°50' - 43°30'	2,000 - 4,000	265
Araucaria	37°40' - 40°48'	2,000 - 4,500	254
Roble-Hualo	32°50' - 36°50'	500 - 2,000	185
Ciprés de la Cordillera	34°45' - 44°	500 - 900	45

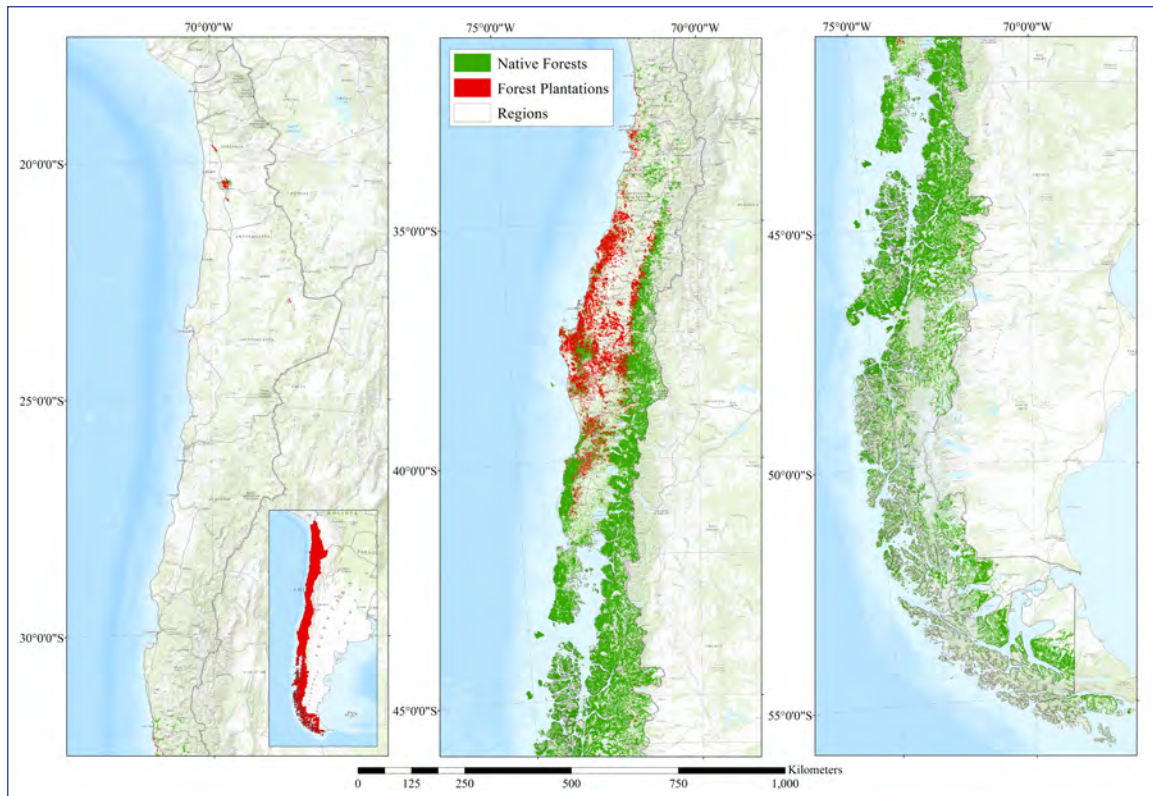
Chile has a highly regulated water managements system, which can be improved with a better articulation and coordination among Government institutions, as well as better policies and more research. Moreover, and considering the geography of the country, the Government is currently giving more relevance to water resources management, though conflicts are advancing faster than solutions due to both climate change and an increase on water demands. Agriculture is, by far, the main water consumer in the country, followed by industries and mining (Table 2).

**Table 2.** Consumptive water uses in Chile.

Source: Adapted from McPhee et al. (2012) and Valdés-Pineda et al. 2014.

Sector	Percent
Agriculture	77.8
Industrial	9.1
Mining	7.2
Municipal	5.9
<i>Total</i>	<i>100</i>

Despite the above, a clear problem in Chile is the fact that there is abundance of water in the sparsely populated south, and not enough water in the densely populated Central and Northern regions (Figure 2). For instance, the Government is currently analyzing several options to transport water from the South to areas where the resource is needed. Among the most relevant ideas are a submarine aqueduct, a subterranean aqueduct, ship marine transportation, transportation through aquifer recharge and pumping, and desalinization of seawater. Each solution has its own advantages and limitations, and each one offers different costs, life expectancies, and flow rates. While the creation of a combined system seems to be the best alternative, a logical fact is that Chile will be transporting water from the South in a decade or two, eliminating significantly the adverse effects of global warming and droughts, and supplying the increasing demands for the resource in areas of water scarcity.

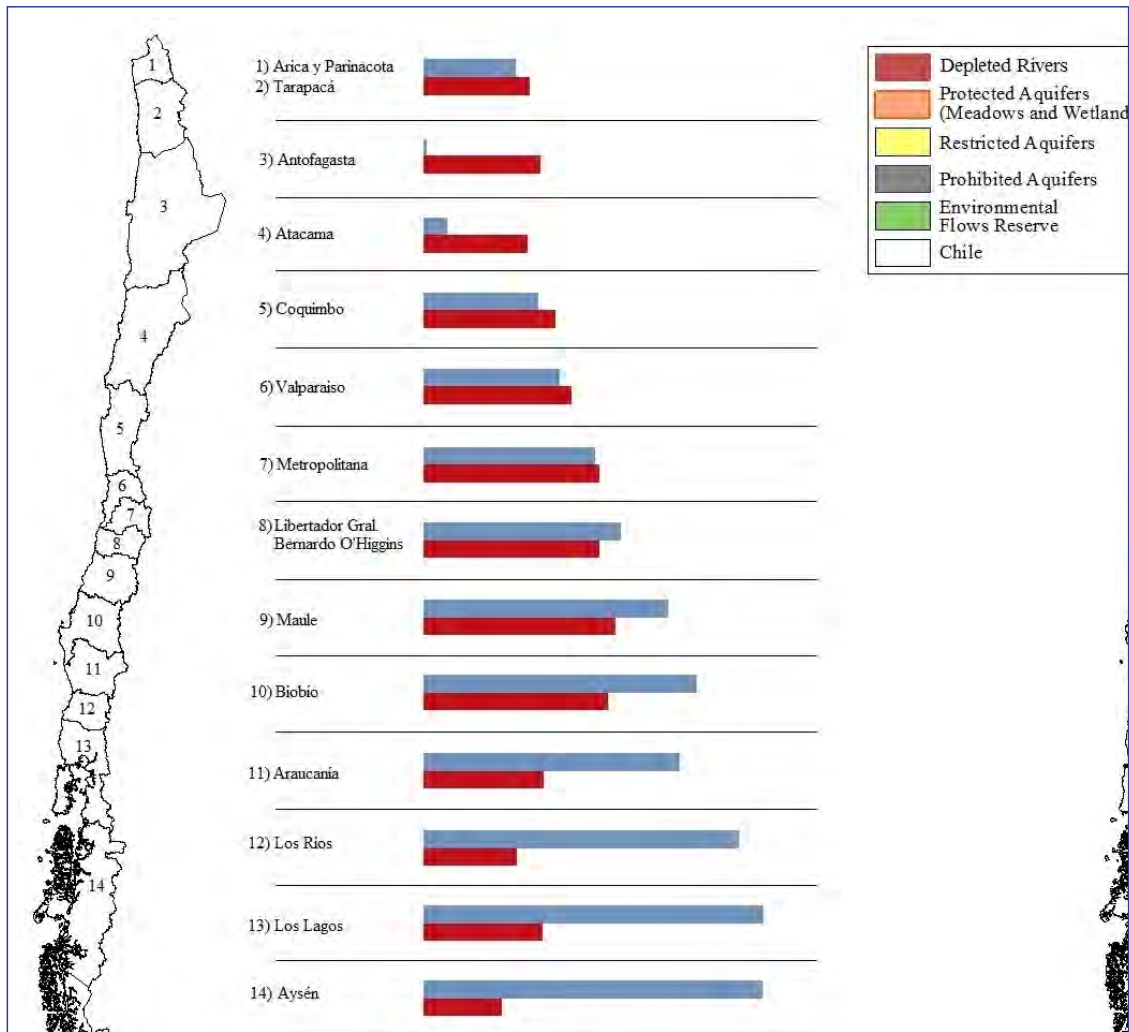


**Figure 1.** Spatial distribution of forest plantations and native forests in Chile.  
Own work. Based on Hansen et al. 2013.

Forest expansion has dramatically changed the traditional rural landscape of agriculture on poor and degraded soils, in a period characterized by increasing water demands and dry years. Conflicts between forest plantations and water are gradually increasing in Chile. This is mostly because, historically, Chile has been a country with plenty of water, and most of its water resources management system is based on surface water flowing from the Andes to the Pacific Ocean. Though forest plantations are commonly blamed for increasing lacks of surface and groundwater flows during the last decade or so, it is still unclear whether such decreases of flowing water are due to the establishment of forest plantations, climate change, increases on surface and groundwater uses, or a combination of all.

## 4.2 Literature review

As forest plantations in Chile have increased tremendously during the last few decades, water resources-related research began slightly on the 1980s, reaching higher numbers after 1996 (Table 3). Up to the year 2012, a total of 91 undergraduate theses were published at national universities (Jofré et al. 2014). Furthermore, there were 67 publications on national ISI journals and scientific magazines (*Bosque, Ecología y Biología de Suelos, Turrialba, Ciencias Forestales, Ciencia e Investigación Forestal, Medio Ambiente, Python, Terra Australis, Agro Sur, Revista U. de Talca, and Revista Infor*). In terms of international ISI journals, there were only 19 water and forestry-related publications (*Hydrological Processes, Journal of Hydrology, Journal of Geophysical Research, Forest Ecology and Management, Biogeochemistry, Revista Científica del INIA (Spain), Revista Ambiente y Desarrollo de CIPMA*), which are listed on Table 4. Most of the above studies have been developed by researches working in national universities, many times in collaboration with international entities.

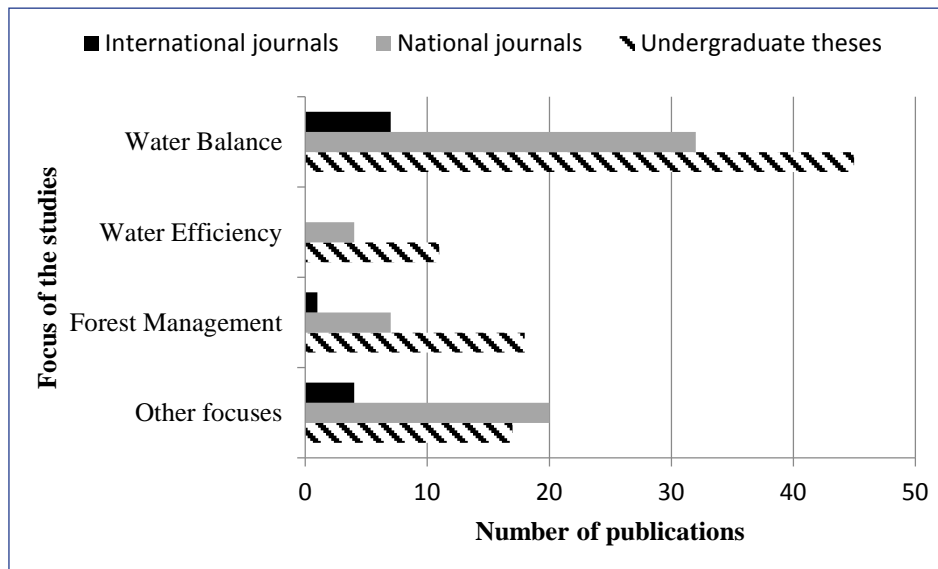


**Figure 2.** Distribution of water availability and demands (a), and groundwater management system (b) along Chile. Adopted from Valdes-Pineda et al. 2014.

According to Jofré et al. (2014), water and forestry-related research in the country can be classified into four main categories: *water balance* (relationship between water consumption efficiency and management activities), *forest management* (plantation density, species, interventions), *water efficiency* (water consumption), and *other topics* (modeling, forest management plans, etc.). Thus, the total number of studies focused on each of the above topics are illustrated in Figure 3. Among the main research topics related to *water balance* are comparison among different plant covers, runoff generation, and special and temporal distribution of soil moisture. Similarly, but in lower number, are studies focused on *forest management*, i.e. the effects of forest management activities on water resources, plant reestablishment, etc. Analysis of soil erosion processes, sediment transport, water quality, and runoff analysis represent the minority of the cases (*other topics*), followed by topics on *water efficiency*, i.e. the analysis of the effects of forest plantations on soil moisture and the comparison of water efficiency among species and soil types (Jofré et al. 2014).

**Table 3.** Number of university theses published since 1983 in Chile.  
Source: University of Chile's electronic database, cited by Jofré et al. 2014.

Period	Number of theses
1983-1990	4
1991-1995	6
1996-2000	31
2001-2005	30
2006-2012	19



**Figure 3.** Distribution of water and forestry-related publications conducted in Chile.  
Partially adopted from INFOR 2014.

From Table 4 below, Iroumé (2001) and Huber et al. (2008) refer to results from experimental plots, a method that has been widely used to study the effects of forests in water resources in Chile. However, Iroumé et al. (2005, 2006) and Huber et al. (2010) are experimental watershed studies in forest plantations. Similarly, Lara et al. (2009) used experimental watersheds on native forests. Also, Oyarzún et al. (2006) based their study on experimental watersheds to compare the hydrology of native forests with that from commercial plantations. Little et al. (2014) used experimental watersheds to determine the buffer effects of streamside native forests on areas with commercial plantation. On the other hand, Pizarro et al. (2005), Little et al. (2009), and Iroumé and Palacios (2013) focused on large-scale river basins.

Information on Chilean studies on water and forests have been generated from a large diversity of geographical areas, treatments, and research methods thus making very difficult the generalization to generate national tendencies. Generally speaking, water and forestry-related studies in Chile suggest that forest plantations strongly affect the hydrologic cycle of small watersheds, decreasing the amount of water available for other uses. However, most forest plantations have been established on areas where old growth native forests were replaced decades and even centuries ago by grasslands (the type of land use with highest runoff-generating potential), which subsequently were afforested.



**Table 4.** International ISI publications from water and forestry-related studies developed in Chile.

Year	Authors	Journal	Title
2014	Little et al.	Ecohydrology	Buffer effects of streamside native forests on water provision in watersheds dominated by exotic forest plantations
2013	Iroumé and Palacios	Journal of Hydrology	Afforestation and changes in forest composition affect runoff in large river basins with pluvial regime and Mediterranean climate, Chile
2013	Mohr et al.	Journal of Geophysical Research	Runoff generation and soil erosion processes after clear cutting
2013	Schuller et al.	Journal of Environmental Radioactivity	Using $^{137}\text{Cs}$ and $^{210}\text{Pb}$ and other sediment source fingerprints to document suspended sediment sources in small forested catchments in south-central Chile
2011	Iroumé et al.	Rev. Téc. Ing. Univ. Zulia	GIS application of USLE and MUSLE to estimate erosion and suspended sediment load in experimental catchments, Valdivia, Chile
2011	Birkinshaw et al.	Hydrological Processes	The effect of forest cover on peak flow and sediment discharge—an integrated field and modelling study in central–southern Chile
2010	Iroumé et al.	Bosque	Runoff and peakflows after clearcutting and the establishment of a new plantation in an experimental catchment, southern Chile
2010	Huber et al.	Bosque	Effect of <i>Pinus radiata</i> and <i>Eucalyptus globulus</i> plantations on water resource in the Coastal Range of Biobio region, Chile
2010	Schuller et al.	Soil & Tillage Research	Use of beryllium 7 to study the effectiveness of woody trash barriers in reducing sediment delivery to streams after forest clearcutting
2009	Lara et al.	Forest Ecology and Management	Assessment of ecosystem services as an opportunity for the conservation and management of native forests in Chile
2009	Little et al.	Journal of Hydrology	Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile
2009	Walling et al.	Water Resources Research	Extending the timescale for using beryllium 7 measurements to document soil redistribution by erosion
2008	Huber et al.	Hydrological Processes	Effect of <i>Pinus radiata</i> plantations on water balance in Chile
2006	Iroumé et al.	Hydrological Processes	Runoff and peak flow responses to timber harvest and forest age in southern Chile
2006	Pizarro et al.	Journal of Hydrology	The effects of changes in vegetative cover on river flows in the Purapel river basin
2005	Iroumé et al.	Journal of Hydrology	Summer flows in experimental catchments with different forest covers, Chile
2005	Oyarzún et al.	Revista Ambiente y Desarrollo de CIPMA	Los servicios ecosistémicos del bosque templado lluvioso: producción de agua y su valoración económica
2002	Iroumé and Huber	Hydrological Processes	Comparison of interception losses in a broadleaved native forest and a <i>Pseudotsuga menziesii</i> plantation in the Andes Mountains of southern Chile
2001	Huber and Iroumé	Journal of Hydrology	Variability of annual rainfall partitioning for different sites and forest covers in Chile
1995	Oyarzún and Peña	Hydrological Processes	Soil erosion and overland flow in forested areas with pine plantations at coastal mountain range, central Chile

Despite the above, a recent study by some of the authors of this Chapter (led by Roberto Pizarro), among other scientists, suggests that forest plantations in Chile do not significantly affect water quantity on large watersheds (Lignum 2015). This revolutionary result disagrees with most of the international research on water and forest plantations, because most studies suggest that forest plantations consume large amounts of water. However, most studies worldwide have been done in areas where precipitation falls during summer, among other seasons, but summer rains is a common denominator. Central Chile's precipitation occurs only during winter months, when trees are dormant. As a result, rainfall infiltrates into the soil horizons, recharging water tables. Despite the above, knowledge of water resources and forestry interactions is still not well known in Chile, which is a problem that needs to be addressed, based on current tendencies on water consumption, as well as climate change effects in the country. Furthermore, the country's forestry-related organizations should incorporate BMP's into their management system, to minimize water consumption from forest plantations.

Additionally, the above paragraph is somehow supported by Pizarro et al. (2005) and Little et al. (2009), who documented no significant hydrological changes after forest conversion. Similarly, Iroume and Palacios (2013) documented no significant runoff changes after increasing the area occupied by forest plantations by 15% or less.

### 4.3 Politics

As previously mentioned, Chile is a country in which severe deforestation took place since mid XIX's century, mostly to habilitate land for agriculture. Such practice was maintained until early XX century, when the "Ley de Bosques" (Forests Law) was created, leading to incentives for the reforestation of thousands of hectares of degraded land along the country. Years later (1974), the DL702 law was created to increase even more the incentives for planting degraded areas, through which the Government reimbursed Between the 75 and 95% of the afforestation costs, providing also work to low-income people, in areas that were previously unproductive and degraded. Thus, more than two million hectares were planted after 1974.

Despite the above, there was no relevant laws or regulations focused on mitigating the impacts of forest practices on water resources, even though between 1990 and 2002 there was a 160% increase on water demands from different productive sectors. However, water issues are now incorporated in Forest Certification protocols and environmental priorities in Chile, leading to a series of new forest management approaches. Other than certain restrictions to plant near watercourses or limiting annual harvested areas, there are no laws or regulations focused on the effects of forestry on water resources in Chile. The main reason for this lack of regulations is the fact that there have not been enough studies to know well the effects of forestry on water resources, combined with the fact that Chile is a country with watersheds that fall 5,000 m in elevation on distances shorter than 200 km, with different precipitation regimes, and with strong influences from important mountain ranges.

In conclusion, it is strictly necessary to create an applied research policy, to understand the behavior of forest ecosystems and to determine where and how forest activities affect the hydrologic cycle of Chilean watersheds.

### 4.4 Climate change and the future of forestry & forest research

Climate change is a growing concern in Chile, mostly because its effects are represented by the concentration of annual precipitation in fewer and more intense storm events, accompanied by more droughts, more wildfires, and more floods during storms (Valdes-Pineda et al. 2014, Pizarro et al. 2012). As a country used to have enough water for all its needs, the above changes on precipitation behavior has caused tremendous damages in all sectors during the last decades, being the last ten years the worse by far. Every year more trees are planted to become commercial plantations,

leading to more conflicts between forestry and other areas (mostly agriculture), resulting on endless discussions in which each sector blames the opposite, or climate change.

Also, there are currently millions of hectares occupied by bare, degraded soils in Chile, and forestry should play a role in recovering such surface to transform them into productive land again.

For the above reasons, the future of forest research is based on several challenges:

- Genetic management to establish trees that are less water demanding, with adaptations to droughts while maintaining fast growing rates.
- Rainwater harvesting practices (e.g. infiltration trenches) to take advantage of the fewer, but intense, storm events resulting from climate change.
- Effects of forest management practices on the quantity and quality of water resources, but most importantly, how forests and forest plantations interact with the hydrologic cycle in Chile, and how other areas contribute to current and future water shortages.
- BMPs in forestry, to minimize water consumption from a forest plantation in a given watershed.
- More research is necessary in the field of ecohydrology, for a better understanding of the role of forests in surface flows and groundwater recharge processes.
- Reforestation programs should be implemented in the country to recover the large amount of hectares that are currently degraded

## 4.5 Acknowledgments

The authors thank the International Hydrology Research Group (University of Chile, Faculty of Forest Sciences and Nature Conservancy), the Technological Center of Environmental Hydrology (University of Talca), the University of Arizona's Department of Hydrology and Atmospheric Sciences, the Austral University of Chile, and the Forest Institute of Chile (INFOR) for their valuable contributions to this Chapter.

## 4.6 References

- Armesto, J.J., Lobos, P.L and M.K. Arroyo, M.K. 1995. Los bosques templados del sur de Chile y Argentina: una isla biogeográfica. In *Ecología de los bosques nativos de Chile*. Eds. J.J. Armesto, C. Villagrán and M. K. Arroyo. Santiago, Chile: Ed. Universitaria, 1995. pp. 23-28.
- Armesto, J.J., Rozzi, R., Smith-Ramirez, C., and Arroyo, M.K. 1998. Conservation targets in South American Temperate Forests. *Science*. 282: 1271-1272.
- Donoso, C. 1981. Tipos forestales de los bosques nativos de Chile. Documento de trabajo No 38. Investigación y Desarrollo Forestal (CONAF/PNUD-FAO) (Publicación FAO Chile).
- Feisenger, P. 1996. Biodiversity knowledge in Chile. *Trends in Ecology and Evolution*. Trends in Ecology and Evolution. 11(11): 451-452.
- Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, D. Thau, S. V. Stehman, S. J. Goetz, T. R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C. O. Justice, and J. R. G. Townshend. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* 342 (15 November): 850-853.
- Huber, A., Iroumé, A., Mohr, C., Frêne, C. 2010. Effect of *Pinus radiata* and *Eucalyptus globulus* plantations on water resource in the Coastal Range of Biobio region, Chile. *Bosque* 31 (3): 219-230.

- INFOR. 2013. Anuario Forestal 2013. Boletín Estadístico N 140. Instituto Forestal, Ministerio de Agricultura. Santiago, Chile.
- Iroumé, A., Carey, P., Bronstert, A., Huber, A., Palacios, H. 2011. GIS application of USLE and MUSLE to estimate erosion and suspended sediment load in experimental catchments, Valdivia, Chile. *Rev. Téc. Ing. Univ. Zulia*, 34 (2): 119-128.
- Iroumé, A., Palacios, H., Bathurst, J., Huber, A. 2010. Runoff and peakflows after clearcutting and the establishment of a new plantation in an experimental catchment, southern Chile. *Bosque* 31 (2): 117-128.
- Iroumé, A., Huber, A. 2002. Comparison of interception losses in a broadleaved native forest and a *Pseudotsuga menziesii* plantation in the Andes Mountains of southern Chile. *Hydrological Processes* 16, 2347-2361.
- Lignum. 2015. Las plantaciones forestales no producirían menor cantidad de agua en cuencas forestadas. Available at <http://www.lignum.cl/2015/04/23/plantaciones-forestales-producirian-menor-cantidad-de-agua-en-cuencas-hidrografica/>
- Pizarro, R. R. Valdes, P. Garcia-Chevesich, C. Vallejos, C. Sanguesa, C. Morales, F. Balocchi, A. Abarza, and R. Fuentes. 2012. Latitudinal analysis of rainfall intensity and mean annual precipitation in Chile. *Chilean Journal of Agricultural Research* 72(2): 252-271.
- Schuller, P., Walling, D.E., Iroumé, A., Quilodrán, C., Castillo, A., Navas, A. 2013. Using  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$  and other sediment source fingerprints to document suspended sediment sources in small forested catchments in south-central Chile. *Journal of Environmental Radioactivity* 124: 147-159.
- Schuller, P., Walling, D.E., Iroumé, A., Castillo, A. 2010. Use of beryllium 7 to study the effectiveness of woody trash barriers in reducing sediment delivery to streams after forest clearcutting. *Soil & Tillage Research* 110: 143-153.
- Valdés, R., Pizarro, R., Garcia-Chevesich, P., Valdés, J.B., Pérez, F., Olivares, C., Vera, M., Balocchi, F., Vallejos, C., Fuentes, R., and Abarza, A. 2014. Water Governance in Chile: Availability, Management, and Climate Change. *Journal of Hydrology* 519(C): 2538-2567.
- Walling, D.E., Schuller, P., Zhang, Y., Iroumé, A. 2009. Extending the timescale for using beryllium 7 measurements to document soil redistribution by erosion. *Water Resources Research* 45, W02418, doi:10.1029/2008WR007143.
- Zamorano-Elgueta, C., Benayas, J. M. R., Cayuela, L., Hantson, S., & Armenteras, D. (2015). Native forest replacement by exotic plantations in southern Chile (1985–2011) and partial compensation by natural regeneration. *Forest Ecology and Management* 345: 10-20.

# Chapter 5. Forest Management and Water in China

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## 5.1 Introduction

With various climatic and topographic conditions, China covers a large geographic territory and owns diversified forest ecosystems ranging from boreal forests in the north to tropical rain forests in the south. Along with the large spatial variation of bio-climate, the distinctive characteristics of topography and landforms, such as the Loess and the Himalaya Plateau, provide China unique forest landscape pattern and processes.

Due to periodic historical wars, population growth and over-exploration of forest resources, forest cover in China has greatly reduced. Estimating from ancient records, the forest cover in Chinese Xia dynasty (about 4000 years ago) was about 60%, in contrast with that 33% in the late Tang dynasty (around year 800 to 900). In the early Qing dynasty, forest cover in China was estimated at only 21%, which further decreased to 12.5% in around 1949 (Fan and Li, 2005). Both the quantity and the quality of forest resources in China sharply decreased during the collectivization period (1958 to 1982), notably during the Great Leap Forward and the Cultural Revolution. This deforestation trend was even further exacerbated at the beginning of the 1980s, during the economic transition from a planned system to a market economy as a result of economic development impulse. In particular, insecure ownership rights over trees or forests granted to rural households have led to massive forest clearings by the contracting farmers (Démurger et al., 2009). Nowadays, the forests in China are mainly distributed in the regions of northeast, southwest and south China.

Since the founding of the People's Republic of China in 1949, forestry practices have gone through significant changes in management objectives over different periods, which can be distinguished by their effects on forest resources: damage, development and rehabilitation. Three distinct periods are recognized. Phase 1 (from the 1950s to the end of 1970s) was characterized by timber utilization, resulting in deforestation. Phase 2 (from the end of the 1970s to the late 1990s) placed equal emphasis on both timber production and ecological improvement. Phase 3 (from the late 1990s to the present) adopts sustainable forest management strategies with the high priority on natural forest protection and ecological restoration (Liu et al., 2010).

To improve environmental quality, China has implemented several large-scale forestation and afforestation programs that contribute to the increased forest cover from 16.0% in the 1980s to 21.63% in 2013. The earliest program is the Three-North Forest Shelterbelt Program. It was mainly designed to combat desertification and dust storms, and to improve hydro-climate conditions by increasing forest cover in arid and semiarid areas from 5% in the 1980s to 15% by 2050. Following the severe flood in 1998 in the Yangtze River Basin, the Natural Forest Protection Program (NFPP) was initiated in late 1998 along the upper reaches of the Yangtze River and the upper and middle reaches of the Yellow River. In addition, "Sloping Land Conversion Program" or "Grain for Green" was launched across China in 1999 to convert farmland on the slopes above 25 degree to forests for halting water and soil erosion through increasing forest cover (Liu et al., 2010). The implementation of the above three large-scale forest restoration programs has generated a significant growth in forest resources. Up to now, the total forest area in China is 208 million ha with a forest cover of 21.63%. The area of planted forests in China is approximately 69 million ha, which accounts for

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one fourth of the world's total forested area (Wang et al., 2011a). Large-scale forestation in China is supposed to provide an opportunity for the study of large-scale forestation hydrology.

Forests play an important role in environmental rehabilitation, biodiversity conservation, carbon sequestration, bio-fuel, and timber production, and also offer numbers of amenities and social benefits (Calder, 2007). However, under some circumstances forests cannot simultaneously produce equal and positive multiple ecosystem services because of the trade-offs among different or competing functions (Wang et al., 2011a). As comparing to environmental issues including sandstorm, desertification, soil erosion, and drought and flood disasters, water quality degradation and water resources shortage are considered as the two major challenges of highly water relevance. In China, forests are believed to be an important instrument for mitigating and solving environmental problems. Therefore, large-scale forestation and afforestation campaigns have been widely conducted for years across China. Nevertheless, the negative impacts resulting from these activities including water yields reduction in semi-arid and arid regions and hydrological regime shift (too-little-too-much-water syndrome) in humid regions have been increasingly concerned by Chinese ecologists and hydrologists (Sun et al., 2008). In the meantime, in the context of global climate change, the question of how to shape forest management to mitigate the likely impacts of climate change on forests, water and forest-water relationship for ensuring national or regional sustainable development is of great concern. Due to the vast land area and various bio-climatic conditions in China, the forest and water related issues are region and forest specific. In southern China, flood disasters, wetland degradation and loss, water pollution (eutrophication) and subsequent biodiversity loss are the key concerns, whereas water shortage and soil erosion are the main problems in northern China.

There were several early reviews on the relationships between water and forest in China (Zhang and Yu, 1988; Liu et al., 1996; Li et al., 2001; Zhang et al., 2003; Zhang et al., 2004b; Wei et al., 2008). However, it is essential to update the recent Chinese research development of forest hydrology. Currently, researchers are focusing on large-scale watershed hydrology, reforestation hydrology and global change hydrology. Hydrological effects of forest management, such as reforestation and deforestation in association with land use and land cover change, are increasingly addressed. Understanding the effects of land use and land cover change on water yield and hydrologic processes, including groundwater recharge or surface runoff, are of significance to the development of sustainable land use planning and integrated watershed management. Therefore, in order to sustainably manage the forest-water relationships under a changing environment in China, this paper reviews the recent Chinese advances in forest-water research, and discusses the future research perspectives of forest eco-hydrology.

## 5.2 Literature review

### 5.2.1 An overview of global forest-water research

For centuries popular opinion on forest and water relation has been forests generate rainfall and increase flows from springs and rivers (Andreassian, 2004). The majority of the studies on forest and water relationship concluded that forests use more water and produce less surface runoff, groundwater recharge and streamflow than shallow rooted forms of vegetation, such as crops, pastures, grasslands or shrub lands. The hydrological response resulting from forest cover change depends on vegetation types and climatic regime. According to Bosch and Hewlett (1982), deciduous hardwoods produced a 25 mm change in water yield per 10% forest cover change, while bush and grassland generated about 10 mm difference. Also, streamflow could not be detected when forest cover change is less than 20%. Streamflow response to deforestation or afforestation depends both on the regional background precipitation and the current annual precipitation. Normally water yield change is greatest in high rainfall areas and less pronounced in low rainfall areas with more persistency due to the slow regrowth of vegetation. Decreases in water yield following afforestation seem to be proportional to the growing rate of the stand, while gains in water yields after clear cut attenuate in proportion to the rate of the vegetation recovery (Fohrer et al., 2005). It is worth pointing

out that most studies were conducted at small paired-watershed or small watershed scale, while the large scale watershed (e.g., >1,000 km<sup>2</sup>) hydrology studies have been few (Wei et al., 2005; Sun et al., 2006).

Even though few large-scale watershed studies were conducted due mainly to the difficulties in locating the similar paired watersheds as a control, there are inconsistent results for large-scale watersheds (Lin and Wei, 2008). For example, Costa et al. (2003) found that the annual mean discharge was significantly enhanced after 19% of the forest land was transformed into cropland and pasture use in an upstream basin of the Tocantins River (175,360 km<sup>2</sup> in area). Significantly increased mean and peak flows over annual and spring periods was indicated after forest harvesting in another large-scale forested watershed study conducted in Central British Columbia (Lin and Wei, 2008). In contrast, some studies found limited or no hydrological responses (Dyhr-Nielsen, 1986; Buttle and Metcalfe, 2000; Wilk et al., 2001; Lin and Wei, 2008). The difficulty of extrapolating the results from different spatial scales, together with existing inconsistent results, and especially significant lack of large-scale watershed studies clearly highlight a critical need to assess the forest and water relationships at large spatial scales. Such a need is further exemplified in the demand for more information on forest hydrological responses and adaptive watershed management under global climate change and large-scale forest disturbances. Three ways, namely: paired watershed, single watershed and simulation models, are widely used to quantify the impact of forest or other vegetation cover change in the hydrologic cycle (Fohrer et al., 2005). In a paired catchment experiment, land use is held constant on the control catchment and changed in the treatment catchment. Differences in hydrologic response with respect to annual runoff, flood, and low flow response and water quality can be then compared with each other under the same climatic conditions. In single-catchment experiments, the effects of land use change are measured by comparing the change in hydrological responses before and after the land use change, but this cannot separate the effect of land use change from the effects of different weather conditions before and after the change. Among the third method, the process based hydrological models, composed of rainfall, canopy interception, soil infiltration and runoff processes are very useful for understanding the mechanisms underlying the hydrological responses by analyzing causal-result relationships. However, the simulation results from the hydrological models are largely a reflection of the assumptions involved and the model structure deliberated. Traditionally, hydrological models are the main tools to study the forest and water relationship. However, the uncoupling of vegetation dynamics, climate change and hydrological processes in hydrological models cannot distinguish the hydrological responses of land use change from that of climate change. Eco-hydrological models through coupling the interactions of climate change, hydrological processes and ecological processes and linking various land use/cover components, such as upland, riparian, and aquatic ecosystems at multi-temporal and spatial scales, can sort out the different hydrological effects from climate change, land use/cover change, and watershed management impacts.

## 5.2.2 Forest-water research in China

### 5.2.2.1 Forest hydrology research methods and technologies

Because there was no real paired watersheds study (Wei et al., 2008), hydrological and eco-hydrological models are widely used in forest and water research at watershed scale in China (Liu et al., 2001; Zhang et al., 2006; Zhang et al., 2008; Deng, 2012; Guo and Su, 2014; Peng et al., 2014). For instance, Deng (2012) applied SSiB4T/TRIFFID model to project the impacts of temperature changes on forest hydrological effects in the mountain region of Southwestern China at basin scale. Other eco-hydrological models including CHARM (Climate and Human Activities-Sensitive Runoff Model) and SWAT model were used to distinguish the effects of climate change and land use change on runoff in Suomo watershed of upper Yangtze River (Chen et al., 2005) and in Shiyang River watershed of northwestern China (Guo and Su, 2014). Recently, Peng et al. (2014) developed a distributed eco-hydrological model by coupling a vegetation ecosystem model (BIOME-BGC) with

a distributed hydrological model (WEPL) to study the eco-hydrological effects of soil and water conservancy measures in Jinghe River basin, Loess Plateau.

Single watershed approach based on statistical analysis is also widely applied (Xu and Niu, 2000; Zhang et al., 2004a; Li et al., 2007; Zhang et al., 2009; Wei et al., 2010; Wang et al., 2011b). For instance, Wang et al. (2011a) made a comparative analysis of the annual runoff and evapotranspiration (ET) between forestlands and non-forestland among the 57 selected basins in the Loess Plateau of China whereas Wang et al. (2011b) gave a literature-review on forest cover and water yield relationships in northern China using statistical approach. Single watershed approach is mainly based on water balance model with the assumption of no change in soil water and groundwater storage at an annual basis and catchment scale, and thus, runoff can be estimated from the difference between precipitation and ET.

Thanks to the rapid development of long-term ecological research sites in recent three decades, forest and water research at plot or small catchment scale has been booming in China. Base on the long term monitoring data, the major hydrological variables such as canopy interception, soil and canopy evapotranspiration, soil infiltration and storage, and root and soil interactions were quantified and compared among different types of forests (Liu et al., 1996, 2003; Wei et al., 2005). Such basic hydrological studies provide useful information for hydrological modeling in China (Wei et al., 2005). Moreover, sap flow (Zhang et al., 1997; Lu et al., 2004; Du et al., 2011; Yu et al., 2014), atmospheric water flux (Yu et al., 2006) and isotope technologies (Gu, 1995; Liu et al., 2006 and 2007; Cui et al., 2009; Xu et al., 2006; Xu et al., 2011) are increasingly measured or used in many forest ecosystems across China recently.

In China, hydrologists have made efforts to partition the relative contributions of climate change/variability and forest cover change to hydrological responses. For instance, Zhang et al. (2012) used the modified Double Cumulative Curve Analysis Method to separate the effects of forest harvesting and climatic variability on runoff in a large watershed of Upper Minjiang River. To separate the hydrological consequences of forest cover change from those of climatic changes, physical and distributed eco-hydrological models are very useful, such as the mentioned models CHARM and SWAT. However, it has been recognized that the complex relationship of forest-water restricts a wide application of models, and it has to compromise the simulation accuracy and reliable results when hydrological models are used.

### 5.2.2.2 Forest hydrology research progress

#### *Water yield*

The effects of forestation on water yield across China varied due to large variations in climate, vegetation and soil condition (Sun et al., 2006; Wei et al., 2008; Wang et al., 2011a). The majority of studies have shown that forestation decreases runoff (Huang et al., 2003; Wang et al., 2011b). The annual water yield loss from afforestation in the Loess Plateau was about 50% (equivalent to 50 mm per year) (Sun et al., 2006). Forest harvesting increased annual water yield, but the magnitude of the increase depended on various factors such as forest types, watershed characteristics, and dominant hydrological processes (snow vs. rain) (Wei et al., 2008).

In contrast, some studies reported that annual discharge is negatively related to forest cover. Earlier studies found much smaller base flow in the catchments after logging primitive old growth forests in west Sichuan area, southwest of China than in intact catchments, suggesting that streamflow response of natural old-growth forest is positively related to forest cover (Ma, 1987). However, a recent study pointed out that this conclusion was not based on real paired watershed comparison, and did not consider the hydrological recovering process resulting from vegetation change from a low ET of old-growth fir forest into a high ET of fast-growing shrubs after logging (Zhang et al., 2011). The conversion from the early succession staged grassland on clear-cut site after logging old growth forests to the dense and fast-growing bushes with a higher ET is the cause of annual discharge

reduction. Another reason was perhaps related to fog interception by forests in mountainous areas at a high elevation where fogs intercepted by forest canopy constitute a significant portion of total precipitation (Wei et al., 2008). There has been a controversy over the relationship between forest vegetation cover and streamflow in China, with a significant positive relationship (Cao, 1991; Wang et al., 2011a) and no significant effect (Qian, 1983; Zhou et al., 2010; Wang et al., 2011b). It should be pointed out that the controversy is associated with statistical analysis that does not account for other human disturbances such as water withdrawal and engineering interference (Cao, 1991), and with no calibration and the control as a comparable unlogged area (Wei et al., 2008), and thus, leading to the question on the validity of some above mentioned results.

It is well known that forests can mitigate flood regime. Such understanding has been demonstrated by numerous experiments at small catchment scale at home and abroad. However, there are many factors would affect the interaction between forest and flood, including antecedent soil water content, soil depth and infiltration, underlying bed-rock properties, water holding capacity in litter layer, intensity and duration of rainfall, forest spatial distribution, and the size of watershed. In the upper Yangtze River, the effect of forests on flood mitigation decreases with the increasing basin size, while forest vegetation loss was not the main reason for the severe flood in 1998 (Xu, 2000). When rainfall intensity is greater than 0.25 mm/min or rainfall amount is larger than 20 mm, forest capacity in intercepting rainfall will be very limited, and this was demonstrated by some experiments in Sichuan province, Southwest China (Xu, 2000). Forest spatial distribution in the upper Yangtze River was not found to be positively related to flood mitigation, because natural forests with deep soil layer and thick litter layer mainly distributed in the areas without storm and heavy rain, whereas storm and heavy rain drop in areas where the vegetation is mainly composed of plantations with shallow soil layer. At the small catchment scale, forests will affect significantly on flood mitigation, but the mitigating effects will attenuate when the severe or heavy flood events occur. This is also true in a large catchment. Meanwhile, forest management activities such as road construction and ditch drainage, through increasing the effective density of the stream network, might cause local flooding (Calder, 2007).

In China, there are few studies on the impacts of forests on low flow and the effects of forest harvesting on low flows varied with climate and forests. Of which some studies reported reductions in low flows after logging (Ma, 1987), and the others show increases in low flows (Zhou et al., 2010; Xu, 2000).

### *Water quality*

Forests play an important role in improving water quality through reducing erosion, since rainfall is intercepted by canopy and litter layers and other biogeochemical cycling processes (Vose et al., 2011). Although water pollution has become global concern with a high priority, water quality relative to water yield has not been paid an equal attention in the field of forest hydrology research in China. Spatial distribution of forests is supposed to have an important effect on hydrological processes at landscape scale, but it had been neglected in small catchment studies before 2000s. Nearly all early studies on forest landscape hydrology applied a simply and non-spatial dimension parameter of forest cover to characterize the relationship between forest and water at large watershed. In fact, few previous studies aimed clearly at examining the effects of land use/cover change on hydrological processes at large watershed by recognizing landscape heterogeneity (Liu et al., 2008). More recently, however, numerous case studies are made relating water quality to watershed landscape pattern using statistical analysis to quantify the relationship between water quality parameters and landscape pattern metrics (Xiao et al., 2007; Ouyang et al., 2008; Yang et al., 2012; Shen et al., 2014). A monograph review titled "*Forest landscape patterns and LUCC on ecohydrological response*" (Yu et al., 2010) well illustrated research progress over the last 10 years. These researches helped to understand the effects of forest landscape pattern on water quality (Fu et al., 2002; Suo et al., 2005; Xia et al., 2012). Traditional landscape metrics give little consideration of ecological processes and then fail to establish the relationship between landscape pattern and processes. To better understand how landscape pattern affects ecological and hydrological processes, some new



parameters such as landscape spatial loading contrast coefficient, contour based connectivity and directional infiltration parameter are proposed to characterize the relationship between landscape pattern and water quality in China (Chen et al., 2006).

### 5.3 Politics

Before 1970s, China's forestry focused on timber production with over-exploitation of forest resources, leading to great loss and degradation of natural forests. Consequently, many severe environmental problems, such as soil and water erosion, biodiversity decline, and catastrophic drought and floods, occur frequently across China (Zhang et al., 2000). For tackling these eco-environmental consequences, Chinese government adopts new forestry development strategies by changing a focus from timber production into forest protection and ecological restoration. In 2003, China released the Resolution on Accelerating Forestry Development, which clearly defined the national forestry development strategy with a high priority on ecological improvement, ecological security and ecological culture, ushering multi-purpose forestry development towards ecosystem services.

Over the past 30 years, forestry development in China has experienced unprecedentedly rapid and extensive changes more than in any comparable period of time in human history. The most remarkable achievement in China is the successful implementations of the five large scale afforestation and reforestation programs aiming at meeting rapidly growing societal demands for ecological amelioration and timber production (Liu et al., 2014). The five large-scale forestry programs include the Natural Forest Protection Program (NFPP), the Conversion of Cropland to Forest Program (CCFP), the Sandstorm Control Program for Areas in the Vicinity of Beijing and Tianjin (SCP), the Key Shelterbelt Development Programs (SDP), the Wildlife Conservation and Nature Reserves Development Program, and the Forest Industrial Base Development Program (FIBDP). These programs are designed mainly for restoring degraded forests, conserving biodiversity, and expanding forest cover, especially in ecologically sensitive areas, such as Yangtze River and Yellow River in western China (Liu et al., 2014). Although these forestry programs aim primarily at tackling the various environmental problems, the actual and potential commercial demand for timber production have been implied in the implementation of reforestation campaigns by local communities. Forest land tenure reform is another mile-stone forestry policy in China, which has generated tremendous impetus to develop the fast-growing and high-yielding plantation in a large scale.

Both government initiated reforestation programs and forest land tenure reform have resulted in a rapid development of planted forests throughout China, and the majority of planted forests are monoculture composed of only a few commercial tree species. The impacts of large-scale reforestation have been increasingly concerned in China, particularly in the arid or semi-arid areas (Li et al., 2001; Sun et al., 2006; Wang et al., 2008; Zhang et al., 2009). Hydrological functions vary with tree species and forest types, and show dynamics over time with forest growth and ecological succession. In fact, tree species differ considerably in the amount of annual and seasonal water use via transpiration and interception (Sun et al., 2011), which suggest that species selection and reforestation spatial planning are of great significance to alleviate the negative impacts of large scale afforestation and reforestation on regional water balance. There are many studies on water use of different tree species by measuring sap flow (Du et al., 2011) and water use efficiency (WUE) of different types of forests (Yu et al., 2008; Zhu et al., 2015), which are helpful for tree species selection, regional reforestation planning and eco-hydrological assessment (Peng et al., 2014). Stand density is an important factor influencing canopy interception, water use by evapotranspiration, therefore optimal stand density needs to be precisely defined in afforestation design and stand management for matching water availability in a particular area. Soil water conditions and water use of tree species can be used to determine appropriate stand density of planted forests in Loess Plateau, northwestern China (Yu et al., 2010).



Healthy forested watersheds efficiently trap and filter suspended sediments while exposed soil surfaces on the forest floor are susceptible to splash displacement, surface runoff, and erosion (Vose et al., 2011). Optimal upland forest management is of importance to the maintenance of structure and function of downstream aquatic and wetland ecosystems, and the spatial linkage or connection between upland catchment and downstream aquatic ecosystems has been paid a great attention by Chinese forest hydrologists and ecologists (Liu et al., 2010). The worldwide water shortage crises and exacerbating climate change highlight the importance of water resource issues in watershed management. Due to the complexity of geo-spatial variations and social-economic diversity, there is no single answer to tackle water resource issues, and the solution should be watershed or region specific. This is particularly true for understanding and solving water issues in China. Ecosystem services of forests and ecological restoration through afforestation and reforestation at local or regional scale should be managed and approached based on the relationship between forest and water at different scales.

In fact, the forest and water relationship varies regionally. Therefore, spatial variations in soil, climate, vegetation and hydrological regime need to be incorporated in reforestation efforts. In humid areas where is rich in water resources, the degradation of water quality, loss of aquatic biodiversity and flood disaster are the key issues among other water related environmental problems. Meanwhile, reforestation efforts would not confront with water shortage, and thus, theoretically reforestation scale is relatively larger in order to maximize ecosystem services of planted forests. In semi-arid and arid regions where suffers water shortage, however, reforestation effort will be greatly limited by availability of water resource, and adverse impacts of large scale reforestation on water yield and consequently regional water balance and water security should be avoided. For balancing the trade-offs of various ecosystem services provided by planted forests, spatially explicit map should be developed for directing reforestation regionalization planning at different scales, including watershed and geographical region. The reforestation planning provides a technical support in determining appropriate size and optimal spatial pattern of reforestation efforts across landscape without compromising the detriment to water resource and the conflict of water use among various land uses. This was exemplified by the Institute of Soil and Water Conservation (ISWC), Chinese Academy of Sciences (CAS) that the spatial suitability of 38 predominately native species in coarse sandy hilly catchments at Loess plateau was mapped at a 100 m resolution using a five-variable (namely: land use/land cover, precipitation, aspect, land position and slope) spatial overlay approach. The spatial context or landscape configure should be also taken into consideration by prioritizing re-vegetation target areas to the zones adjacent to and down slope along the steep landscape, in order to reduce sediment input to the river network and adverse impact on regional stream flow. A very good decision support tool named ReVegIH (Re-Vegetation Impacts on Hydrology) can help land managers to determine afforestation area, spatial pattern and plant species (McVicar, et al., 2007).

Forest management in the context of global change is more complex and cannot be approached only at stand level and within forestry sector. Instead, forest management should be implemented at a landscape level and across multi-sectors (Liu et al., 2010). Forest landscape management approach recognizes the interrelationships among land uses, sustainability of landscape resources in terms of desired goods and services, and diversified adaptive options for different stakeholders to cope with global change and land use conflicts (Yu et al., 2014). Sustainable forest management (SFM), which is guided by explicit goals, executed by policies and protocols, and monitored as well as assessed by defined indicators and standards, has been widely advocated, and has been mainstreamed in the national forestry development planning (Liu et al., 2014). The Chinese forest ecosystem monitoring network covering different geographical regions provides a useful instrument for the monitoring and assessment of forest management performance and implication.

## 5.4 Climate change and the future of forestry & forest research

### *Interactive effects of forest, water and soils on hydrology*

Like forest canopy and litter, soils play a significant role in regulating hydrological processes. Actually, forest, water and soil interacts each other in a consolidated way to sustain ecosystem processes and functions. To this end, structure and function of forest soils are largely dependent on root system, soil microbes, soil physical properties and litters, which are further affected by aboveground canopy processes. There exist differences in hydrological functions between natural forests and planted forests, and monoculture and mixed stands, which are the result of different soil biological processes and physical properties in the forests. Thus, there is a need to study the interactive effects of forests, water and soils for deepening insight into the hydrological mechanisms of different forest ecosystems and under various water and soil regimes.

### *Hydrological impacts of large-scale reforestation and afforestation*

As China has the largest scale reforestation and afforestation in the world, it provides a good opportunity to study effects of large-scale plantation forests on regional water resources and hydrological cycling, especially in arid and semi-arid areas with water-shortage. The general conclusion seems that forest removal or harvesting increases streamflow, whereas reforestation causes water yield reduction, but there have been great uncertainties or variations in hydrological responses to forest changes among different case studies and geographical regions in China. This implies a complicated interaction among forest, water, soil and climate, which is especially exemplified in China with diversified climate, vegetation, soil and topography. Therefore, understanding the ecological effects of large-scale reforestation in China is of significance to develop theory and methodology of large scale eco-hydrology, and contributes to developing forestry mitigation and adaption strategy to global climate change.

### *Development of spatial explicit and process-based eco-hydrology models*

Forest change or land use/cover change and climate change along with other factors interactively affect regional hydrological processes and water resource, leading to the difficulty in distinguishing one kind of hydrological response from another. Despite some methods like statistical analysis can be used to separate hydrological impacts from some influencing factors, they are strictly limited in understanding the mechanism underlying hydrological responses. In this regard, there is a clear need to develop process based eco-hydrological models as an effective tool for assessing forest-water relationship under a changing environment. Long-term forest ecosystem monitoring research, hydrological measurements across scales from small catchment or plot scale to large watershed, and geo-spatial monitoring, are all available now for providing a full dataset needed to develop and validate process-based eco-hydrological models for separating, assessing and forecasting hydrological responses resulting from climate change and land use/cover changes.

### *Application of forest-water research to forest management*

Although a great achievement in forest-water research has been made in China, little research knowledge is transferred into forestry policy-making and applied in forest management practices. In many regions, forest managers have still been applying conventional forestry concepts and methods to direct afforestation and reforestation efforts. Water use or water requirement of specific tree species, site condition differences in soil water and rainfall availability, and the likely impacts of climate change have not precisely incorporated into afforestation/reforestation planning in terms of planting area regionalization, planting scale, tree species selection and site classification. The determination of afforestation sites, reforestation scale and stand density should take into consideration of regional

water resource use and balance, and forest landscape pattern optimization for mitigating adverse hydrological impacts while maximizing ecosystem services across a landscape.

### *Balancing trade-offs of multiple ecological service of forests*

Despite afforestation/reforestation is essential for carbon sequestration, soil erosion control, flood disaster mitigation, poverty alleviation, biodiversity conservation and many other benefits, a growing concern over water or streamflow reduction due to the large-scale reforestation effort, particularly in the arid and semi-arid regions of China has intensified. Therefore, it is imperative to study how to balance the trade-offs of multiple forest ecosystem services by harmonizing synergy. Water problems in China are region specific, and accordingly, managing forest-water relation should be approached differently from region to region. Water related ecological issues such as water pollution, downstream hydrological regime shift and resulting aquatic biodiversity loss are worth integrated with water resource in forest management at large-scale (landscape or regional scale). In southern China, water pollution rather than water shortage is the major problem that has been inadequately addressed, whereas northwestern China is facing serious water shortage problem. Therefore, these differences should be clearly recognized in regional forest management and forest-water research with addressing regional key water-related environmental problems while balancing trade-offs of forest ecosystems services.

## 5.5 Acknowledgments

We are grateful to Prof. Jingxin Wang for helpful comments and revisions that improved this paper. Shirong Liu was jointly funded by the Ministry of Finance (201404201; 201104006 and 200804001), the Ministry of Science and Technology (2012BAD22B01), and China's National Natural Science Foundation (31290223, 31100380, and 31200477). The co-author, Dr. Yong Lin was supported by special fund for marine and ocean research in the public interest (201405007).

## 5.6 References

- Andreassian V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology*, 291(1):1-27.
- Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55(1-4):3-23.
- Buttle JM, Metcalfe RA. 2000. Boreal forest disturbance and streamflow response, northeastern Ontario. *Canadian Journal of Fisheries and Aquatic Sciences*, 57(S2):5-18.
- Calder IR. 2007. Forests and water-Ensuring forest benefits outweigh water costs. *Forest Ecology and Management*, 251(1-2):110-120.
- Cao YJ. 1991. The impact of the forests in Songhuajiang basin on river discharge in forest ecosystem research in fixed stations, Eds by Zhou XF. Northeast Forestry University Press, Harbin. p396-402.
- Chen JF, Li XB, Zhang M. 2005. Simulating the impacts of climate variation and land-cover changes on basin hydrology: A case study of the Suomo basin. *Science on China Ser.D Earth Sciences*, 48(9):1501-1509.
- Chen LD, Fu BJ, Zhao WW. 2006. Source-sink landscape theory and its ecological significance. *Acta Ecologica Sinica*, 26(5):1444-1449 (in Chinese)
- Costa MH, Botta A, Cardille JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology*, 283(1-4):206-217.
- Cui J, An SQ, Wang ZS, Fang CM, Liu YH, Yang HB, Xu Z, Liu SR. 2009. Using deuterium excess to determine the sources of high-altitude precipitation: Implications in hydrological relations between sub-alpine forests and alpine meadows. *Journal of Hydrology*, 373(1-2):24-33.

- Démurger S, Hou YZ, Yang WY. 2009. Forest management policies and resource balance in China an assessment of the current situation. *the journal of environment and development*. 18(1):17-41
- Deng HP. 2012. Modelling the impacts of temperature changes on hydrological effects of forests in the mountain region of southwestern China at basin scale. *Ecology and Environmental Sciences*, 21(4):601-605 (in Chinese).
- Du S, Wang YL, Kume T, Zhang JG. 2011. Sapflow characteristics and climatic responses in three forest species in the semiarid Loess Plateau region of China. *Agricultural and Forest Meteorology*, 151(1):1-10.
- Dyhr-Nielsen M. 1986. Hydrological effect of deforestation in the Chao Phraya basin in Thailand. The paper presented at the International Symposium on Tropical Forest Hydrology and Application, Chiangmai, Thailand. 11–14 June 1986, p12.
- Fan BM, Li ZY. 2005. Forest, evapotranspiration, climate and desert: effects on desertification since the change of forests in China. *Scientia Silvae Sinicae*, 41(2):154-159.
- Fohrer N, Haverkamp S, Frede H. 2005. Assessment of the effects of land use patterns on hydrologic landscape functions: development of sustainable land use concepts for low mountain range areas. *Hydrological Processes*, 19(3):659-672.
- Fu BJ, Qiu Y, Wang J, Chen LD. 2002. Effect simulations of land use change on the runoff and erosion for a gully catchment of the Loess Plateau, China. *Acta Geographica Sinica*, 57(6):717-722 (in Chinese).
- Gu WZ. 1995. Various patterns of basin runoff generation identified by hydrological experiment and water tracing using environmental isotopes. *Journal of Hydraulic Engineering*, (5):9-17,24.
- Guo J, Su XL. 2014. Application of conceptual eco-hydrological model to distinguish effects of climate change and land use change on runoff. *Hydroelectric Engineering*, 33(3):36-41 (in Chinese).
- Huang M, Zhang L, Gallichand J. 2003. Runoff responses to afforestation in a watershed of the Loess Plateau, China. *Hydrological Processes*, 17(13):2599-2609.
- Li LJ, Zhang L, Wang H, Wang J, Yang JW. 2007. Assessing the impact of climate variability and human activities on streamflow from the Wuding River basin in China. *Hydrological Processes*, 21(25):3485-3491.
- Li WH, He YT, Yang LY. 2001. A summary and perspective of forest vegetation impacts on water yield. *Journal of Natural Resources*, 16(5):398-406 (in Chinese).
- Lin Y, Wei XH. 2008. The impact of large-scale forest harvesting on hydrology in the Willow watershed of Central British Columbia. *Journal of Hydrology*, 359(1-2):141-149.
- Liu ML, Tian HQ, Chen GS, Ren W, Zhang C, Liu JY. 2008. Effects of land-use and land-cover change on evapotranspiration and water yield in China during 1900-2000. *Journal of the American Water Resources Association*, 44(5):1193-1207.
- Liu SR, Wen YG, Wang B, Zhou GY. 1996. *Ecohydrological functions of forest ecosystems in China*. China Forestry Publication House, Beijing. (in Chinese).
- Liu SR, Sun PS, Wen YG. 2003. Comparative analysis of hydrological functions of major forest ecosystems in China. *Acta Phytoecological Sinica*, 27(1), 16-22.
- Liu SR, Lin Y, Zhang YD, Guo ZH, Zhang L, Li C, Wang JX. 2010. Landscape ecology contributions to forestry and forest management in China: Progress and research needs. (Chapter 2 in landscape ecology in forest management and conservation: Challenges and solutions for global change Eds by Li C, Laforzezza R, Chen JQ. Higher Education Press, Beijing. p23-46.
- Liu SR, Wu S, Wang H. 2014. Managing planted forests for multiple uses under a changing environment in China. *New Zealand journal of forestry science*, 44(suppl 1), S3
- Liu SX, Zhang SF, Liu CM. 2001. Advances on the research into the mechanism of hydrological cycle in Yellow river catchment. *Geographical Research*, 20(3):257-265.
- Liu WJ, Liu WY, Li PJ, Gao L, Shen YX, Wang PY, Zhang YP, Li HM. 2007. Using stable isotopes to determine sources of fog drip in a tropical seasonal rain forest of Xishuangbanna, SW China. *Agricultural and Forest Meteorology*, 143(1-2):80-91.
- Liu YH, An SQ, Deng ZF, Fan NJ, Yang HB, Wang ZS, Zhi YB, Zhou CF, Liu SR. 2006. Effects of vegetation patterns on yields of the surface and subsurface waters in the Heishui Alpine Valley in west China. *Hydrology and Earth System Sciences Discussions*, 3(3):1021-1043.
- Lu P, Urban L, Zhao P. 2004. Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: Theory and practice. *Acta Botanica Sinica*, 46(6):631-646.



- Ma XH. 1987. Preliminary Study on Hydrologic Function of fir Forest in the Miyaluo Region of Sichuan. *Scientia Silvae*, 23(3):253-265 (in Chinese).
- McVicar TR, Li LT, Van Niel TG, Zhang L, Li R, Yang QK, Zhang XP, Mu XM, Wen ZM, Liu WZ, Zhao YA, Liu ZH, Gao P. 2007. Developing a decision support tool for China's re-vegetation program: Simulating regional impacts of afforestation on average annual streamflow in the Loess Plateau. *Forest Ecology and Management*, 251: 65–81.
- Ouyang W, Hao FH, Wang XL. 2008. Regional nonpoint source organic pollution modeling and critical area identification for watershed best environmental management. *Water Air and Soil Pollution*, 187(1-4): 251-261.
- Peng H, Jia YW, Niu CW, Gong JG, Hao CF, Gou S. 2014. Eco-hydrological simulation of soil and water conservation in the Jinghe River Basin in the Loess Plateau, China. *Journal of Hydro-environment Research*, xx:1-13.
- Qian WC. 1983. Effects of deforestation on flood characteristics with particular reference to Hainan island, China. *International Association of Hydrological Sciences Publication*, 140:249-258.
- Shen ZY, Hou XS, Li W, Aini G. 2014. Relating landscape characteristics to non-point source pollution in a typical urbanized watershed in the municipality of Beijing. *Landscape and Urban Planning*, 123:96-107.
- Sun G, Alstad K, Chen JQ, Chen SP, Ford CR, Lin GH, Liu CF, Lu N, McNulty SG, Miao HX, Noormets A, Vose JM, Wilske B, Zeppel M, Zhang Y, Zhang ZQ. 2011. A general predictive model for estimating monthly ecosystem evapotranspiration. *Ecohydrology*, 4(2):245-255.
- Sun G, Zhou GY, Zhang ZQ, Wei XH, McNulty SG, Vose JM. 2006. Potential water yield reduction due to forestation across China. *Journal of Hydrology*, 328(3-4):548-558.
- Sun P S, Liu SR, Jiang H, LÜ Y L, Liu J T, Lin Y, Liu X L. (2008) Hydrologic effects of NDVI time series in a context of climatic variability. *Journal of the American Water Resources Association* 44(5):1132-1143
- Suo AN, Hong J, Lin Y, Ge JP. 2005. Relationships between soil and water loss and landscape pattern on Loess Plateau. *Chinese Journal of Applied Ecology*, 16 (9):1719-1723 (in Chinese).
- Vose JM, Sun G, Ford CR, Bredemeier M, Otsuki K, Wei XH, Zhang ZQ, Zhang L. 2011. Forest ecohydrological research in the 21st century: what are the critical needs?. *Ecohydrology*, 4(2):146-158.
- Wang YH, Yu P, Xiong W, et al. 2008. Water-yield reduction after afforestation and related processes in the semi-arid Liupan Mountains. *JAWRA journal of the American water resources association*, 44(5):1086-1097
- Wang S, Fu BJ, He CS, Sun G, Gao GY. 2011a. A comparative analysis of forest cover and catchment water yield relationships in northern China. *Forest Ecology and Management*, 262(7):1189-1198.
- Wang YH, Yu PT, Feger K, Wei XH, Sun G, Bonell M, Xiong W, Zhang SL, Xu LH. 2011b. Annual runoff and evapotranspiration of forestlands and non-forestlands in selected basins of the loess plateau of China. *Ecohydrology*, 4(2), 277-287.
- Wei X, Liu S, Zhou G, Wang C. 2005. Hydrological processes in major types of Chinese forest. *Hydrological Processes*, 19(1):63-75.
- Wei XH, Sun G, Liu SR, Jiang H, Zhou GY, Dai LM. 2008. The forest-streamflow relationship in China: a 40-years retrospect. *Journal of the American Water Resources Association*, 44(5):1076-1085.
- Wei XH, Zhang MF. 2010. Quantifying streamflow change caused by forest disturbance at a large spatial scale: a single watershed study. *Water Resources Research*, 46(12):1-15.
- Wilk J, Andersson L, Plermkamon V. 2001. Hydrological impacts of forest conversion to agriculture in a large river basin in northeast Thailand. *Hydrological Processes*, 15(14):2729-2748.
- Xia LL, Liu RZ, Zao YW. 2012. Correlation analysis of landscape pattern and water quality in Baiyangdian watershed. *Procedia Environmental Sciences*, 13(10):2188-2196.
- Xiao H, Wei J. 2007. Relating landscape characteristics to non-point source pollution in mine waste-located watersheds using geospatial techniques. *Journal of Environmental Management*, 82(1):111-119.
- Xu JH, Niu YG. 2000. Study on the impact of hydraulic engineering and soil water conservation works on streamflow and sediment load in the coarse sandy hilly region of the Yellow River basin. *Yellow River Water Conservancy Press: Zhengzhou, China* (in Chinese).
- Xu JX. 2000. Runoff and sediment variations in the upper reaches of Changjiang River and its tributaries due to deforestation. *Journal of hydraulic engineering*, (1):72-80 (in Chinese).
- Xu Q, Li H, Chen JQ, Cheng XL, Liu SR, An SQ. 2011. Water use patterns of three species in subalpine forest, Southwest China: the deuterium isotope approach. *Ecohydrology*, 4(2):236-244.



- Xu SG, Liu YF, Sun WG. 2006. Research on the Stable Isotope for Soil Water Vertical Transporting in Unsaturated Zone of Zhalong Wetland. *Journal of China Hydrology*, 26(5):1-6 (in Chinese).
- Yang X. 2012. An assessment of landscape characteristics affecting estuarine nitrogen loading in an urban watershed. *Journal of Environmental Management*, 94 (1):50–60.
- Yu GR, Song X, Wang QF, Liu YF, Guan DX, Yan JH, Sun XM, Zhang LM, Wen XF. 2008. Water-use efficiency of forest ecosystems in eastern China and its relations to climatic variables. *New Phytologist*, 177(4):927-937.
- Yu GR, Wen XF, Sun XM, Tanner BD, Lee X, Chen JY. 2006. Overview of ChinaFLUX and evaluation of its eddy covariance measurement. *Agricultural and Forest Meteorology*, 137(3-4):125-137.
- Yu XX, Li XB, Xia B. 2010. Forest landscape patterns and LUCC on ecohydrological response. Science Press, Beijing (in Chinese).
- Yu XX, Wang YH, Wang YJ, Bi HX, Cai TJ, Zhang JC, Yan WD, Liu XD, Zhou P. 2014. Forest eco-hydrological processes and mechanisms in China's typical regions. Science Press, Beijing (in Chinese).
- Zhang HP, Simmonds LP, Morison JII, Payne D. 1997. Estimation of transpiration by single trees: comparison of sap flow measurements with a combination equation. *Agricultural and Forest Meteorology*, 87 (2-3):155-169.
- Zhang L, Hickel K, Dawes WR, Chiew FHS, Western AW, Briggs PR. 2004a. A rational function approach for estimating mean annual evapotranspiration. *Water Resources Research*, 40(2):1-14.
- Zhang M, Wei XH, Sun PS, Liu SR. 2012. The effect of forest harvesting and climatic variability on runoff in a large watershed: The case study in the Upper Minjiang River of Yangtze River Basin. *Journal of Hydrology*, 464(13):1-11.
- Zhang PC, Shao GF, Zhao G, Master DC, Parker GR, Dunning JB, Li QL. 2000. China's forest policy for the 21st century, 288(5474):2135-2136.
- Zhang XP, Zhang L, Li R, Yang QK. 2009. DEM-based modeling of the impact of vegetation restoration on annual streamflow in the Loess Plateau of China. *Chinese Journal of Plant Ecology*, 33(6): 1056-1064 (in Chinese).
- Zhang XP, Zhang L, McVicar TR, Van Niel TG, Li LT, Li R, Yang QK, Wei L. 2008. Modelling the impact of afforestation on average annual streamflow in the Loess Plateau, China. *Hydrological Processes*, 22(12):1996-2004.
- Zhang YD, Liu SR, Wei XH, Liu JT, and Zhang GB. Potential impact of afforestation on water yield in the subalpine region of southwestern China. *Journal of the American Water Resources Association*. 2008, 44(5): 1144-1153
- Zhang YD, Liu SR, Gu XF. 2011. The impact of forest vegetation change on water yield in the subalpine region of southwestern China. *Acta Ecologica Sinica*, 31(24):7601-7608 (in Chinese).
- Zhang Z, Wang S, Sun G, McNulty S, Zhang M, Li J. 2006. Application of a physically based distributed watershed hydrological model MIKESHE in a small watershed of the Loess Plateau, Western China. In: Liu S, Sun G, Sun P. (Eds.), *Extended Abstracts from the Conference on Forest and Water in a Changing Environment*, Chinese Academy of Forestry, Beijing, China, August 8-1, 2006.
- Zhang ZQ, Wang LX, Wang SP. 2004b. Forest hydrology research in China. *Science of Water and Soil Conservation*, 2(2):68-73.
- Zhang ZQ, Yu XX, Zhao YT, Qin, YS. 2003. Advance in researches on the effect of forest on hydrological process. *The Journal of Applied Ecology*, 14(1):113-116 (in Chinese).
- Zhang ZZ, Yu XX. 1988. The Major Progress on Chinese Forest Hydrological Research. *Journal of Beijing Forestry University*, 10(2):79-87 (in Chinese).
- Zhou GY, Wei XH, Luo Y, Zhang MF, Li YL, Qiao YN, Liu HG, Wang CL. 2010. Forest recovery and river discharge at the regional scale of Guangdong Province, China. *Water Resources Research*, 46(9):5109-5115.
- Zhu XJ, Yu GR, Wang QF, Hu ZM, Zheng H, Li SG, Hao YB. 2015. Spatial variability of water use efficiency in China's terrestrial ecosystems. *Global and Planetary Change*, 129:37-44.

# Chapter 6. Forest Management and Water in the Democratic Republic of Congo

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## 6.1 Introduction

The Democratic Republic of Congo (DRC) is the second largest African country and is located in the Central African zone. The DRC is the fifth largest country in the world in terms of forest cover, and the largest in Africa. Its forest cover, estimated to be more than 166 million hectares, represents more than 62% of the Congo forests (the second largest block of tropical forest in the world). Congo's forests are compound by 69% of dense forest and only a little more than 30% of other types of forest (Tchathou *et al.* 2015). The Congo forest represents 10% of the world's tropical forests and more than 47% of those in Africa (Tchathou *et al.* 2015), thus having 11 forest types: swamp forest, tropical lowland rainforest, tropical sub-montane rainforest, three types of Afromontane forest, Zambezian forest (Muhulu), Zambezian woodland (Miombo), Sudanese woodland, coastal sclerophyllous forest and mangroves (Musampa *et al.* 2012).

Several studies (De Merode 1998, Yamba 2009, Nelson *et al.* 2012, Samndong and Nhantumbo 2014), have identified the Congo forest as a critical livelihood source for about 40 million people, providing food, medicine, domestic energy, building materials, and monetary income. The country also plays an important role in regulating the regional and global climate, while commercial logging generates a great deal of state income (Debroux *et al.* 2007, Mbala and Karsenty 2010, Musampa *et al.* 2012). The forest harbors an enormous amount of the world's biodiversity and the DRC ranks as the fifth among countries for its rich diversity of flora and fauna (Musampa *et al.* 2012). The DRC forests contain a vast plant and animal diversity and include five national world heritage sites (Yanggen *et al.* 2010). However, these forests are under increasing pressure that could eventually lead to very high degradation and increase poverty among many people who still depend heavily on the resources offered by the forest (de Wasseige *et al.* 2010).

The availability and quality of water in many regions of the world are more and more threatened by misuse and pollution, being increasingly recognized that both are strongly influenced by forests. Moreover, climate change is altering forest's role in regulating water flows and influencing the availability of water resources (Bergkamp *et al.* 2003). Therefore, the relationship between forests and water is a critical issue that must be accorded high priority (Calder *et al.* 2007). West (1990) and Ice and Stednick (2004) found the relationship between forests and water resources as subjects of speculation, controversy, and scientific inquiry. Perceptions that forests have important roles in water resource conservation, for example, were important factors leading to the creation of forest reserves more than a century ago in the United States. Since then, hundreds of field studies have been conducted on various aspects of forest watersheds and their management (Ice and Stednick 2004).

Intensive research on forest and watershed hydrology conducted in developed and developing countries, such as the United States (Hamilton 1985, Hornbeck *et al.* 1993, Ice and Stednick 2004, NCASI 2009, Neary *et al.* 2012, Wright 2016), Canada (NCASI 2009), Australia (Hewlett and Nutter

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1968, Holmes and Colville 1970, Ruprecht *et al.* 1991, Cornish 1993, Bren 2015), Brazil (Bonnet *et al.* 2005, Germer *et al.* 2006, Martinez and Toan 2007, Coe *et al.* 2009, Callède *et al.* 2010, Melack and Hess 2010, Coe *et al.* 2011, Levia *et al.* 2011, Nobrega 2016), and South Africa (Pereira 1962, Wicht 1967, Van Der Zel 1974, Van Wilgen 1982, Hewlett and Bosch 1984, Van Wyk 1987, Bernnett and Kruger 2015), led to the creation of BMPs that helped mitigate or alleviate the impact of forest management on water resources. For the Amazon, the first largest tropical forest in the world, there is a vast literature on forest and water (e.g. Franken and Leopoldo 1984, Furk 1984, Lesack 1993, Mertes *et al.* 1995, Laurance and Williamson 2001, Nepstad *et al.* 2004, Jirka *et al.* 2007, D'Almeida *et al.* 2007, Celleri and Feyen 2009, Cabral *et al.* 2010, Ellison *et al.* 2012). Surprisingly, however, the limited number of studies and publications on forest hydrology in the second world largest tropical forest is alarming. The creation of effective politics will not be possible as a consequence of scarce research and data pertaining a fully understanding of the relationship between forests and water systems in the Congo forest.

Tchatchou *et al.* (2015) noted that in the absence of decisions and vigorous actions, deforestation will increase substantially in the Congo basin because of large programs that are being put in place in view of their emergence, such as the need to generate more capital from the exploitation of forests and other natural resources within its perimeter or watershed. Conducting research on forest hydrology at both large and small watershed scales will definitely fill the knowledge gap for a better and sustainable exploitation and management of the forest resources, mitigating or reducing its impact on water resources (the atmospheric, surface, sub-surface water, and deep groundwater) linked to the forest. In deep root tropical forest ecosystems like those at the Congo and the Amazon, groundwater resources underneath the forest catchment should also be considered, because deep groundwater bodies sustain the forests during a long dry period and groundwater hydrology might mitigate against any adverse effects of predicted lengthening of the dry season (Hulme and Viner 1995 in Bonell 1998). This chapter summarizes the state of current knowledge about forest and water interactions in the DRC.

## 6.2 Literature review

Though characterized as a worldwide worth, the literature on forest hydrology of the DRC is very poor to inexistent and unavailable. This is probably caused by a lack of funding to support the related researches from the governmental institutions. International organizations have sponsored few researches on the Congo forest and the hydrology of the Congo river, but none of them was directly oriented to forest hydrology, but rather to forest or ecosystem mapping, deforestation, hydrological modeling, and climate change and its impact on water resources. Below are listed or summarized a few of these studies, though not directly dealing with forest hydrology itself.

Recent publications on deforestation in the DRC are those from Ickowitz *et al.* (2015) and Tchatchou *et al.* (2015), giving a detailed review on the agriculture and deforestation in the Democratic Republic of Congo. In the first paper, 44 papers of which 16 from Web of Science and 28 from Google Scholar are published on the DRC. Only 15 of these papers made a specific claim about the relationship between agriculture and deforestation (or forest degradation) in the DRC. Ickowitz *et al.* (2015) found that deforestation is taking place, albeit at a slower rate than in the rest of the tropics and is concentrated in Kinshasa and Bas Congo provinces, in the eastern DRC, and around medium-sized cities along the Congo River. Rates of primary forest loss appear to be very slow, but are accelerating.

Tchatchou *et al.* (2015) attempted to present the current state of forests at the Congo Basin, to analyze the main current factors of deforestation and forest degradation, making projections in the light of the vision of the emergence of the various countries concerned. They reported that forest exploitation and the extraction of wood energy represent the main causes of forest degradation. Furthermore, the authors recommended additional studies on how to reconcile economic development and environmental concerns in the region. Both Ickowitz *et al.* and Tchatchou *et al.* identified agriculture to be the main cause of deforestation, and its impact will likely increase as the population of the

DRC grows. Similarly, Alisdorf *et al.* (2016) published a detailed review of results on the hydrology of the Congo Basin and summarized the historic and ongoing research. The main goal of this paper was to provide a basis for new hydrologic research in the Congo Basin, and thus allowing a better understanding of the potential for climate change impacts on the hydrology of the area.

From a relative comparison of the total peer reviewed papers (33 for Congo and 299 for the Amazon), the authors found that our contemporary understanding of the Congo Basin and its hydrology is about an order of magnitude less than that of the Amazon. Few conclusions are drawn from this review. On precipitation, based on the studies that address multi-decadal in-situ measurements of rainfall, Alisdorf *et al.* (2016) noted that there is not a clear agreement that precipitation has significantly declined from 1960 to 1990 across the entire basin. On evapotranspiration, Bultot and Griffiths (1972) concluded that the annual potential evapotranspiration (PET) does not differ greatly from one region to the next (from about 1,100 to a little over 1,200 mm); actual evapotranspiration (AET) in wet seasons is really equal to potential evapotranspiration; whereas in dry seasons the AET is less PET. The AET does vary from region to region across the basin from “a little more than 800 mm in Katanga to a little less than 1,200 mm in Uele.

Hydrological models were applied to evaluate the surface water resources of the Congo Basin. Though most of these models are applied for the entire basin, their results are perfectly applied to the DRC, owing to its position inside the basin and surface proportion as compared to other countries. In order to understand and evaluate the spatial and temporal distribution of water resources of the Congo Basin, a Hybrid Atmospheric and Terrestrial Water Balance (HATWAB) model was parameterized and applied to the Congo Basin (Chishugi and Alemaw 2009). The simulated results (the integrated moisture convergence, soil moisture, actual evapotranspiration, and runoff) indicate a strong correlation with rainfall patterns, especially in the high rain-fed region corresponding to the heart of the equatorial forest.

Tshimanga *et al.* (2011) applied a monthly time-step hydrological model to address the challenge of water resources estimation in the Congo basin. Moreover, and highlighting the lack of accurate and continuous climatic and hydrological data in the Congo basin, Tshimanga and Hughe (2014) applied a semi-distributed rainfall-runoff model (PITMAN) using available historical data. Their model was able to capture the timing and magnitude of high- and low-flows satisfactorily, regardless to the location of the sub-basins in headwater areas, downstream areas, or at the outlet. However, the authors identified several challenges in modeling the Congo Basin's hydrology, including phenomenon such as the south-to-north large changes in seasonal rainfall, the varying lithologies and resultant soil types, and differing vegetation types and thus varying ET (Alisdorf *et al.* 2016). For example, many of the observed data that are available for the Congo Basin are at the outlets of large sub-basins where it is difficult to interpret the hydrological response characteristics because of the large scale of the basins and because of a multiplicity of interacting processes. These processes not only include surface and subsurface response to rainfall at the small scale but also include storage and attenuation effects of wetlands, floodplains, natural lakes, and the channel systems of large rivers. The same difficulties were recognized during the development of a wetland model for the areas of Lake Tanganyika, Lake Upemba, and the Bangweulu Swamps (Hughes *et al.* 2014 in Alisdorf *et al.* 2016). The authors concluded that the dynamics of the interchange of water between wetlands and river channels can be complex and different (depending on their physical configuration) and that remote sensing has the potential to contribute to this understanding (Alisdorf *et al.* 2016).

Recently, Lee *et al.* (2015) developed a linear regression model based on PALSAR ScanSAR backscattering coefficient, water levels from Envisat radar altimetry, and MODIS Vegetation Continuous Field (VCF) products, to generate water depth maps over the flooded forests (wetlands) of the Central Congo Basin. This is the first time such methods are applied on these wetlands. Similarly, Becker *et al.* (2014) used ENVISAT satellite altimetry data and derived water level fluctuations in the Congo Basin, between 2003 and 2009. The remotely sensed mapping was also conducted by Lee *et al.* (2011) using GRACE and satellite radar altimetry data to characterize the dynamics of terrestrial water in the Congo Basin. They found that from 2007 to 2011 in the radar frame over the Cuvette Centrale, flooded forest areas covered between 17,700 km<sup>2</sup> and 29,400 km<sup>2</sup> (December),



whereas the low-water areas varied from 7,600 km<sup>2</sup> to 3,400 km<sup>2</sup> (March). Previously, Bwangoy *et al.* (2009) used an optical and radar remotely sensed data to derive topographical indices and generate a wetlands probability map of the Central Congo Basin. They found that wetlands predominate (about 56%) in the CARPE Lake Tele Tumba landscape, located in the western part of the DRC and the south-eastern Republic of Congo. Crowley *et al.* (2006) used GRACE satellite gravity data to estimate the land water storage within the Congo Basin. Laraque *et al.* (1998, in Alisdorf *et al.* 2016) measured depths of 3 m in Lake Tele from the northwestern Cuvette Centrale, noticing mud marks on trees, an indication of annual range in level of about 1 m. Laraque *et al.* (1998) quoted three references from 1959 to 1961, indicating that Lake Tumba is 3 to 8 m deep and Lake Mai-Ndombe is 3 m deep, both with annual level fluctuations of 2 to 4 m. For the Lake Tumba, the same depths were reported by Marlier (1973). The reader can also consult Brummett *et al.* (2009) for more details on water resources, forests, and ecosystems in the Congo Basin.

The success of satellite applications on surface and subsurface water storage mapping in the Congo can be justified by the continental size of these forests and catchment, as well as the scarcity of reliable and continuous ground-based hydrological and climatic data for the region. For decades, several authors (UNFCCC 2009, Tshimanga *et al.* 2011, Ludwig *et al.* 2013, Tshimanga and Hughes 2014, de Wasseige *et al.* 2015, Alisdorf *et al.* 2016) noted the unreliability and scarcity of data in the Congo Basin, as compared to other regions of the world. This unresolved issue needs to be given high priority by governmental and international organizations.

A paper in review by Yollande Munzimi (a PhD candidate at the Department of Geographical Sciences, University of Maryland) on streamflow characterization and the hydrological impact of forest cover change will be of utmost importance (personal communication, 22<sup>nd</sup> September 2016). August (2013) assessed the effects of land use/cover change on streamflow in the Ndjili River basin (a 2,088 km<sup>2</sup> watershed), located in the western side of the DRC. The author found that owing to uncontrolled development activities such as informal settlements, deforestation, vegetation clearance, and mining, between 1987 and 2001, the Ndjili catchment's forests have decreased 8%, while agricultural land and urbanization have slightly increased 1.4% and 4%, respectively; also, the decrease in natural vegetation cover caused peak flows and mean flows to increase 21.5% and 7.1%, respectively.

The study by Brummett *et al.* (2009) about the role of forests in the Congo Basin's water balance, exhibits the usefulness of studies from other areas of the world as they provide insights on how forest cover may affect water systems. Some evidence from other regions are that (1) deforestation will increase discharge and runoff on smaller tropical watersheds and (2) mature tropical rainforest deforestation has the potential to degrade the regulation of hydrological flows through changes in evapotranspiration, canopy interception, surface runoff, and groundwater recharge. Brummett *et al.* (2009) concluded that the results of local, short-term studies provide important information but cannot necessarily be extrapolated to the larger scales and time frames of relevance when discussing vast river systems like the Congo Basin. The authors agree with the statements that the changes in land cover had a significant impact on discharge, although not precipitation in the Amazonian river basin (Costa *et al.* 2003), and that the effects of deforestation on evapotranspiration rates in the Congo river basins are expected to be particularly significant because of a large portion of rainfall (between 75-95%) coming from recycling moisture on the region's forests (Brinkman 1983).

The aforementioned books and papers on forest hydrology, added to the recent works of Bosch and Hewlett (1982), Bruijnzeel (2002), Bruijnzeel (2004), NCASI (2009), Jofré *et al.* (2014), and Garcia-Chevesich *et al.* (2015a and b) give a detailed review on effect of forest management on water resources. These findings could be applied in the DRC forest provided the climatic aspects of the region are considered.



*Forest and land-cover change mapping (from de Wasseige et al. 2010, with updates)*

The Observatoire Satellital des Forêts d’Afrique Centrale (OSFAC, South Dakota State University) and the University of Maryland, have implemented wall-to-wall mapping at moderate spatial resolution (60 m), to better quantify spatio-temporal trends in forest cover changes for Central Africa (De Wasseige et al. 2010). The initial results of this mapping, the “Forêts d’Afrique centrale évaluées par télédétection (FACET)” product suite, quantifies DRC’s forest cover and forest cover loss between 2000 and 2010, using Landsat imagery. Three forest types were mapped: (i) primary forest (mature forest with >60% canopy cover), (ii) secondary forest (regrown forest with >60% canopy cover), and (iii) woodlands (woodland formations with 30-60% canopy cover). During the year 2000, the total forest cover was estimated to be 159,529 thousand hectares, with gross forest loss from 2000 to 2010 totaling 2.3% of total forest area (De Wasseige et al. 2010). The results indicate that, for the active period of 1990-2000, the yearly rates of deforestation in central Africa and more especially in the DRC, were 0.21% and 0.25%, respectively (Duveiller et al. 2008). The authors estimated an annual rate of 0.12% for the deterioration of the forests in the RDC and, considering ongoing reforestation, the annual net deforestation rate was 0.16% for central Africa and 0.20% for the RDC. The results of the forest change sampling method estimated that the Congo Basin’s gross annual deforestation rate was 0.13% in the 1990-2000 period; however, such rate doubled by 2005. The annual net degradation rate was 0.05% (1990-2000) and 0.09% (2000-2005), as indicated in Table 1a. For the DRC alone, the evolution of gross and net deforestation between 1990-2000 and 2000-2005 is quite significant (WRI 2010). The most affected regions are north of the Equatorial provinces, the Oriental province, and the Kivu region (Duveiller and al. 2008). In fact, an assessment of the forest change cover map produced for the DRC by the Decadal Forest Change Monitoring (DFCM) Program confirmed these observations and indicated a concentration of the deforestation zones along axes of transportation (road or fluvial), around large urban areas (Gemena, Lisala-Bumba, Kisangani, etc.), and in the high density population zones of Kivu. The Virunga region showed the highest annual deforestation rate (0.57%, nearly 3 times higher to the national average) (Lindquist et al. 2010). More details about the DRC’s forest evolution are shown Tables 1b, and illustrated in Figure 1.

**Table 1a.** Annual deforestation, reforestation, degradation, and regeneration rates in the dense forest zones of the DRC and Congo Basin, for the 1990-2000 and 2000-2005 periods.  
(from Ernst et al. 2010, in de Wasseige et al. 2010).

	DRC		Congo Basin	
	1990 - 2000	2000 - 2005	1990 - 2000	2000 - 2005
<i>Number of processed samples</i>	334	242	547	337
Gross deforestation (%)	0.15 ± 0.02	0.32 ± 0.05	0.13 ± 0.02	0.26 ± 0.04
Gross reforestation (%)	0.04 ± 0.01	0.10 ± 0.03	0.04 ± 0.01	0.09 ± 0.02
Net deforestation (%)	0.11	0.22	0.09	0.17
Gross degradation (%)	0.07 ± 0.01	0.16 ± 0.03	0.07 ± 0.01	0.14 ± 0.02
Gross regeneration (%)	0.02 ± 0.00	0.04 ± 0.02	0.01 ± 0.00	0.04 ± 0.01
Net degradation (%)	0.06	0.12	0.05	0.09

The increase in net deforestation rate from 0.09% between 1990 and 2000 to 0.17% between 2000 and 2005 has been worsened in the DRC, where the rate has doubled between the two periods, from 0.11% (1990-2000) to 0.22% (2000-2005). Note that these rates have remained low compared to other regions of the world (Tchatchou et al. 2015). A deforestation rate of 0.3% was already estimated for the Congo basin by Giralowski (2002), who considered the 1955-1989 period, based

on extrapolation of maps. This rate could be higher compared to the rate estimated by De Wasseige *et al.* (2010), probably due to scale errors that originate from extrapolation of maps.

Similarly to other countries in the Congo Basin, the several causes that can explain deforestation include direct causes (e.g. infrastructure development, mining, collection of wood energy and agricultural expansion) and the underlying or structural causes (e.g. economic development or population expansion). Nevertheless, agriculture is the main cause – particularly “slash-and-burn” agriculture, practiced by different populations (Geist and Lambin 2001, Giralowski 2002, De Wasseige *et al.* 2010, Tchatchou *et al.* 2015).

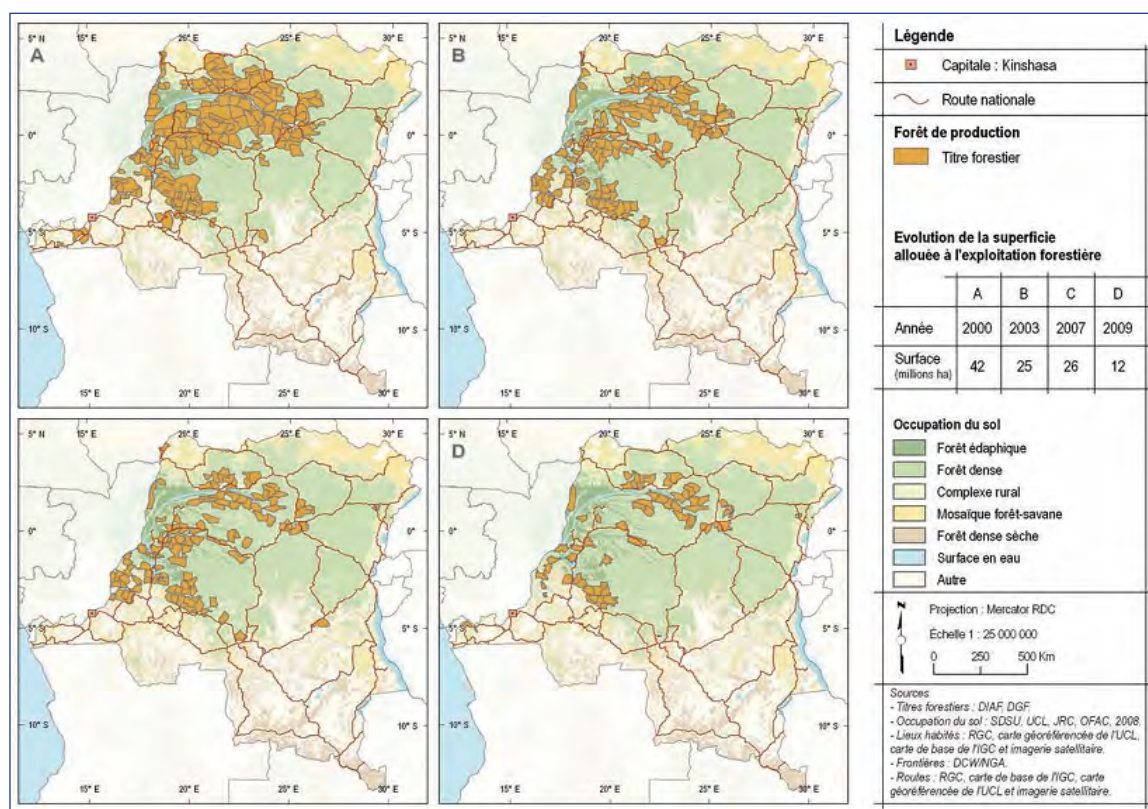
Total forest cover (Table 2) decreased by 13.8 % between the 2000-2005 and 2005-2010 intervals, with the greatest increase occurring within primary tropical forests. Forest cover loss intensity was distributed unevenly and was most correlated with areas of high population density and mining activity. While gross deforestation for all protected areas increased 64% between the 2000-2005 and 2005-2010 periods, protected areas and Congo Basin Forest Partnership (CBFP) landscapes had lower rates of gross deforestation than areas outside of them (De Wasseige *et al.* 2010).

**Table 1b.** Area estimates (in hectares) of the land cover types for the DRC as derived from the Congo Basin land cover map (Source: Verhegghen and Defourny 2010).

Land cover class	DRC	Congo Basin	DRC (%)
Lowland dense moist forest	101,822,027	161976107	<b>62.9</b>
Submontane forest	3,273,671	3,576,307	<b>91.5</b>
Montane forest	930,863	1,203,462	<b>77.3</b>
Edaphic forest	8,499,308	12666681	<b>67.1</b>
Mangrove forest	181	428060	<b>0.04</b>
<b>Total dense forest</b>	<b>114,526,051</b>	<b>186,765,850</b>	<b>61.3</b>
Forest-savanna mosaic	6,960,040	21,370,825	<b>32.6</b>
Rural complex and young secondary forest	21,425,449	32,253,138	<b>66.4</b>
Tropical dry forest- Miombo	23,749,066	28,840,818	<b>82.3</b>
Woodland	36,994,935	87,400,481	<b>42.3</b>
Shrubland	6,705,478	16,360,746	<b>41.0</b>
Grassland	4,372,677	6,501,378	<b>67.3</b>
Aquatic grassland	75,888	541004	<b>14.0</b>
Swamp grassland	701,308	832,136	<b>84.3</b>
Sparse vegetation	2,129	2224	<b>95.7</b>
Mosaic of cultivated land and natural land	12,907,360	22,008,226	<b>58.6</b>
Agriculture	0	807,396	<b>0.0</b>
Irrigated agriculture	181	88043	<b>0.2</b>
Bare land	41,935	42030	<b>99.8</b>
Cities and developed area	41,716	109382	<b>38.1</b>
Water	3,944,206	5,068,923	<b>77.8</b>
<b>Total</b>	<b>232,448,419</b>	<b>408,992,600</b>	<b>56.8</b>

**Table 2.** Forest cover and loss in DRC (x 1,000 ha) (Source: OSFAC 2010).

Forest type	2000 Forest cover	2000 - 2005 Forest loss	2005 - 2010 Forest loss
Primary forest	104,455	367	701
Secondary forest	18,293	1,168	947
Woodland	36,781	201	328
Total	159,529	1,736	1,976

**Figure 1.** Evolution of the allocated area for forest exploitation (WRI 2010).

### Forest plantations

In a report on the state of Congo forests, de Wasseige *et al.* (2015) noted that forest plantations are not much developed in the Congo Basin, mostly because of the need for major investments required to start with planting species of high genetic value, as well as the risky country profile over rotation period (which may exceed ten years). However, the authors observed that forest plantations could and should be developed in the next decades, since they play a more prominent role both in the national economy and national strategies to mitigate climate change. Developing forest plantations for wood energy, developing sustainable management of forests, and improving energy processing will have major positive impacts on the state of the forests, especially peri-urban forests (de Wasseige *et al.* 2010). Sustainable management of natural forests can also be complemented by the development of fast-growing tree plantations, such as woodlots in degraded areas and agroforestry systems, with the participation of local communities and entrepreneurs to meet rising demand (Samndong and Nhantumbo 2014).

Forest plantations currently occupy a limited space in Central Africa, both in terms of area and in terms of production. Several plantation programs took place on the Batéké plateau, located north of Kinshasa in DRC. From 1987 to 1992, over 8,000 hectares of acacias were planted in Mampu and are now managed using an agro-forestry approaches. In the year 2007, only 345 hectares were planted in the DRC. Finally, the makala project specifically aims to encourage agro-forestry plantations in villages (de Wasseige *et al.* 2010) and planted about 100 ha of Eucalyptus around Kinshasa (de Wasseige *et al.* 2014). Ten thousands of hectares of Hevea plantation are distributed all along the Congo River and its tributaries around Kisangani. Unfortunately, though the plantations are still in place, political instability has stopped latex production (de Wasseige *et al.* 2014). In the view to create a buffer zone around protected areas, 5,000 ha of Arcacia plantations have been under development since 2005 around the Virunga Park, under the Ecomalaka Project. This project aimed to develop an alternative activity to wood-cutting and poaching within the Park (de Wasseige *et al.* 2014).

Although the development of forest plantations has been positive in term of boosting the economy and the GDP of the country, its impact on forest hydrology in term of quality and quantity has been observed on other regions of the world. Putzel *et al.* (2008) and Karsenty (2010a) noted that future deforestation may be driven largely by the expansion of palm oil plantations into forest regions. Virtually all of the dense humid (high carbon) forests of the DRC are on soils and in climatic conditions that are suitable for palm oil production (Tollens 2010). The main question remains to identify and investigate the impact of forest plantations on the hydrology of these Congo forests.

### 6.3 Politics

Since the beginning of the XXI century, the Government begun a national dialogue aiming to inform the legislative reforms considered to reinforce the follow-up of the forest industry activities, to stop illegal exploitation, fight against deforestation, and to increase the role of local populations in the management of forests. These efforts led to the adoption of the Forest Code law #011/2002 (August 29, 2002), in replacement of the colonial rules and create a more favorable foundation to a sustainable and socially responsible management of the forests in RDC. Still in 2002, the Government of the RDC put a moratorium in place on the distribution of new concessions for logging, followed in 2005 by a legal investigation of all forest titles that aimed to convert those in forest concessions, so that these respected the new code that implied a long list of environmental and social conditions concerning the logging (a process that succeeded in 2009). The results of the conversion process established the base for a great transparency in the forest sector in RDC: for the first time, complete and actualized information on the exploitation titles have been accessible to the public and debated with the local and international concerned institutions.

The article #103 of the Forest Code of 2002 gave the right to forest concessionaires or operators to access public ways of evacuation (roads, tracks, sorting paths or railroad, rivers) but without any hindrance by the occupant or the concessionaire on the crossed domain. In addition, the Article #48 of the same code forbids any deforestation within a distance of 50 meters on both sides of the rivers and within a radius of 100 meters from their sources. However, Lindquist *et al.* (2010) identified a high occurrence of deforestation along the axes of transportation (rivers and roads); water resources pollution is still being reported consequently to agricultural, industrial, mining, and petroleum activities (Saudi 2005) within and around the Congo forest.

Although the decree #08/08 (April 08, 2008) considers quality and quantity of water resources (surface and ground water) as one of the factors to assess the environmental impacts owing to forest exploitation, and the law #15/026 (December 31, 2015) related to key points for the protection of water resources in the DRC, it has been observed that in reality, less efforts have been applied to reduce or eradicate the impacts of forest exploitation on water resources.

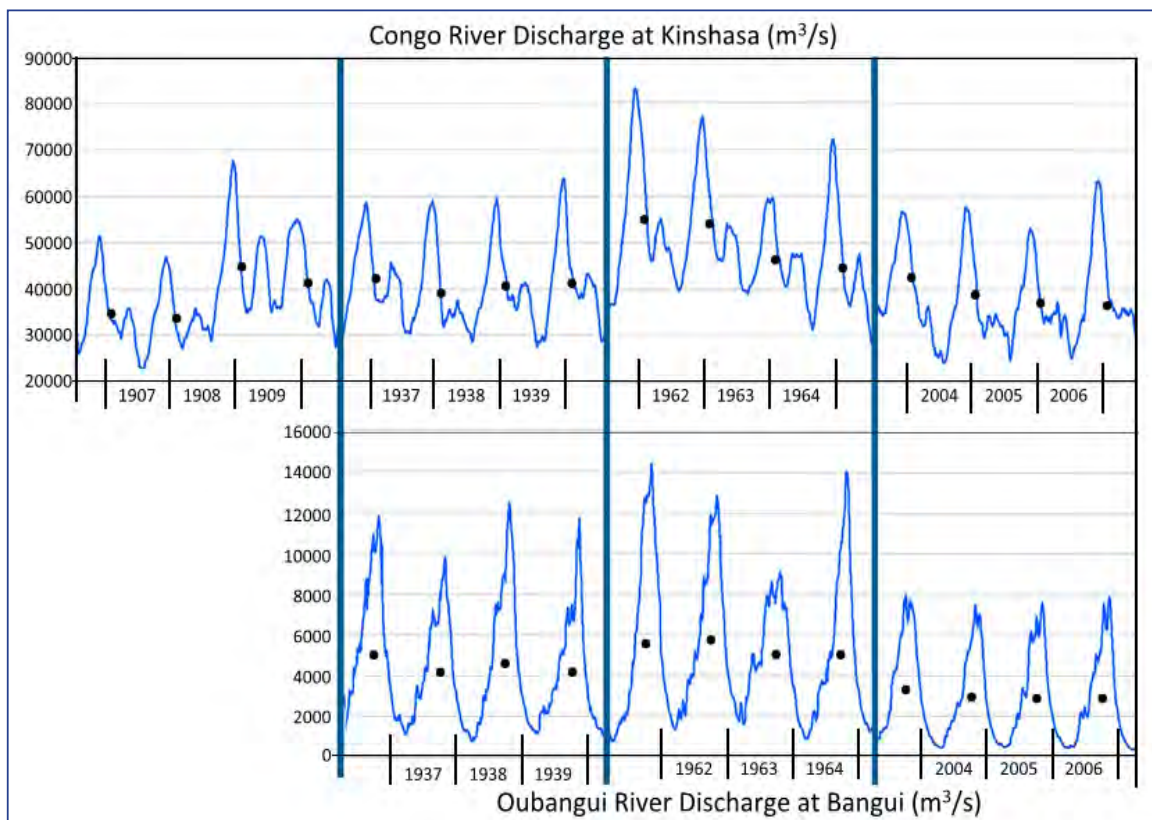


## 6.4 Climate change and the future of forestry & forest research

### Water resources

Having its tributaries in both the northern and southern hemispheres, the Congo River flows throughout the year. Its flow has for years remained between the high level of 65,411.92 m<sup>3</sup>/s (in 1908) and the low level of 21,407.54 m<sup>3</sup>/s (in 1905). However, during the unusual flood of 1962, by far the highest for a century, the flow probably exceeded 73,623.8 m<sup>3</sup>/s. At Kinshasa flow gauging station, the river's regime is characterized by a main peak flow at the end of the year and a secondary peak in May, as well as by a major low flow during July and a secondary low flow between March and April. In reality, the downstream regime of the Congo river represents a climatic influence extended over 20° of latitude on both sides of the equator, a distance of about 2,253 km. Owing to its immense size and distribution of its tributaries on both sides of the equator, the weather pattern in one particular region would not have much effect on the overall river's levels (Chishugi 2008); thus, in overall Congo flows are more constant than many other African rivers (Brummett *et al.* 2008).

As previously mentioned, Alsdorf *et al.* (2016) give a detailed and comprehensive review on the hydrology of the Congo river. Figure 2 shows discharge values from mid-1906 to mid-2010 for the Kinshasa gauge and from 1936 to 2007 for the Bangui gauge. The authors used low flows as the water year delineator; thus, the Congo River water year at Kinshasa starts in early August and ends in late July. Oubangui River water year, on the other hand, starts in early April, ending in late March. Using daily streamflow values from 2001 to 2010 reported from the Kinshasa-Brazzaville gauge, the authors estimated an annual flow of 40,662 m<sup>3</sup>/s, which is in agreement with the 40,612 m<sup>3</sup>/s reported by Laraque *et al.* (2013), who calculated their average from a century of data between 1902 and 2010.



**Figure 2.** Evolution of Congo River discharge at Kinshasa and Oubangui River discharge at Bangui. Dots are the average of daily discharge values for a given water year (Source: Alsdorf *et al.* 2016).



The above is interesting because the Congo River discharge has varied considerably between 1960 and 1995, and it is only now returning to its long-term average. In the view of the impact of forest management on water resources, a question rises on the factors that control the discharge of the Congo River. An increase (twice) of the net deforestation during the 2000-2005 period was observed in the DRC, while this was the period when the Congo discharge is returning to normal (see Figure 2, from 2003 to 2006 for Kinshasa gauge). Could this reflect the effect of deforestation on runoff and stream flow? Several authors reported an increase of discharge with tree cutting but the proportion of the cleared area was about 20% of the catchment size. This is one of many cases in the Congo basin that need more attention.

On the time that it takes for water masses to leave their initial basins until their arrival at Brazzaville-Kinshasa gauge, Bricquet (1995) in Alsdorf *et al.* (2016) gave the following estimates: two months from the confluence of the Lualaba and Elila Rivers to Brazzaville; one month from the confluence of the Kotto and Oubangui Rivers; and about 15 days from the confluence of the Loange and Kasai Rivers. These numbers can help assessing the movement of pollution, as well as flooding, generated from a particular region in the country.

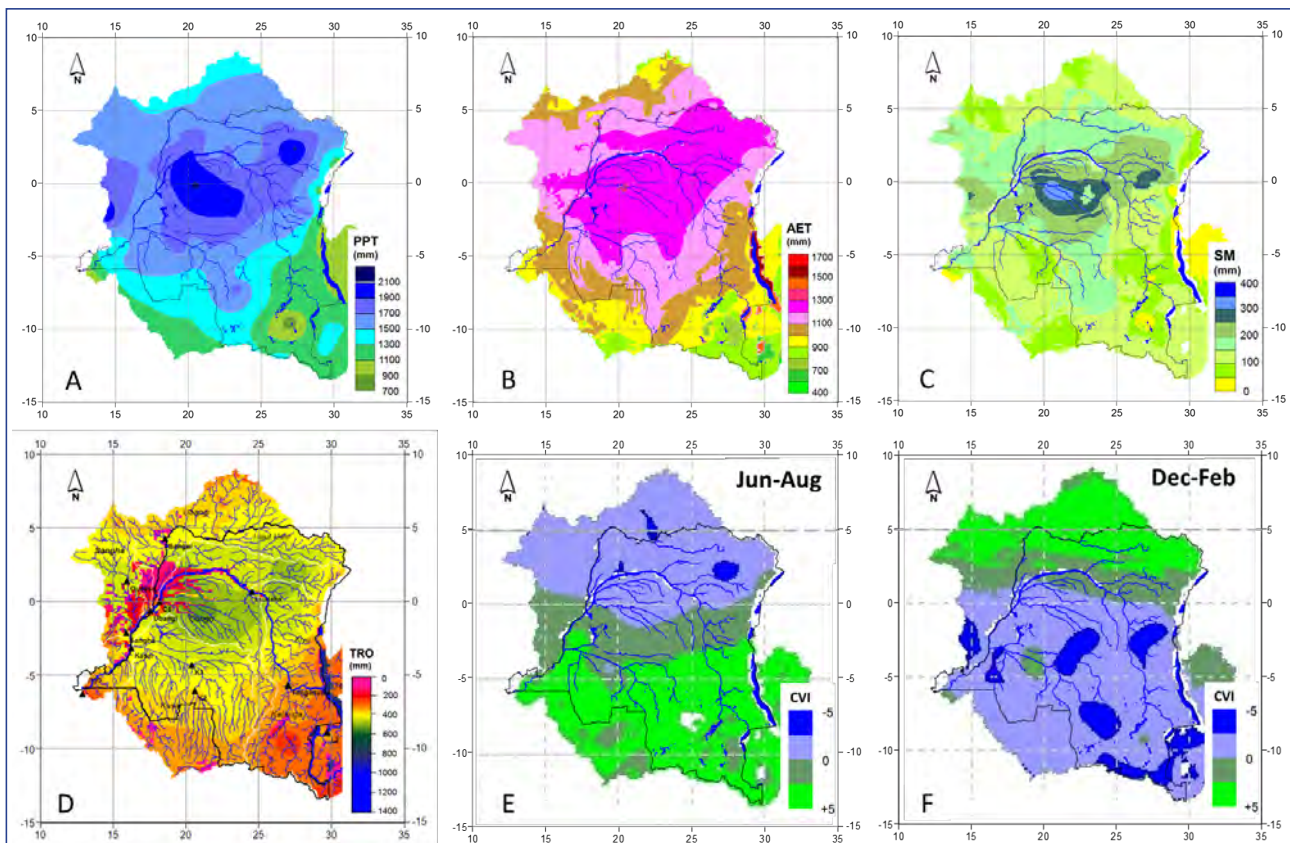
### *Spatial distribution of water resources*

In order to understand and evaluate the spatial and temporal distribution of water resources of the Congo Basin, a distributed GIS-based hydrological model, named Hybrid Atmospheric and Terrestrial Water Balance (HATWAB), was developed and parameterized for the Congo basin using GIS and computational hydrology techniques (Chishugi and Alemaw 2009). The model simulated water balance components by taking rainfall-runoff processes in the basin including soil-texture controlled moisture in the terrestrial system and the vertical integrated moisture convergence that accounts for the net water vapor flux from the basins in order to close the hydrologic water budget.

Figure 4 illustrates the simulated spatial distribution of precipitation (A), actual evapotranspiration (B), soil moisture (C), and total runoff (D), among other variables, for the Congo basin. The simulated annual total runoff (Figure 3) varies between 0 and 1945 mm with a mean annual runoff of 342 mm, indicating a general trend strongly influenced by the distribution patterns of precipitations. The lowest runoff values are located in central wetlands and the south-eastern region of the country. Apart from lakes and wide rivers, the highest runoff values are located in the heart of the equatorial forest, and decrease progressively towards the tropics. This trend is relatively correlated with soil types, especially in the south-eastern portion of the country, in the wetland regions and along the main Congo river. The AET varies between 400 and 1700 mm/year with highest values, excluding lakes and water pools, around the equator and the Oriental provinces, between -5 and 5 degrees of latitude. The moisture convergence (negative values) and the moisture divergence fluctuate around the equator during different seasons, winter and summer seasons occurring in the two main climatic regimes of the basin.

### *Climate Change simulation and impact on water resources for the DRC*

According to Ludwig *et al.* (2013), there is not enough information about the impacts of climate change on the Central African Region. Few authors (Tshimanga and Hughes 2012, CSC 2013, Ludwig *et al.* 2013, de Wasseige *et al.* 2015) reported climate change vulnerability in regards to hydrology, agriculture, forest functioning, and hydropower. The DRC, as well as the entire Congo basin region, is going to experience an increase in climate variability and changes in the hydrological systems, and will experience more intense rainfall and flash floods during the wet seasons, while the dry seasons could become wetter. Just like other forests types, the forest ecosystems in the region are sensitive and exposed to the changing climate, which will further be exacerbated by other drivers such as land use change, land fragmentation, and over exploitation of forest resources (Sonwa *et al.* 2012 in Tsalefac *et al.* 2015).



**Figure 3.** Water resources of the Congo Basin in terms of mean annual values. Precipitation (A), Actual Evapotranspiration (B), Soil moisture (C), Total runoff (D). 5.E and 5.F illustrate the simulated vertically integrated moisture convergence C in Jun to Aug and Dec to Feb, respectively (own data, Chishugi 2008).

In humid tropical Africa, the repercussions of past climate variations on watercourses have caused a decrease of about 32% of the rivers flowing to the Atlantic Ocean. Conway *et al.* (2009), on the other hand, reported an increase in precipitation, which started to be noticed at the beginning of the 1990s in certain regions of the Congo Basin, leading to an increase in flow in certain watercourses. In most scenarios used by Beyene *et al.* (2013), the authors found that runoff is increasing by 15% (A scenario) and 10% (B1 scenario) all over the Congo Basin by 2050 (Table 3). Previously, a study by Aerts *et al.* (2006) using a different dataset, the authors exhibited a runoff increase of 12% in the Congo River basin. Runoff is especially increasing in the central and western DRC (Tsalefac *et al.* 2015).

Beyene *et al.* (2013) also found the river flow to be consistent with projected runoff changes, using multi-modal average annual flows documented at Kinshasa gauging station. They concluded that discharge is projected to increase between 11 and 17% by 2050, depending on the emission scenario and by 27 to 38% by 2080, compared to the historical period (1960-2000, Table 4). Increased discharge changes have been especially observed during wet seasons (October, November, and December). Ludwig *et al.* (2013) found similar results on the changes in mean flow using different approaches (Figure 4). During the dry season, however, Beyene *et al.* (2013) found uncertain results, stating that flows could both increase or decrease. They noted that, though total water availability is likely to increase in the future, this does not mean that droughts or low flow frequencies will decrease in the future. For all their scenarios, the difference in discharge between the dry and wet seasons are increasing, indicating that both wet and dry extremes could increase in the future, towards a more seasonal and tropical climate type. In general, the discharge of the Congo river at Kinshasa has been rerunning “normally” since 1995. It is important to highlight the climatic disturbances observed in the far north-western zone of the DRC, in the Ubangi watershed, whose river reached its lowest level in 100 years in 2012, at Oubangi streamflow gauging station (Beyene *et al.* 2013).

**Table 3.** Summary of change in precipitation, evapotranspiration and runoff across the Congo basin using climate change scenarios (30-year average change not weighted) for the 2050s and 2080s, for SRES A2 (high) and B1 (low) emission scenarios, expressed as percent change of the historical base simulation (1960-2000) (Beyene *et al.* 2013)

Climate Model	Precipitation				Evapotranspiration				Runoff			
	A2		B1		A2		B1		A2		B1	
	2050	2080	2050	2080	2050	2080	2050	2080	2050	2080	2050	2080
CNCM3	+8	+12	+10	+6	+8	+11	+8	+9	+12	+15	+10	+9
ECHAM5	+6	+21	+8	+15	+13	+17	+3	+5	+16	+60	+24	+42
IPSL4	+11	+9	+5	+13	+9	+12	+9	+11	+19	+6	-3	+20
Multi-model average	+8	+14	+8	+11	+10	+10	+7	+8	+15	+27	+10	+23

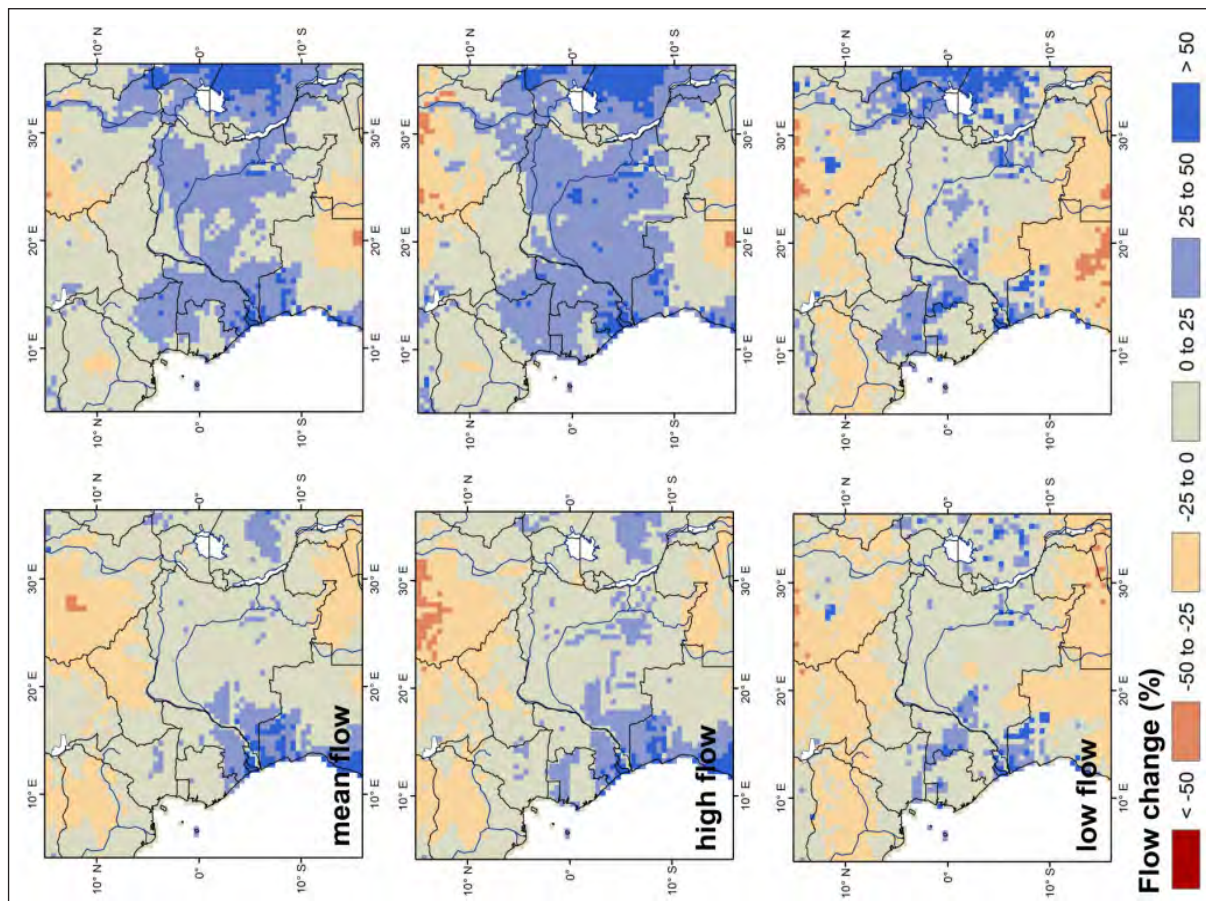
**Table 4.** Projected relative changes in annual average flow for the Congo river at Kinshasa, for two future periods, expressed as percent change, compared to the time period 1960-2000. Three different climate models were used, in combination with a high-emission scenario (A2) and a low-emission scenario (B1) (Beyene *et al.* 2013)

Climate Model	2036 – 2065		2071 – 2100	
	A2	B1	A2	B2
CNCM3	20 %	5 %	27 %	17 %
ECHAM5	23 %	28 %	73 %	46 %
IPSL4	8 %	1 %	14 %	18 %
Multi-model average	17 %	11 %	38 %	27 %

In addition to analyzing the average flows, Ludwig *et al.* (2013) also looked at changes in high flows (Q95) and low flows (Q10) (Figure 4). According to the authors, high flows are increasing more than average flows in most parts of the region. Throughout large parts of the region, high flows are increasing more than 25% for the high-emission scenario (A2). The impact under the low-emission scenario (B1) is less severe, but high flows are increasing throughout most of the region, even under the low-emission scenario. Similarly, low flows decreased over a larger area, compared to the average flow (Figure 4). Additionally, most climate scenarios indicate an increase in flows during the wet season, while during the dry season more scenarios show lower flows.

Based on Beyene *et al.* (2013)'s climate change model, increased evaporation will be observed in most of the DRC. The change is evenly distributed throughout the basin but the increase in evaporation will be slightly higher towards the edge, compared to the central Congo Basin. On average, the increase in evaporation by the end of the century will be about 10% for the A2 emission scenario and 8% for the B1 scenario (Table 4).





**Figure 4.** Projected changes in mean flow (a), high flow (Q95) (b), and low flow (Q10) (c), for the 2071-2100 period, relative to the 1971-2000 period, averaged for the three different climate models (GCMs), considering both the high- (A2) and low- (B1) emission scenarios (Ludwig et al. 2013).

### *An illustrative example on the impact of climate change on water availability and supply*

In order to emphasize the vulnerability and adaptation to climate in the DRC, we present the results of a study carried by UNFCCC (2009) in the following sections. This research used rainfall records from 17 stations, representing the four main hydrologic watersheds in the DRC, which coincide with the four climate areas of the country defined by the climate change projection models, for the year 2100. Owing to the disparity of the observation periods and the number of stations per sub-basin, the data had to be homogenized by considering the stations that has provided the longest series. These stations are: Boma (Climate Area I), Kinshasa/Binza (Climate Area II), Bukavu (Climate Area III), and Lubumbashi/Kipopo (Climate Area IV). The data relating to these hydrologic sub-basins are included in Table 5. This surface water resources assessment per hydrologic sub-basin and climate area is presented in Table 6.

The numbers obtained from the UNFCCC report (2009) are similar to those from Beyene *et al.* (2013), though the latter estimated higher precipitation and temperature. Moreover, Ludwig *et al.* (2013) noted that some bias corrections were operated on Beyene *et al.*'s results. From all the 20 global circulation models available in the MAGICC/SCENGEN 5.3 package, only five (CCSM-30, GFDLCM20, GFDLCM21, GISS-EH, and GISS-ER models) are concordant, within an acceptable margin of uncertainty, with the climatic parameters observed in DRC. Table 7 gives an overall summary of the range of projected variations (extreme values, minimum and maximum, across both scenarios) for the years 2010, 2025, 2050, and 2100, with regard to temperature (°C), precipitation (%), and atmospheric pressure (hPa) throughout the entire country (UNFCCC 2009). The annual rain and temperature trends (Table 8) and water volume trends (Table 9) for each geographical area, indicate an increase of rain over most of the country and a reduction of which the dimension

is worsening with effect from Area 3 (Maniema), passing through the coastal fringe regions (Low-Congo), and finally in Area 4 (especially the extreme South of the country, including Katanga).

**Table 5.** Annual or seasonal acreage and rainfall averages of the hydrologic sub-basins or climate areas (UNFCCC 2009)

Hydrologic Sub-basin	Composition	Acreage (Km <sup>2</sup> )	Average Annual Pp (mm) 2005
I	Lower-Congo	54,078	1,000
II	Kinshasa + Bandundu + Equator + Eastern Province + 1/4 Western Kasai	1,251,396	1,800
III	North Kivu + South Kivu + Maniema + 3/4 Eastern Kasai	382,965	1,700
IV	Katanga + 3/4 Western Kasai + 1/4 Eastern Kasai	656,656	1,100

**Table 6.** Surface water resources assessment per climate area (UNFCCC 2009).

Climate Area	Total Volume (litres)	Evaporation (%)	Flow & Infiltration (litres)
I	540,780 x 10 <sup>8</sup>	77	124,379.40 x 10 <sup>8</sup>
II	22,525,128 x 10 <sup>8</sup>	77	5,180,779.44 x 10 <sup>8</sup>
III	6,510,405 x 10 <sup>8</sup>	80	1,302,081.00 x 10 <sup>8</sup>
IV	7,223,216 x 10 <sup>8</sup>	84	1,155,714.56 x 10 <sup>8</sup>

**Table 7.** Field of climatic parameter variation after projection with the model (UNFCCC 2009).

Parameter	2010	2025	2050	2100
Temperature (°C)	0.45 to 0.52	0.91 to 1.03	1.72 to 2.08	2.69 to 3.22
Precipitation (%)	0.3 to 2.5	0.4 to 4.2	0.3 to 7.5	0.8 to 11.4
Atmospheric Pressure (hPa)	-0.08 to -0.006	-0.16 to -0.13	-0.29 to -0.25	-0.5 to -0.39

**Table 8.** Annual Average rain (mm) and temperature (°c) trends of the four climate areas (UNFCCC 2009).

Climate Area	Town/Marker	Years	Rain (mm)	Temperature (°C)
I	Boma/ Matadi	2005	1000	25.2
		2050	900	28.4
		2100	850	29.1
II	Kinshasa	2005	1800	25
		2050	1840	27.5
		2100	1900	28.2
III	Kindu	2005	1700	25.2
		2050	1650	28.2
		2100	1630	29.1
IV	Lubumbashi	2005	1100	20.4
		2050	1000	23.7
		2100	900	24.7



The details perceptible from the monthly totals distinctly predict a shortening of the rainy season period, which increases as one approaches the extreme south of the country. Katanga in particular, will have, in the long run - as from 2020 -, a rainy season of less than 5 months, compared to the current 7 months. On the one hand, the entire country will continue to suffer from global warming (UNFCCC 2009). The total volume delivered by the Congo River, which has been estimated on the basis of its average flow, is 40,000 m<sup>3</sup>/s (or 4 x 10<sup>7</sup> l/s), i.e. a volume of 126,144 x 10<sup>10</sup> liters in a year. Therefore, the Congo Basin empties 1,262,304 x 10<sup>9</sup> liters of water into the Atlantic Ocean every year (UNFCCC 2009).

**Table 9.** Water volume trend (in liters) for each geographical area in the DRC (x 10<sup>8</sup>). Values in brackets give the water volume trend as percentages per climate area

Parameter	2005	2050	2010
I. Boma - Matadi	124,380 (1.6 %)	111,940 (1.4 %)	105,720 (1.30 %)
II. Kinshasa	5,180,779 (66.7 %)	5,295,907 (68.6 %)	5,468,600 (70.4 %)
III. Kindu	1,302,081 (16.8 %)	1,263,784 (16.3 %)	1,248,466 (16.1 %)
IV. Lubumbashi	1,155,715 (14.9 %)	1,050,649 (13.7 %)	945,585 (12.2 %)
TOTAL	7,762,955 (100 %)	7,722,280 (100 %)	7,768,371 (100 %)

### Conclusions and recommendations

It is clear that more work is needed in the Democratic Republic of Congo to fully understand the relationship between forests and water systems. With enough research, the creation of effective politics will be possible. For the mean time, the authors recommend to find and apply BMPs that have been effective in other countries, under similar climatic conditions, in order to minimize the adverse effects of forest logging and plantations on the quality and quantity of water resources.

Paired watershed studies have been common in the USA, Canada, Brazil, Australia, and South Africa, among many other countries. However, no even a single case has been reported for the Congo basin. This could be a starting point as the methods and results are available for comparison. Research teams can be organized through academic institutions as several universities around the country run programs on water, biology, soil, and the environment.

## 6.5 References

Alsdorf, D., E. Beighley, A. Laraque, H. Lee, R. Tshimanga, F. O'Loughlin, G. Mahé, B. Dinga, G. Moukandi, and R. G. M. Spencer (2016), Opportunities for hydrologic research in the Congo Basin, *Rev. Geophys.*, 54, 378–409, doi:10.1002/2016RG000517.

August, C.M. (2013) Assessment of the effect of land use/cover change on streamflows. MSc. Diss, University of Dar es Salaam

Becker, M., Santos da Silva, J., Calmant, S., Robinet, V., Linguet, L. and Seyler, F. (2014), Water Level Fluctuations in the Congo Basin Derived from ENVISAT Satellite Altimetry. *Remote Sensing*, 6: 9340-9358, doi:10.3390/rs6109340.

- Bergkamp, G., Orlando, B. & Burton, I. 2003. Change: adaptation of water resources management to climate change. Gland, Switzerland, World Conservation Union (IUCN).
- Bernnett, B. and Kruger, F. (2015). Forestry and water conservation in South Africa: History, Science and Policy. ANU Press.
- Beyene, T., Ludwig, L. and Franssen, W., 2013. The potential consequences of climate change in the Congo river basin. In: Climate Change Scenarios for the Congo Basin. [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.
- Bonnet, M.-P., G. Barroux, P. Seyler, G. Peclý, P. Moreira-Turcq, C. Lagane, G. Cochoneau, J. Viers, F. Seyler, and J.-L. Guyot (2005), Seasonal links between the Amazon corridor and its flood plain: The case of the varzea of Curuai, in Dynamics and Biogeochemistry of River Corridors and Wetlands (Proceedings of symposium S4 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005), IAHS Publ., 294.
- Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55, 3–23.
- Bren, L. (2015). Forest hydrology and catchment management. An Australian perspective. Springer. ISBN: 978-94-017-9337-7.
- Brinkman, W.L.F. 1983. Hydrology. in H. Lieth and M.J.A. Werger (Eds.). Tropical Rain Forest Ecosystems: Biogeographical and Ecological Studies, Pp. 89-98. Elsevier, Amsterdam.
- Bruijnzeel, L.A., 2002. Hydrological impacts of converting tropical montane cloud forest to pasture, with initial reference to northern Costa Rica. Project Memorandum Form, Project No. R7991 within the Forestry Research Programme of the Department for International Development of the UK, Aylesford, UK, 60 pp.
- Bruijnzeel, L.A. (2004) Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems and Environment* 104:185–228. doi:10.1016/j.agee.2004.01.01
- Brummett R., Tanania C., Pandi A., Ladel J., Munzimi Y., Russell A., Stiassny M., Thieme M., White S., Davies D., 2009. Water resources, forests and ecosystem goods and services. In: de Wasseige C., Devers D., de Marcken P., Eba'a Atyi R., Nasi R., and Mayaux P. (eds), 2009. The forests of the Congo Basin - State of the forest 2008, Luxembourg: Publications office of the European Union, 411 p, ISBN 978-92-79-13210-0, doi: 10.2788/32259, pp 141-157
- Bultot, F. (1972), Atlas Climatique du Bassin Congolais Publications de L'Institut National pour L'Etude Agronomique du Congo (I.N.E.A.C.), Troisieme Partie, Temperature et Humidite de L'Air, Rosee, Temperature du Sol.
- Bwangoy, J.B., Hansen, M.C., Roy, D.P., De Grandi, G., Justice, C.O. (2009) Wetland mapping in the Congo Basin using optical and radar remotely sensed data and derived topographical indices. *Remote Sensing of Environment*, 114 (2010) 73-86.
- Cabral, OMR, Rocha, HR, Gash, JHC, Ligo, MAV et al., 2010. The energy and water balance of a Eucalyptus plantation in southern Brazil. *Journal of hydrology*, 388, 208-216.
- Calder I., T. Hofer, S. Vermont and Warren, P. 2007. Towards a new understanding of forests and water. *Unasylva* Vol. 58, No. 229. FAO: Rome.
- Callède, J., G. Cochonneau, F. Vieira Alves, J.-L. Guyot, V. S. Guimarães, and E. De liveira (2010), Les apports en eau de l'Amazonie à l'Océan Atlantique, *Rev. Sci. Eau/J. Water Sci.*, 23, 247–273.
- Celleri, R. and Feyen, J., 2009. The hydrology of the tropical Andean Ecosystems: Importance, knowledge status, and perspectives. *Mountain Research and Development*, Vol. 29, 4: 350 – 355. doi: 10.1659/mrd.00007.
- Chishugi, C.J. (2008), Hydrological Modeling of the Congo River Basin: A Water Balance Approach. MSc. Dissertation, University of Botswana, Botswana.
- Chishugi, B. J., and Alemaw, B. F. (2009), The hydrology of the Congo River basin: A GIS-based hydrological water balance model. *World environmental and water resources congress 2009: Great Rivers*, ASCE Conf. Proc., pp. 1–16, doi:10.1061/41036(342)593.
- Coe, M. T., M. H. Costa, and B. S. Soares-Filho (2009), The influence of historical and potential future deforestation on the streamflow of the Amazon River -Land surface processes and atmospheric feedbacks, *J. Hydrol.* 369, 165–174, doi:10.1016/j.jhydrol.2009.02.043.
- Coe, M. T., E. M. Latrubesse, M. E. Ferreira, and M. L. Amsler (2011), The Effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil, *Biogeochemistry*, 105, 119–131, doi:10.1007/s10533-011-9582-2.
- Cornish, PM. (1993), The effects of logging and forest regeneration on water yields in a moist eucalypt forest in New South Wales, Australia. *Journal of hydrology*, 150, no 2, p301-322.

- Costa et al. (2003), Combined effect of deforestation and doubled atmospheric CO<sub>2</sub> concentrations on the climate of Amazonia. *Climate journal*, 13: 18-34.
- CSC, 2013. Climate change Scenarios for the Congo Basin. Climate Service Centre Report No. 11. Eds, Haesnsler A., Jacob D., Kabat P. and Ludwig F. Hamburg, Germany. 210p. ISSN: 2192-4058
- D'Almeida, C., Vorosmarty, C.J., Hurtt, G.C., Marengo, J.A., 2007. The effects of deforestation on the hydrological cycle in Amazonia: a review on scale resolution. *International Journal of Climatology*. 27 (5): 633- 647.
- Debroux, L. et al. 2007 (eds). *Forests in Post-Conflict Democratic Republic of Congo: Analysis of a Priority Agenda*. center for International Forestry Research, World Bank, et al., Bogor.
- Defourny P., Delhage, C. et Kibambe Lubamba J-P., 2011. Analyse quantitative des causes de la déforestation et de la dégradation des forêts en République Démocratique du Congo. UCL/FAO/CN REDD, Kinshasa.
- De Merode, E. 1998. Protected areas and livelihoods. Contrasting systems of wildlife management in the RDC. PhD dissertation. University College, London.
- De Wasseige C, de Marcken P, Bayol N, Hiol Hiol F, Mayaux Ph, Desclee B, Nasi R, Billand A, Defourny P and Eba'a Atyi R. 2012. The forests of the Congo Basin: State of the forest 2010. Luxembourg: Publications Office of the European Union, ISBN 978-92-79-22716-5, DOI: 10.2788/47210
- Duveiller, G., P. Defourny, B. Desclée et P. Mayaux. 2008. Deforestation in Central Africa: Estimates at regional, national and landscape levels by advanced processing of systematically-distributed Landsat extracts. *Remote Sensing of Environment* 112: 1969–81.
- Ellison, D., Futter, M., Bishop, K., 2012. On the forest cover – water yield debate: from demand – to supply –side thinking. *Global Change Biology*, 18 (3): 806 – 820.
- Ernst C., A. Verhegghen, C. Bodart, P. Mayaux, C. de Wasseige, A. Bararwandika, G. Begoto, F. Esono, M. Bara, A. Kondjo, H. Koy, J. S. Makak, J. D. Menomo, C. Musampa, R. Ncogo, G. Neba, B. Nkoumakali, C. B. Ouissika, and P. Defourny. 2010. Congo Basin forest cover change estimate for 1990, 2000, and 2005, by Landsat interpretation using an automated object-based processing chain. *The International Archives of the Photogrammetry, remote sensing and spatial Information sciences XXXVIII-4/C7*.
- Franken, W. & Leopoldo, P.R. (1984). Hydrology of catchment areas of Central-Amazonian forest streams. In *The Amazon* (pp. 501-519). Springer Netherland.
- Furk, K. (1984). Water chemistry of the Amazon basin: the distribution of chemical elements among freshwaters. In *The Amazon* (pp. 167-199). Springer Netherlands.
- Garcia-Chevesich, P. 2015a. Erosion control and land restoration. Outskirts Press. Denver, CO. 451 p
- Garcia-Chevesich, P., R. Pizarro, and R. Valdes. 2015b. How forestry in the southern hemisphere can help address desertification and global climate change. *Journal of Forestry* 113(1): 72-74.
- Geist HJ and Lambin EF. 2001. What Drives Tropical Deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence. pp. xiii + 116 pp. LUCR Report.
- Germer SH, Elsenbeer H, Moraes JM (2006) Throughfall and temporal trends of rainfall redistribution in an open tropical rainforest south-western Amazonia (Rondonia, Brazil), *Hudrol Earth Syst Sci* 10:383-393.
- Giralowski J. (2002), La déforestation en Afrique centrale. Les facteurs de la dégradation des forêts denses humides équatoriales dans la République démocratique du Congo, Varsovie, Editions Académiques DIALOG, 82 p., 3 cartes h.-t.
- Hamilton, L. 1985. Overcoming myths about soil and water impacts of tropical forest land uses. In S. A. ElSwaify, W. C. Moldenhauer & A. Lo, eds. *Soil erosion and conservation*, pp. 680–690. Ankeny, Iowa, USA, Soil Conservation Society of America.
- Hewlett, J.D. and Nutter, W.L., (1968). An outline of the forest hydrology (p.81). Athens, G.A. University of Georgia Press.
- Hewlett, J.D. and Bosch, J.M., (1984). The dependence of storm flow on rainfall intensity and vegetation cover in South Africa. *Journal of hydrology*. 75: 365-381.
- Holme, J.W. and Colville, J.S. (1970). Forest hydrology in karstic region of Southern Australia. *Journal of hydrology*, 10(1) 59-74.
- Hornbeck, J.W, Adams, M.B., Corbett, E.S., Verry, E.S., and Lynch J.A. 1993. Long term impacts of forest treatment on water yield: a summary of the Northeastern USA. *Journal of Hydrology* 150: 323-344.

Hughes, D. A., R. M. Tshimanga, S. Tirivarombo, and J. Tanner (2014), Simulating wetland impacts on streamflow in southern Africa using a monthly hydrological model, *Hydrol. Processes*, 28, 1775–1786, doi:10.1002/hyp.9725.

Hulme, M. and Viner, D.: 1995, *A Climate Change Scenario for Assessing the Impact of Climate*

*Change on Tropical Rain Forests*. A report prepared by the Climate Research Unit for WWF (U.S.A.), Univ. East Anglia, U.K., p. 34.

Ice, G.G. and Stednick, J.D. 2004. Introduction. In *A century of forest and wildland watershed lessons*, ed. G.G. Ice and J.D. Stednick. Bethesda, MD: Society of American Foresters.

Ickowitz A, Slayback D, Asanzi P and Nasi R. 2015. Agriculture and deforestation in the Democratic Republic of the Congo: A synthesis of the current state of knowledge. Occasional Paper 119. Bogor, Indonesia: CIFOR. ISBN 978-602-1504-67-3.

Jirka, S., McDonald, A.J., Johnson, M. S., Feldpausch, T.R., Couto, E.G. & Riha, S.J. 2007. The relationships soil hydrology and forest structure and composition in the southern Brazilian Amazon. *Journal of Vegetation Science*, 18(2), 193-194.

Jofré, P., C. Büchner, R. Ipinza, C. Bahamondes, S. Barros, P. García, and J. Cabrera. 2014. State of the art on water and forest plantations (Spanish). Agricultural Innovation Foundation (FIA) and Forest Institute of Chile (Infor). Government of Chile. Ministry of Agriculture. 120 p.

Karsenty, A. 2010a. Large-Scale Acquisition of Rights on Forest Lands in Africa. Rights and Resources Initiative, Washington, D.C.

Laraque, A., M. Bellanger, G. Adèle, S. Guebanda, G. Gulemvuga, A. Pandi, J. E. Paturel, A. Robert, J. P. Tathy, and A. Yambele (2013), Recent evolution of Congo, Oubangui and Sangha Rivers flows, *Académie Royale des Sciences de Belgique, Geogr. Ecol. Trop.*, 37(1), 93–100.

Laurance, W.F., & Williamson, G.B. (2001). Positive feedbacks among forest fragmentation, draught, and climate change in the Amazon. *Conservation Biology*, 15(6), 1529-1535.

Lee, H., Jung, H.C., Alsdorf et al. (2011) Characterization of terrestrial water dynamics in the Congo Basin using GRACE and satellite radar altimetry. *Remote Sensing of Environment*, 115, 3530-3538. doi:10.1016/j.rse.2011.08.015.

Lee, H., Yuan, T, Jung, H.C. and Beighly, E. (2015) Mapping wetland water depths over the the Central Congo Basin using PALSAR ScanSAR, Envisat altimetry and MODIS VCF data. *Remote Sensing of Environment*, 152, 136-149.

Lesack, L.F., 1993. Water balance and hydrologic characteristics of a rain forest catchment in the central Amazon basin. *Water Resources Research*, 29(3), 759-773.

Levia, D.F., Carlyle-Moses, D., Tanaka, T. (2011), *Forest hydrology and Biogeochemistry: Synthesis of Past Research and Future*. Ecolog. studies. Dordrecht; London: Springer.

Lindquist, E., A. Altstadt, M. Hansen, C. Justice, D. Slayback and B. Adusei. 2010. Tree cover cleaning in the Congo Basin from 1990 to 2000 to 2005: Exhaustive monitoring of forest loss with Landsat and MODIS. Note technique en préparation; non publiée.

Ludwig F., Franssen W., Jans W., Beyenne T., Kruijt B., Supit I. (2013) Climate change impacts on the Congo Basin region. In: Haensler A., Jacob D., Kabat P., Ludwig F. (eds.) *Climate Change Scenarios for the Congo Basin*. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

Marlier, G. (1973), *Limnology of the Congo and Amazon Rivers*, in *Tropical Forest Ecosystems in Africa and South America: A Comparative Review*, edited by B. J. Meggers, E. S. Ayensu, and W. D. Duckworth, pp. 223–238, Smithsonian Institution Press, Washington, D. C.

Martinez, J.-M., and T. Le Toan (2007), Mapping offlood dynamics and vegetation spatial distribution in the Amazon floodplain using multitemporal SAR data, *Remote Sens. Environ.*, 108, 209–223.

Mbala, S.M., Karsenty, A. 2010. Forest Revenue Decentralization and profits Redistribution in the Democratic Republic of Congo. In: German, L., Karsenty, A., and tiani, A-M (eds). *Governing Africa's Forests in a Globalized World*. 8. Earthscan, London.

Melack, J. M., and L. L. Hess (2010), Remote sensing of the distribution and extent of wetlands in the Amazon basin, in *Amazonian Floodplain Forests: Ecophysiology, Ecology, Biodiversity and Sustainable Management*, *Ecol. Stud.*, edited by W. J. Junk et al., pp. 43–59, Springer, Dordrecht, Netherlands.

Mertes, L.A., Daniel, D.L., Melack, J.M., Nelson, B., Martinelli, L.A. and Forsberf, B.R. (1995). Spatial patterns of hydrology, geomorphology, and vegetation on the floodplain of the c Amazon River in Brazil from a remote sensing perspective. *Geomorphology*, 13(2), 215-231.



- Musampa Kamungandu, C. et al. 2012. Cartographie des bénéfices potentiels liés à la biodiversité dans le cadre de REDD+. République Démocratique du Congo. Préparé par UNEP-WCMC, Cambridge, Royaume-Uni; Ministère de l'Environnement, conservation de la Nature et tourisme de la RDC et l'observatoire Satellitaire des Forêts d'Afrique centrale. Programme ONU-REDD, Kinshasa.
- National Council for Air and Stream Improvement, Inc. (NCASI). 2009. Effects of forest management on water resources in Canada: A research review. Technical Bulletin No. 969. Research Triangle Park, N.C.: National Council for Air and Stream Improvement, Inc
- Neary, D., Hayes, D., Rustad, L., Vose, J., Gottfried, G., Sebesteyn, S. et al., (2012). US Forest Service Experimental Forests and Ranges Network: a continental research platform for catchment-scale research. *Revisiting Experimental Catchment Studies in Forest Hydrology*, 49-57.
- Nelson, J., Kipalu, p., Vig, S. The Forest Dialogue: Field Dialogue on Free and Informed Consent. Bas Congo and Kinshasa the Democratic Republic of Congo. Background Paper, Forest peoples programme, Moreton-in-Marsh, 21-25 May 2012
- Nepstad, D., Lefebvre, P., Lopes da Silva, U. et al, 2004. Amazon drought and its implications for forest flammability and tree growth: A basin-wide analysis. *Global change biology*, 10(5), 704-717.
- Nobrega, R.L.B., Guzha, A.C., Torres, G.N., Kovacs, K., Lamparter, G., ... & Gerold, G. (2016), Identifying hydrological responses of micro-catchments under contrasting land use in the Brazilian Cerrado. *Hydrol. and Earth System Sci. Discuss.*, 12, 9915-9975, 2015.
- OSFAC, 2010. Forêts d'Afrique centrale évaluées par télédétection FACET. Étendue et perte du couvert forestier en république démocratique du Congo de 2000 à 2010. Publié par l'université d'État du dakota du sud, Brookings, dakota du sud, États-unis d'Amérique. ISBN: 978-0-9797182-5-0. Site web: <http://osfac.net>.
- Pereira, H.C., 1962. Hydrological effects of changes in land use in some South African catchment areas. *East Afr. Agric. For. J., Spec. Iss*, 27, 131pp.
- Putzel, J., Sefan, L., Schouten, c. 2008. Drivers of Change in the Democratic Republic of Congo: The Rise and Decline of the State and Challenges for Reconstruction. Working Paper No 26, Destin Development Studies Institute, London.
- Ruprecht, J.K., Schofield, N.J., Crombie, D.S., Vertessy, R.A. and Stoneman, G.L. (1991). Early hydrological response to intense forest thinning in southwestern Australia. *Journal of hydrology*, 127(1), 261-277.
- Samndong, R.A. and Nhantumbo, I., 2014. Natural resources governance in the Democratic Republic of Congo: Breaking sector walls for sustainable land use investments. IIED Country Report. IIED, London. <http://pubs.iied.org/13578IIED>, ISBN 978-1-78431-132-2
- Saudi, K. K. (2005). National Nile Basin Water Quality Monitoring Baseline Report for the Democratic Republic of Congo. Nile Basin Initiative - Transboundary Environmental Action Project. Final version: 5/8/2005
- Sonwa D.J., Nkem J.N., Idinoba M.E., Bele M.Y. and Jum C., 2012a. Building regional priorities in forests for development and adaptation to climate change in the Congo Basin. *Mitigation and Adaptation Strategies for Global Change*, 17(4): 441-450. Doi:10.1007/s11027-011-9335-5.
- Tchatchou B, Sonwa DJ, Ifo S and Tiani AM. 2015. Deforestation and forest degradation in the Congo Basin: State of knowledge, current causes and perspectives. Occasional Paper 144. Bogor, Indonesia: CIFOR. DOI: 10.17528/cifor/005894, ISBN 978-602-387-021-9.
- The forests of the Congo Basin – State of the Forest 2013. Eds: de Wasseige C, Flynn J., Louppe D., Hiol Hiol F, Mayaux Ph, - 2014. Weyrich. Belgium. 328 p. ISBN 978-2-87489-299-8, DOI: 10.2788/47210
- Tslefac, M., Hiol Hiol, F., Mhe, G., Laraque, A., Sonwa, D., ... & Doumenge, C. (2015) Climate of Central Africa: Past, present and future. In de Wasseige C, Tadoum M., Eba'a Atyi R and Doumenge C. (ed), *The Forest of the Congo 2015– Forests and climate change*. Weyrich. Belgium. 128 p. ISBN: 978-2-87489-355-1.
- Tshimanga, R.M., D.A. Hughes, and E. Kapangaziwiri (2011), Initial calibration of the Pitman rainfall-runoff model for the Congo River basin, *Phys. Chem. Earth*, 36, 14 – 15.
- Tshimanga, R.M., Hughes, D.A. Climate change and impacts on the hydrology of the Congo Basin: The case of the northern sub-basins of the Oubangui and Sangha Rivers. *J. Phys. Chem. Earth* (2012), <http://dx.doi.org/10.1016/j.pce.2012.08.002>
- Tshimanga, R.M., and D.A. Hughes, (2014), Basin-scale performance of a semi-distributed rainfall-runoff model for hydrological predictions and water resources assessment of large rivers: The Congo River. *Water Resour. Res.*, 50, 1174-1188, doi:10.1002/2013WR014310.



UNFCCC (2009). Executive Summary report : "La Communication Nationale Initiale sur les changements climatiques/RDC" (@ [www.unfccc.int/resource/docs/natc](http://www.unfccc.int/resource/docs/natc)).

Van der Zel, D.W. (1974) Catchment research at Zachariashoek. For. in S. Africa. 15:23 -30.

Van Wilgen, B.W. (1982) Some effect of post-fire age on above ground plant biomass of fynbos (macchia) vegetation in South Africa. J. of Ecology, 70: 217-225.

Van Wyk, DB. (1987) Some effects of afforestation on streamflow in the Western Cape Province, South Africa. Water SA, 13(1) 31-36.

Verhegghen A., defourny P., 2010. A new 300 m vegetation map for Central Africa based on multi-sensor times series. In: sobrino J.A. (ed.), Third recent Advance in Quantitative remote sensing. Publicaciones de la universitat de Valencia, Valencia, spain.

Wicht, C.L. (1967) Forest hydrological research in S. Afr. Republic. In W.E. Sopper and H.W. Lull (eds) Proceedings of Intern. Symp. on Forestry Hydrology. Penn. State Univ. Pennsylvania, USA. 75-84.

West, T.L. 1990. Research in the USDA Forest Service: A historian's view. Paper presented at the Third Symposium on Social Science in Resource Management, College Station, TX, May 1990.

WRI, 2010. Atlas forestier interactif de la république démocratique du Congo. Version 1.0 – données 2009. Document de synthèse. WRL, MECNT. Washington D.C. 68p.

Wright, K.I. (2016). Long-term effects of forestry best management practices on the hydrology and water chemistry in three appalachian headwater catchments.

Yamba, p.K., 2009. Congo Basin-DRC: Case study on the Ngiri-Tumba-Maindombe Wetland Landscape Environmental Security. Institute for Environmental Security, The Hague.

Yanggen d., Angu K. and Tchamou N. (eds), 2010. Landscape-scale Conservation in the Congo Basin: Lessons Learned from the Central African Regional Program for the environment (CARPE). Gland, Switzerland: IUCN. Xiv +262 p.

# Chapter 7. Forest Management and Water in India

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## 7.1 Introduction

India underwent a major transformation of its landscape and land-cover after approximately 1860, when large parts of the country came under the British Colonial rule (Gadgil and Guha, 1993; Goldewijk and Ramankutty, 2004; Kumar, 2010), spurred by demands for timber destined to shipbuilding, railways, expansion of agriculture, and plantations for tea, further continuing in the post-independence period for dams and reservoirs, agricultural expansion, and refugee resettlement.

It is estimated that in the period 1875-1900, roughly one-third of India was cultivated, an equal expanse was forested, and about twenty percent of the land was grassland and savannah-woodlands (Lynch and Talbott 1995; Sivaramakrishnan, 2009).

Overall estimates of deforestation are between 40%-50% of original cover lost between 1860s and 1990s. However, according to Laurance 2007, India has already lost nearly 80% of its original native forest cover. Using the best available datasets, his analyses suggest that the remaining native forests in India are declining at a rapid pace, from 1.5% to 2.7% per year.

According to data from Global Forest Watch ([www.globalforestwatch.org](http://www.globalforestwatch.org)), approximately 100,000 hectares of forest were lost from Arunachal Pradesh, between 2001 and 2013, representing more than one percent of the State's entire area.

A report on the forest cover of Arunachal Pradesh, which is India's last remaining massive forest landscape, noted that 70 percent of the state was forested in 1988. By computing projected population growth and its resultant resource extraction pressures, the study estimated 50 percent of the State's forests would be lost by 2021 (Menon et al. 2001).

### *Regional case: The Western Ghats land-cover change*

The Western Ghats is one of the global biodiversity's hotspots and it is an area where some rigorous estimates of forest loss and conversion are available. Menon and Bawa (1997) estimated that out of 81,870 km<sup>2</sup> of the southern Western Ghats in Karnataka, Kerala and Tamil Nadu, there was a loss of 40% of the original forest and scrub between 1920 and 1990.

Jha et al. (2000) estimated changes in forest cover between 1973 and 1995 in the southern part of the Western Ghats using satellite data. The study area of approximately 40,000 km<sup>2</sup> showed a loss of 25.6% in forest cover over 22 years. The dense forest was reduced by 19.5% and open forest decreased by 33.2%. As a consequence, degraded forest increased by 26.64%.

By the 1990s, estimated forest cover in India was 20%. According to FAO (2006), the area under forests and other wooded land in India has increased from 63.93 mha in 1990 to 67.70 mha in 2005. Thus, FAO estimates do not significantly differ from the Forest Survey of India ([fsi.nic.in](http://fsi.nic.in)) estimates.

### *State of India' forests*

Periodically, the Forest Survey of India publishes statewide forest cover estimates based on automated algorithms using remotely sensed data. A study by Puyravaud et al. (2010) suggests that India has some of the globally most imperiled forests. They state that even as the Forest Survey of India recently announced that forest cover in India had expanded by nearly 5% over the past

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decade, this is misleading. They state that methodology fails to distinguish native forests from tree plantations, which are often monocultures of exotic species.

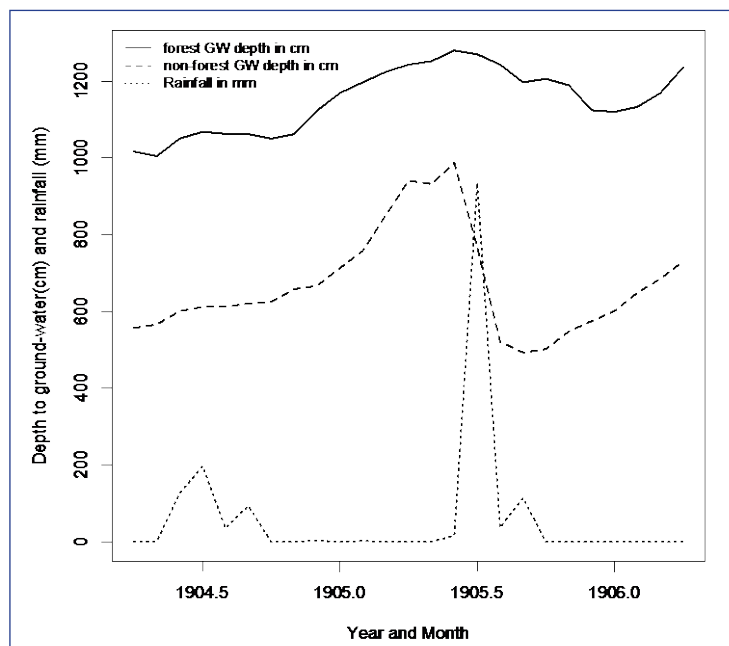
They estimate that, since the early 1990s, tree plantations have expanded in India at an estimated rate of roughly 15,400 km<sup>2</sup>/year. Subtracting plantations from total forest cover shows **that native forests in India have declined by 1.5%–2.7% per year.**

## 7.2 Literary Review

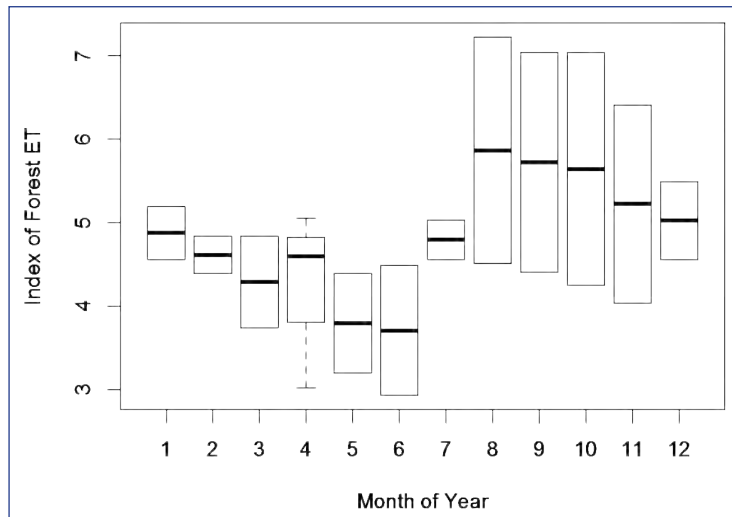
The large scale transformation of India and loss of forest cover raised concerns about the hydrological consequences of these, and while the early discourse was dominated by the effects of this on rainfall, increasingly the effects of land-cover and land-use change within forests on stream flows and sediment load became an area of policy and management interventions by the colonial Forest department. As loss of forest cover mounted, earlier discussions were dominated by the “dessicationist” discourse, a concern about how loss or degradation of forests could reduce rainfall and was also articulate about the “sponge” functions of intact forests (Saberwal, 1999).

The first empirical enquiry into the role of forest cover on sub-surface flows was a “space for time” type of substitution study by Pearson (1907), who measured depth to groundwater in wells located inside and outside forests, and found that depth was 4.74 deeper under forests than outside (Figure 1), perhaps the first empirical study of evapotranspiration by forests in India, even though its value was not recognized as such at that time, even by the author (Saberwal, 1999). Pearson’s study took place in Ghodra Forest Range in Panchmahals, what is now “Gujarat”. As previously mentioned, the depths to groundwater was shallower under the non-forest site (100m outside a forest) compared to the well in the forest (1200m inside a mixed teak forest) and was much more responsive to rainfall as well. The measurements were taken early in the morning to avoid any effects of water abstraction by local people.

The difference in depths to groundwater between forest and non-forest Wells from Pearson’s data (Pearson, 1907) was used as a crude index of forest evapotranspiration and the results are consistent with what we know about phenology and evapotranspiration of a dry deciduous forest, with least ET during dry months (January through June), when moisture is limiting, leaves are progressively being shed, and ET is highest during the Monsoon and early post-Monsoon period (July-December), when moisture is available (Figure 2).

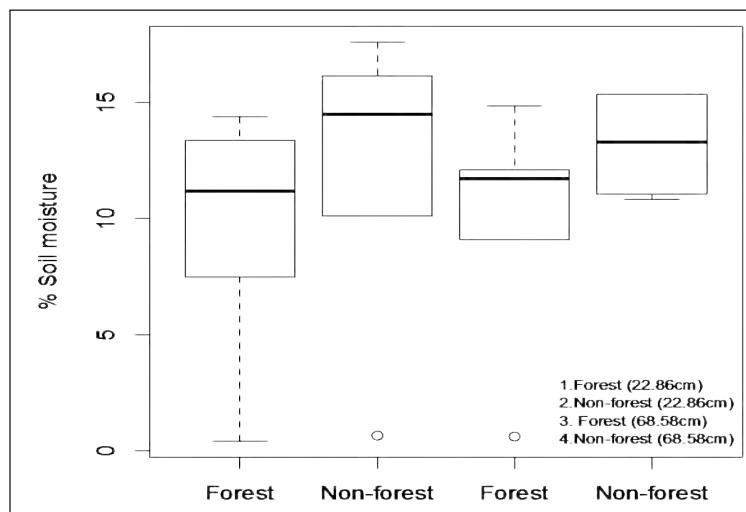


**Figure 1.** The first forest hydrology observations in India (Pearson, 1907).



**Figure 2.** Evapotranspiration response of a deciduous forest, Data source: Pearson, 1907.

The second study was done by E. Benskin on the Indian Forest Service, and consisted of comparative soil moisture measurements under “poor quality” forest and a denuded site in the Monsoon of 1930 in the Chota Nagpur area in what is now Jharkand state (Benskin, 1930). The author made measurements at two depths: 22.86 cm (9 inches) and 68.58 cm (27 inches), the latter depth would thus correspond to active root activity of trees (Figure 3).



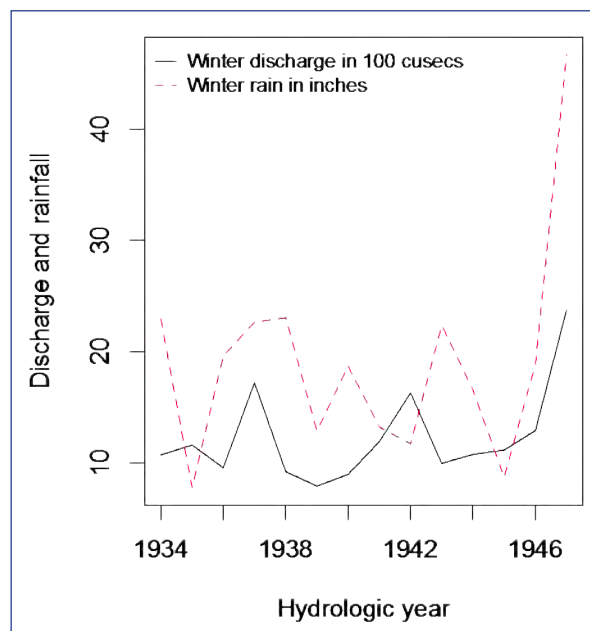
**Figure 3.** Benskin’s soil moisture measurement at two depths under forest and non-forest in the Monsoon of 1930. Data source: Benskin, 1930.

Benskin is probably the first researcher to recognize transpiration by forest trees as a process. He attributed the difference in soil moisture *largely to transpiration demand of the forest* and also noted that even in high intensity rains, the forest soil was less prone to saturation compared to the denuded sites, and linked this to possible benefits for flood-regulation (Benskin, 1930).

*India's first forest hydrology experiment*

The consolidation of British colonial administration over the hill and mountain forests of what is now Himachal Pradesh soon after 1865 empowered the government revenue and forest departments with their separate and often conflicting agendas and interests to manage forest resources. This invariably resulted in control over those dependent on them for their needs. One such group of people is the nomadic pastoral communities that ascended with their flocks of sheep and goats to grazing areas near and above the tree line in summers, descending to lower elevation forests during winters. In 1923, a hydro-electric project was constructed at Barot on Uhl River, in what was then the Punjab Himalayas (Saberwal, 1999; and references therein).

Upstream of this site was the Chota Bangahal catchment in The Western Himalayas, in what is now Himachal Pradesh, covering approximately 283 km<sup>2</sup> between 2133 m.o.s.l. to over 4900 m.o.s.l., largely forested with high elevation meadows, and some permanent snow cover was the site of an interesting forest hydrologic experiment between 1934 and 1947. In this period, grazing by over 95,000 sheep and goats was stopped, and river discharge and rainfall gauged (see Figure 4). It was fitted a regression model to this data and annual winter rainfall explained 40% of the variability in winter discharge ( $p < 0.02$ ). This study was discontinued in 1947 to the detriment of the field of hydrology in India (Saberwal 1999, and references therein).



**Figure 4.** The second forest hydrology experiment in India.

We are now aware that the hydrologic response of catchments to land use change is controlled by a complex function of ecologic, climatic, and geomorphic processes. In general, a few key factors combine to limit our ability to quantitatively express the hydrologic and sedimentation response of a Himalayan mountainous catchment to land use and land-cover. These include the large inter-annual variability in precipitation, evapotranspiration, the heterogeneity of large catchments, natural sources of instability, characteristic of a geologically and tectonically active young mountain system, together with non-availability of high-quality, long-term data on rainfall, streamflow, and sedimentation. Even when these are available, rigorous experimental and statistical methods to separate the influence of human use from natural variability are required. Well-instrumented and rigorously conducted long-term studies on land use impacts on watershed hydrology are still an exception in India.



### *Hydrologic services*

While explicit reference to the term “hydrologic services” is relatively new in India, the concept has been in practice for a long time. One of the earliest examples of a policy decision in India, specifically recognising and valuing hydrologic services, dates back to 1899. The Periyar River in the princely state of Travancore (now in Kerala) was dammed in 1895 to irrigate drylands in Madras Presidency (now in Tamil Nadu). The catchment area upstream of the dam was gazette as a protected sanctuary. Threats to forest cover from the expansion of tea plantations led to the designation of “wildlife sanctuary” to the catchment area of the reservoir, mainly to regulate the sediment inflow into reservoir.

Another well-known example of managing natural systems for the provision of hydrological services was the conservation of forests to protect water sources of Shimla town from pollution and degradation. This was carried out for many decades in the 19th and 20th century, leading to the establishment of the “Shimla water catchment sanctuary” in 1958, under the Municipality of Shimla.

### *The Plantation era*

In the last 150 years, the need for timber and wood-based raw materials led to the establishment of tree plantations on grasslands, converted natural forests, and degraded natural forests. The species consisted of both native species (such as Teak and Sal, but sometimes planted in sites where they were not originally dominant, especially for former species), as well as exotic species from around the world, especially eucalyptus and acacias from Australia.

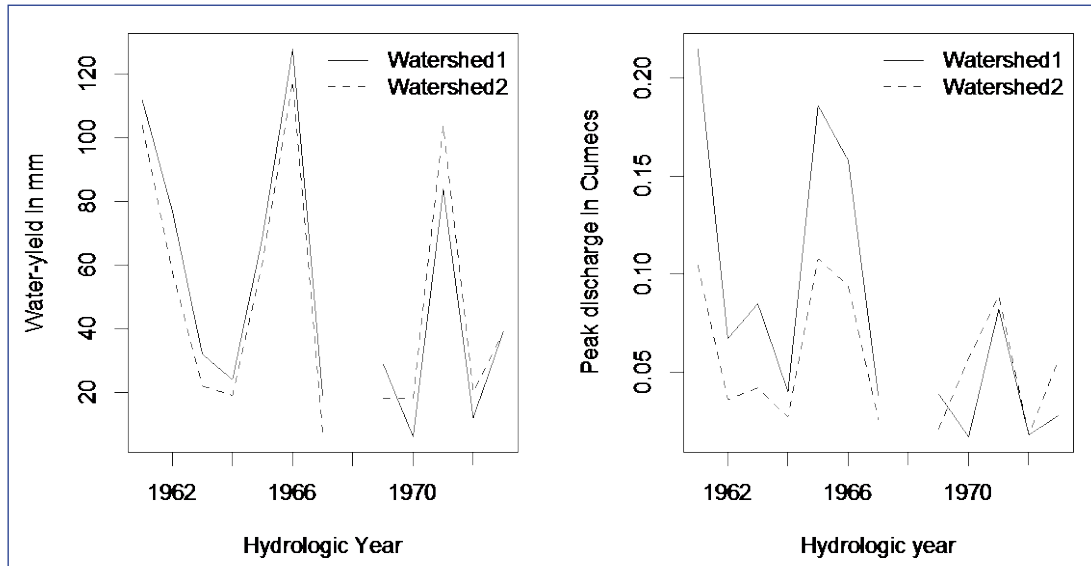
According to Ravindranath et al. (2006), the area under forests and other wooded land in India has increased from 63.93 mha in 1990 to 67.70 mha in 2005, and if one considers that some deforestation was still occurring in this period, the increase in area under plantations would be even more significant. The authors found that this is similar to estimates from the Forest Survey of India. The estimated cumulative area afforested in India during the period 1980-2005 is about 34 mha, at an average annual rate of 1.32 mha (Ravindranath et al 2008), suggesting that India is one of the globally significant leaders in afforestation and reforestation. A series of studies that are briefly described here were in response to questions related hydrologic effects of tree plantations at various stages of their growth.

### *India’s first paired catchment studies*

A pair of small forested catchments (Sal forest clear-felled in 1955 and allowed to regenerate and described as “brush”) near Dehradun were calibrated for 8 years (1961-1968) (Gupta et al. 1980). One forested watershed was then clear-cut and re-afforested with Eucalyptus trees. The flow-recording gauge did not function in the first year after cutting but, subsequently, they estimated that reforestation resulted in 28% reduction of streamflow and 73% reduction in peak flows (see Figure 5).

Curiously, many researchers in this period who reviewed the results from such studies did not seem to be aware or under-played the major role of transpiration in determining hydrologic response as evident in this statement: “Some hydrological responses such as soil and water loss through runoff, interception, infiltration, and soil moisture under different forest influences in experimental basins of India were reviewed. These studies show that the moisture regime of basins can be improved with reforestation and controlled grazing, thus improving the productivity of the land and mitigating the effects of droughts and floods”. “Rainfall, being the primary source of all water, is influenced in its disposal by the vegetation through interception by the plant canopy and its infiltration into the soil, parts of which go to deep percolation, to streamflow and to channel flow, thus influencing the moisture regime both within and outside the soil profile” (Gupta et al. 1980). To their credit, the authors don’t end the review with some possible questions about transpiration demand of trees and

its effects on hydrology. Overall, the emphasis was on peak-flows reductions, and rarely was there an emphasis on low flows or dry-season flows. Furthermore, the size of the catchments studied were often too small in relation to the prevailing climate to sustain perennial flows and this was a constraint that prevented researchers to understand the effects of afforestation on low flows and to better understand evapotranspiration.



**Figure 5.** One of India's first post-independence paired catchment studies in the lower Himalayas (Gupta et al. 1980).

The emphasis in this period was largely on the role of afforestation in decreasing peak runoff. However, one major exception was a study of soil moisture at different depths under Acacia, Eucalyptus, grassland, and fallow land up to 90 cm in a semi-arid area (Gupta et al. 1975). The study concluded that Eucalyptus was drawing moisture from much deeper in the soil, but its implications was not incorporated into the design of more studies or existing catchment studies.

### *The Nilgiris experience*

The upper plateau of the Nilgiris, which originally had high-elevation grasslands, montane evergreen forests called "Sholas", and swamps, was increasingly planted with exotic tree species, especially eucalyptus and Wattle.

### *India's most significant paired catchment study*

Two adjacent similar catchments with grassland and Shola (the natural vegetation), approximately 32 ha each, were selected in 1964 at the Glenmorgan Research Farm of the Central Soil and Water Conservation Research and Training Institute (Udhagamandalam) in the Nilgiri Hills of South India.

These were instrumented in 1968 and calibrated for four years, before one of the catchments was planted with eucalyptus. Over the next few decades, streamflow, soil moisture, and piezometer levels were monitored as the trees were harvested in 1981, allowing to coppice after that. This is considered one of the best-managed and published hydrologic experiments in India to date. It is interesting to see in the course of this long-term experiment, that the early focus was on water yield and peak flows, and the positive impacts of afforestation. However, towards the end of the study, the

emphasis shifted to see the impacts on low flows and reduction in hydrologic services (i.e. hydro-electric power generation).

In addition to the above, Samraj et al. (1977) and Sharda et al. (1998) reported that conversion of grasslands into bluegum plantations reduced annual water yield by 16% during the first rotation and 25.4% during the second rotation, i.e. first generation coppiced bluegum. Moreover, Sikka et al. (2003) emphasized the domination of sub-surface pathways and their implications on low flows. These studies were the first in India to clearly demonstrate at a catchment scale the effects of varying transpiration demands of trees as a function of size-class and age.

### *The Himalayan experience*

The “Kumaon school” of ecosystem ecologists was pioneer in India, in terms of taking a comprehensive view of hydrologic processes, sediment production, and nutrient cycling, all related to the complex vegetation and litter characteristics in the Himalayas (e.g. Pandey et al. 1983, Pathak et al. 1985). They were the first to report that rainfall represented an important source of nutrient cations to ecosystems. Average overland flow was often below 1% of the total incident rainfall, indicating that these catchments are “subsurface flow systems”, attributing sediments to large landslides rather than overland flow (Singh et al. 1983).

Negi et al. (1998) reviewed some aspects of partitioning rainfall into interception, stem-flow, and throughfall across species in the Central Himalayas, concluding that interception from conifers was as high as 30%, compared to 20% or lower in broad-leaved species. Furthermore, the authors emphasized that sub-surface flows are more relevant in the Himalayan systems. Similarly, Pathak et al. (1985) noted the influence of species on streamflow, throughfall, and interception, concluding that interception was between 8.1 to 25% of rainfall. They also conclude that overland flow was low for all forests and that forest hydrology is dominated by subsurface flow systems and, consequently, they are particularly susceptible to the effects of deforestation on the hydrologic cycle. In their words, after deforestation the pathways could shift more towards overland flow. However, infiltration rates reported in Himalayan studies are generally high, and overland flow is rare. For example, Rai and Sharma (1998) also report very low overland flow in agro-forestry systems compared to agricultural areas on Eastern Himalayas.

Reportedly, the first hydrological monitoring station in the Himalayas in an undisturbed Pine forest catchment of 1.1 km<sup>2</sup>, at an elevation of 1,615 m.o.s.l. in Central Himalayas, was established by Kumaon University and Oxford Polytechnic at Almora in 1987 (Haigh et al. 1990). The analyses of hourly data from a Himalayan forested catchment were a pioneer contribution from this study. They reported that discharge response to rainfall was quick, within an hour. They also state that “it is, of course, no coincidence that most flow minima are achieved in the late afternoon, when both evaporation and transpiration rates are the highest”. To the author’s knowledge, this is the first study to explicitly report diurnal cycle in streamflow in India, attributed to evapotranspiration.

### *Direct measurements and modelling of transpiration and evapotranspiration*

The growing concern over the negative effects of Eucalyptus, which was planted all over India, required rigorous measurements of transpiration at the scale of trees and tree-stands. Pioneering independent work by Kallarackal et al. (1997a, 1997b) and Calder et al. (1986, 1993, 1997, 1998), indicated the plasticity of transpiration rates by eucalyptus in response to moisture availability, with annual rates exceeding the total rainfall in semiarid sites, where tree roots had access to groundwater. Stomatal conductance measurements showed that the increase in atmospheric vapor pressure deficit induced stomatal closure and was possibly regulated by leaf-water potential. Kallarackal’s (1997a, 1997b) results from a 4-year-old coppiced plantation showed that water loss from plantations ranged between 2.5 and 6.5 mm day<sup>-1</sup>, depending on the season, estimating annual transpiration to

be over 90% of precipitation. The authors concluded, from photosynthesis measurements, that the dry season did not affect photosynthetic rate on a leaf unit area basis. However, the collaboration between ecophysiolgists working on individual trees and wood stands, and catchment hydrologists, in this period could have been very fruitful but it did not occur.

### *The beginnings of ecohydrology in India*

A series of studies using both rigorous measurements and modeling in the last fifteen years, located in humid Western Ghats and dry forests east of the Western Ghats in Karnataka, have added much to our knowledge of hydrologic processes and hydrology from evergreen and deciduous forests. These include the first observations of the relevance of large macro-pores or soil pipes (Putty and Prasad 2000), a distinct feature of humid forests and converted sites in Western Ghats, in determining runoff responses, which is sub-surface but very quick, and could be confused with overland flow by cursory examination of hydrographs. The above brought into question the relevance of assuming “average” infiltration characteristics of any landcover type based on limited measurements. Putty and Prasad (2000) also suggested that afforestation activities could damage soil pipes, resulting in substantial overland flow, a new mechanism for generating surface runoff.

The pioneering work of Sekhar et al. (2004) in a semi-arid region, combining well observations and groundwater modeling, showed that groundwater regimes are quite independent of surface catchment boundaries and that over-exploitation of groundwater in agricultural sites could be resulting in deeper groundwater levels under forests in neighbouring basins; this was further supported by simulations and observations in the forest itself.

Hydrologic measurements in the dry forests east of the Western Ghats was initiated for the first time (~2003) by two projects, which were Indo-UK and Indo-French collaborative projects led by ATREE, National Institute of Hydrology-Belgaum and IISc, respectively. The ATREE team indicated the difficulty of selecting catchments of sufficient size for hydrologic studies as even in protected streams with checkdams (Krishnaswamy et al. 2006a, 2006b), sometimes to create water-holes and ostensibly to trap sediment.

Measurements of soil properties and infiltration in Bandipur revealed that the density of human and cattle trails has a major impact on increasing surface runoff in degraded sites (Mehta et al. 2008). The trails occupied a small part of the landscape but had a major impact on runoff because such hydrologic variable is a very small percentage of the total annual hydrologic budget to begin with. Catchments with a higher length of trails and roads showed distinct responses to rainfall, compared to sites with lower density of trails. They estimated that 7-h rainfall events will cause the trails to generate Hortonian overland flow just about every year, but will rarely result in Hortonian flow from the off-trail areas. They show that trail density is also higher in degraded watersheds, thereby increasing the chances and contribution of Hortonian flow in storm runoff events.

In the humid parts of the Western Ghats, infiltration measurements took place in the late 1990s across diverse forest plantations and soil types upto 1.5m. Subsequently, the determined  $K^*$  was then linked to rainfall intensity–duration–frequency (IDF) characteristics, to infer the dominant stormflow pathways (Bonell et al. 2010). This study revealed that plantations still retained the “memory” of multi-decadal use and that Black soils (Vertisols), had low permeabilities irrespective of land cover. Furthermore, only the natural forest surface soils had permeabilities high enough to cope with intense rains (one in 25 or one in fifty year storms).

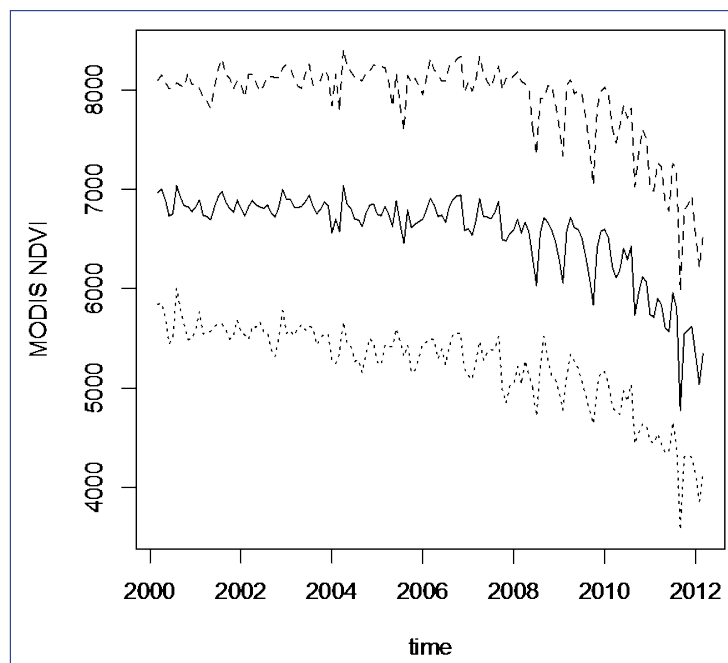
The Indo-French collaborative work in the 4.1-km<sup>2</sup> Moolehole experimental catchment in the sub-humid Bandipur forests (Figure 6), has added much to our knowledge of ecohydrology of semi-arid forests in India. In these forests, which are globally recognized for their large mammal wildlife (especially tigers and elephants), the estimated evapotranspiration is between 80 and 90%, and recharge to groundwater from both direct and indirect flashy streamflow is typically less than 10% of annual rainfall. Furthermore, the deep regolith is a major water reservoir that provides upto 100 mm



of water for transpiration by trees in a region where rainfall is only 800-1000 mm yr<sup>-1</sup>. Their work also suggests that regolith depth variability is an important determinant of groundwater table response to rainfall. One could extend this further and suggest that vegetation access to water itself is a function of regolith depth. Figure 7 shows the trends in Bandipur MODIS, indicating a significant decline in leaf area during recent years, with average and one-standard-deviation intervals (based on spatial variability across the 1 km<sup>2</sup> pixels, covering 130 km<sup>2</sup>).



**Figure 6.** Dry deciduous forests in Bandipur Tiger Reserve. Storage of moisture and ground water in deep regolith sustains these forests in the dry-season. Regolith depth may be an important determinant of spatial variability in water availability for trees and may provide upto 100 mm annually. Photo by author.



**Figure 7.** Response of deciduous forests to depleting moisture availability in Bandipur (graph by author).



Previous work had established dependence of trees in this site on stored groundwater in the regolith and also possible movement of groundwater from this area to a neighboring agriculture basin, where groundwater extraction is very high. Observations and simulations suggest that groundwater levels may have dropped by 4.5 m between 2004 and 2008 (Ruiz et al. 2010).

Sekhar et al. (2004) reported that exploitation of groundwater in the agricultural areas outside the forest was potentially affecting groundwater levels in a neighboring basin in the Bandipur forests. Whether the negative trends canopy biomass in the Bandipur area shown in Figure 7 are due to loss of access to groundwater, is something that needs to be investigated. If this was the case, forests in semiarid parts of India, adjacent to over-exploited agricultural areas, could suffer ecohydrological and ecological degradation. Furthermore, groundwater levels in observation wells became deeper after around 2004, suggesting possible stress to deep-rooted trees, which depend on groundwater to survive.

The Indo-UK collaborative project looked at (1) remnant tropical evergreen forest (NF), (2) heavily-used former evergreen forest, which now has been converted to tree savanna known as degraded forest (DF), and (3) exotic Acacia plantations (AC, *Acacia auriculiformis*) on degraded former forest land.

In the humid Western Ghats, land cover differences translated into distinct hydrological responses at various temporal scales (Krishnaswamy et al. 2012): on an annual scale, Natural Forests (NF) converted  $28.4\% \pm 6.41$  (st. dev.) of rainfall into total streamflow, in comparison to  $32.7\% \pm 6.97$  in Acacia plantations (Ac) and  $45.3\% \pm 9.61$  in degraded or multiple use forests (DF). However in terms of quickflow, the degraded site had the highest and the natural forest the lowest. Delayed flow was most evident in the natural forest. Their analyses suggested the existence of alternative stormflow pathways with multiple lags, with peaks occurring between ~12 and 24 h. Their cross-correlations and lag regression approaches indicate a lag of 4 h in NF, compared to respective bimodal peaks at 1 and 16 h in AC, and 1 and 12 h in DF. The long time lags for NF are especially suggestive of deep sub-surface stormflow and groundwater, as the contributing sources to the storm hydrograph. They further speculate that “As potential and actual evapotranspiration is likely to be depressed during the monsoon, differences in streamflow and runoff responses between land cover types is largely attributed to differences in soil infiltration and hydrologic pathways”, although no direct evidence is presented. However their study was a space for time substitution type, and attributed differences to land cover effects between sites, with different current land cover/land use to be interpreted with some caution.

In the Western Ghats of India, the Indo-UK team (Krishnaswamy et al., 2013) examined the hydrologic responses and groundwater recharge and hydrologic services linked with the three ecosystems mentioned above (1 Instrumented catchments ranging from 7 to 23 ha), representing the three land covers (3 NF, 4 AC, and 4 DF, in total 11 basins). They were established and maintained between 2003 and 2005 at three sites in two geomorphological zones, Coastal and Up-Ghat (Malnaad). Four larger (1-2 km<sup>2</sup>) catchments downstream of the headwater catchments in the Malnaad, with varying proportions of different land covers and providing irrigation water for areca-nut and paddy rice were also measured for post-monsoon baseflow. They observed higher frequency and longer duration of low-flows under NF, when compared to the other more disturbed land covers. Groundwater recharge was estimated using water balance during the wet season in the Coastal basins under NF, AC, and DF, with values to be 50%, 46% and 35%, respectively, whereas and in the Malnaad it was 61%, 55%, and 36%, respectively. Soil water potential profiles using zero flux plane methods suggest that during the dry-season, natural forests depend on deep soil moisture and groundwater. In some of the same sites, Venkatesh et al. (2011) reported that significant differences in soil moisture with depth were observed under forested watershed, whereas no such changes with depth were noticed under acacia and degraded land covers, hinting at dependence of deep-rooted natural forests on deeper sources of moisture, compared to shallow rooted systems.

Catchments with higher proportions of forest cover upstream were observed to sustain flow longer into the dry-season. These hydrologic responses provide some support towards the “infiltration-

evapotranspiration trade-off” hypothesis, in which differences in infiltration between land cover and evapotranspiration determines the differences in groundwater recharge, low-flows, and dry-season flow (Bruinjeel 2004). Groundwater recharge was most temporally stable under natural forest, although substantial recharge occurred under all three ecosystems, which helps to sustain baseflow in rivers of higher order downstream.

### 7.3 Politics

Forests and wildlife are on the concurrent list in India and both federal (centre) and states can make laws and policies based on them. The National Forest Policy (1988) explicitly mentions protection of forests for soil conservation and catchment of rivers and reservoirs. These include the various Forest Acts in the state and the central Forest Conservation Act (1981) that requires central permission for diversion of forest land in development projects. There is also provision for protection to upper catchments in hill areas due to state government legislation, such as the Tamil Nadu Hill Areas (Preservation of Trees) Act.

The Wildlife Protection Act (1972) allows for manipulation of vegetation and water bodies inside protected areas (over 5% of India), authorized by the Chief Wildlife Warden of the state *if it is to the benefit of wildlife*. A 1991 amendment to the Wildlife Protection Act specifies that, in wildlife sanctuaries, the chief wildlife warden must certify that any manipulation does not harm wildlife, and that the manipulation needs to be approved by the state government. Under this legal and management umbrella, streams have been dammed, fire-lines cut, grasslands maintained through management, old tree plantations thinned, and weeds or invasive species cleared: all of these have implications on forest hydrology.

Under the 1972 Act, one could argue that manipulation of water resources or vegetation that directly or indirectly harms any protected species, including aquatic species, is prohibited within protected areas and to some extent outside. **Sec 29** states that “No person shall destroy, exploit, or remove any wildlife, including forest products, from a sanctuary, or destroy, damage, or divert the habitat of any wild animal by any act whatsoever, or divert, **stop, or enhance the flow of water into or outside the sanctuary**, except under and in accordance to a permit granted by the Chief Wildlife Warden, and no such permit shall be granted unless the State Government is satisfied in consultation with the Board that such removal of wildlife from the sanctuary **or the change in the flow of water into or outside the sanctuary** is necessary for the improvement and better management of wildlife therein, authorises the issue of such permit”. Thus, manipulation of forest and grassland vegetation that indirectly changes the hydrology to the detriment of riparian vegetation of aquatic or terrestrial wildlife is not allowed. However, so far this legal protection for maintaining ecohydrology for the benefit of endangered species has not been invoked to influence forest management practices, but could be used by civil society to legally challenge habitat manipulation that changes ecohydrology.

In 1996, the Supreme Court of India in a landmark judgement based on a citizen’s petition, banned the felling of trees without central permission on public or private land that could be defined as “forest”. Although it was motivated by the need to stem deforestation, this had and still has implications for any large-scale removal of trees, including invasive or exotic species, even for desirable changes in forest hydrology.

In the state of Tamil Nadu, the government has acted upon a recent ruling of the Madurai High Court (informed by growing realization of the ecological, and to some extent hydrological, consequences of large scale wattle and eucalyptus plantations in the montane grasslands) is cautiously pursuing a policy of experimental removal of these exotic tree plantations.

Finally, in terms of legal aspects of forest-water issues, the recent setting up of the National Green Tribunals under the **National Green Tribunal Act (2010)**, created under an Act of the Parliament of India, enables the creation of a special tribunal to handle the expeditious disposal of the cases pertaining environmental issues. It draws inspiration from the India’s constitutional provision of Article

21, which assures the citizens of India the right to a healthy environment. This is likely to inform many aspects of forest-water linkages, including protection of catchments and ecohydrological functions of forests.

## 7.4 Climate change and the future of forestry & forest research

### *Green India Mission*

The National Mission for Green India (GIM) is one of the eight Missions outlined under the National Action Plan on Climate Change (NAPCC). Currently under this programme, India is planning to reforest and restore 10 million hectares in both existing “degraded” forest and non-forested areas as part of the Green India Mission to sequester carbon and help regulate atmospheric CO<sub>2</sub> concentrations. However, we know very little about the synergies and trade-offs between carbon and water cycles, and how this is influenced by phenological responses that are driven by changes in climate, both historical and in the future. Establishing monitoring sites to assess the impact of afforestation, especially in semiarid ecosystems, should be a priority and encouraging restoration of grasslands and savannah-woodlands rather than dense tree-plantations should be considered as part of the experiments that would hopefully lead to changes in policy and management.

### *Invasive species in India’s forests: A major threat*

Across India, forests have been transformed by invasive species (Singh 2005, Kohli et al. 2006, Hiremath and Sundaram 2005, Kannan et al. 2013). This is particularly evident in sub-humid forests. Species such as Lantana (Figure 8), which is a significant part of the biomass on a per-unit-area basis, could potentially have changed soil moisture regimes through evapotranspiration. The impact of Lantana on linked plant carbon and water relations, and the effects of it on forest hydrological responses should be investigated urgently.

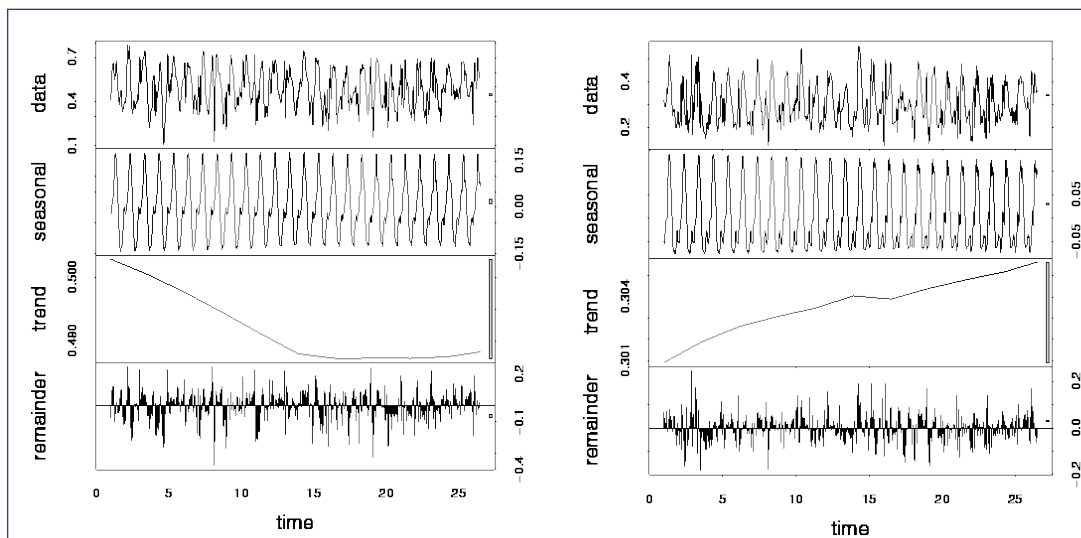


Photos: Bharat Sundaran

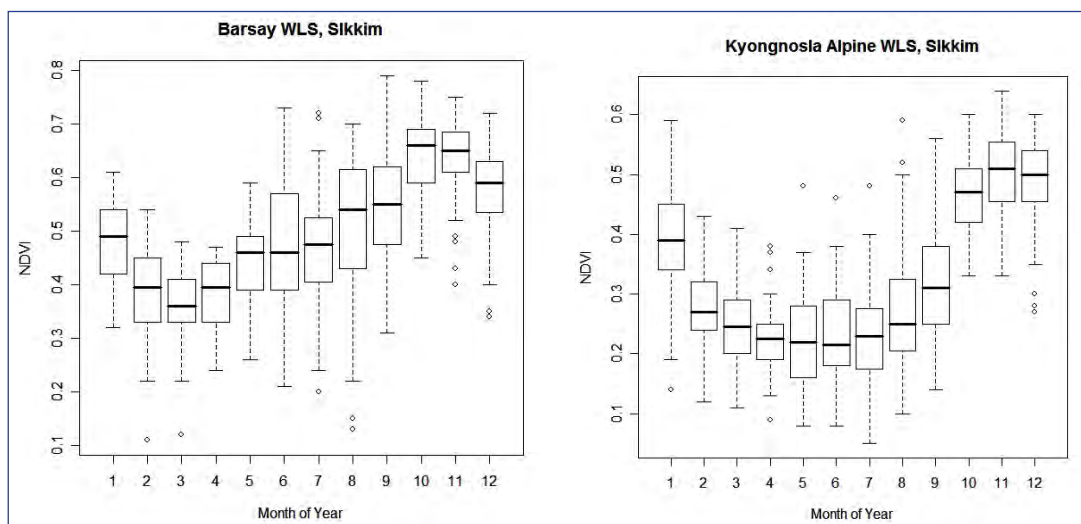
**Figure 8.** India’s remnant forests, especially in the sub-humid zones have been invaded by invasive species such as Lantana which potentially have transformed soil moisture and evapotranspiration regimes.

### *Climate change, climate variability, and Indian forests*

The Indian Monsoon systems are changing with shifts in the role of ocean-atmosphere phenomena such as ENSO and Indian ocean Dipole. Additionally, it has been observed a decrease in the Monsoon since the 1950s, but rainfall events are increasing (Krishnaswamy et al. 2014, Guo et al. 2015). Some of these trends are poorly simulated by climate models thus increasing uncertainty about future trends. However, even though there is uncertainty about precipitation, there are no doubts about warming trends, especially in the Himalayas (Shreshta et al. 2012). Browning has been reported in the Himalayan forests in recent decades in response to warming (Krishnaswamy et al. 2014) and supported by ground-observations of leaf-water potential in dry years (Singh et al. 2006); the implications of these for eco-hydrology in the Himalayas needs investigation. Figure 9 shows the findings of Krishnaswamy et al. (2014) on browning trends in the Himalayas. Andermann et al. (2012) reported a deep ground-water reservoir in the Himalayas that regulates streamflow at larger spatial scales. They infer that water is stored temporarily in a reservoir with a response time of about 45 days, hinting at the role of fractured basement aquifers. How warming and precipitation changes will alter the role of Himalayan forests in hydrology (see Figure 10) at different temporal and spatial scales, and whether this groundwater contribution to streamflow will alter in the future is unknown.



**Figure 9.** Both mild browning and greening in response to recent climate change are both observed in different Himalayan sites (Krishnaswamy et al. 2014).



**Figure 10.** How does the seasonal phenology of Himalayan forests influence hydrologic fluxes? NDVI based phenology cycle for two protected areas in Sikkim, Eastern Himalayas. Data source: Jagdish Krishnaswamy, Robert John Chandran, and Manish Kumar (ATREE).



### *The way forward*

India and its scientific institutions have lost excellent opportunities to become world leaders in experimental hydrology and eco-hydrology, especially given the long history of the Indian Forest Service and the Forest Research Institute, besides other institutions. Even when some sites were setup by dedicated researchers, they were not maintained beyond 5-10 years. We need to foster a culture of collaboration and shared sites to restore forest hydrologic research to international standards in India.

The failure to maintain long-term monitoring sites in different eco-climatic zones of the country is one of the reasons for our inability to predict future hydrologic responses to land-use and land-cover changes, as well as climate change and other aspects of global change such as nitrogen deposition and aerosols and pollutants. It is obvious that we must quickly establish hydrologic observatories in diverse natural and managed ecosystems at various spatial scales. The entire network of gauging stations maintained by the Central Water Commission (CWC) and state agencies must be open to scrutiny for quality control, especially their rating curves, and calibrations. If we do not improve the quality of data collection at state managed gauging stations, Indian hydrology will be the loser, as no amount of sophisticated modeling can make up for poor quality data. Monitoring of both ground and surface water and soil moisture linked to hydrologic response from transpiration in trees to catchment response at larger scales linked to high-resolution, remotely sensed time-series, should be initiated in different eco-climatic zones immediately. New techniques such as salt-dilution and continuous monitoring of electrical conductivity offer good alternatives to stream gauging in remote sites in the Himalayas (Figure 11).



**Figure 11.** Linking tree water functions with catchment hydrology is an important way forward for ecohydrologists in the Himalayas and the Western Ghats in India (e.g from author's and his student Manish Kumar's instrumented sites in Sikkim, Eastern Himalayas). Photos by: Manish Kumar.

Institutions such as the Ministry of Earth Sciences and state agencies should set aside resources for long-term maintenance of well-instrumented catchments by research institutions and NGOs, which are already in existence. There is an urgent need to train and empower NGOs and local communities to monitor streams and wells with simple but rigorous techniques, as India is very diverse and we need to generate base-line information quickly. Citizen science can play a big role in complementing what detailed hydrologic studies can accomplish.

Finally, India needs a culture of collaboration among hydrologists, with links to experienced hydrologists abroad and establish hydrologic observatories that cater to a range of disciplines and techniques and reach out to communities whose water resources are under threat.



## 7.5 Acknowledgments

The author would like to thank the jointly administered Changing Water Cycle programme of the Ministry of Earth Sciences (Grant Ref: MoES/NERC/16/02/10 PC-11), the Government of India, and the Natural Environment Research Council, United Kingdom (Grant Ref: NE/I022450/1), for their financial support during the course of the preparation of this chapter. The Department of Biotechnology, Government of India, supported our work in Sikkim, which is described in this chapter. The author dedicates this chapter to our colleague and mentor, Professor Mike Bonell, who passed away on July 11th, 2014. The author also thanks Susan Varughese, Manish Kumar, Nachiket Kelkar, and Mayukh Dey for their help editing, adding references, data entry, and finding citations. Finally, many thanks to Joaquin Jafif of UNESCO for his kind help with editing and correcting this chapter.

## 7.6 References

- Andermann, C., Longuevergne, L., Bonnet, S., Crave, A., Davy, P., & Gloaguen, R. (2012). Impact of transient groundwater storage on the discharge of Himalayan rivers. *Nature geoscience*, 5(2), 127-132.
- Benskin, E. (1930) Forest and Stream Flow. *Indian Forester*, 56, p. 440-442 & 521-523.
- Bonell M., Purandara B.K., Venkatesh B., Krishnaswamy, J., Acharya H.A.K., Singh U.V., Jayakumar R. & Chappell N. (2010), "The impact of forest use and reforestation on soil hydraulic conductivity in the Western Ghats of India: Implications for surface and sub-surface hydrology", *Journal of Hydrology*, Vol. 391, pp: 47–62.
- Bruijnzeel, L.A., 2004. Hydrological functions of tropical forest: not seeing the soil for the trees? *Agriculture, Ecosystems and Environment* 104, 185–228. doi:10.1016/j.agee.2004.01.015.
- Calder, I. R. (1986). Water use of eucalypts—A review with special reference to south India. *Agricultural Water Management*, 11(3), 333-342.
- Calder, I. R. (1998). Water use by forests, limits and controls. *Tree physiology*, 18 (8-9), 625-631.
- Calder, I. R., Hall, R. L., & Prasanna, K. T. (1993). Hydrological impact of Eucalyptus plantation in India. *Journal of Hydrology*, 150(2), 635-648.
- Calder, I. R., Rosier, P. T., Prasanna, K. T., & Parameswarappa, S. (1997). Eucalyptus water use greater than rainfall input—a possible explanation from southern India. *Hydrology and Earth System Sciences*, 1(2), 249-256.
- Food & Agriculture Organization, (FAO, UN). 2006. Global Forest Resources Assessment 2005, Rome. URL: [www.fao.org/docrep/009/a0773e/a0773e00.htm](http://www.fao.org/docrep/009/a0773e/a0773e00.htm).
- Gadgil, M., & Guha, R. (1993). *This fissured land: an ecological history of India*. Univ of California Press.
- Goldewijk, K. and N. Ramankutty (2004). Land use changes during the past 300 years, in *Natural Resources Policy and Management*, ed. by W. Verheye, Encyclopedia of Life Support Systems (EOLSS), Eolss Publishers, Oxford, UK, [<http://www.eolss.net>]
- Guo, L., Turner, A. G., and Highwood, E. J.:2015. Impacts of 20th century aerosol emissions on the South Asian monsoon in the CMIP5 models, *Atmos. Chem. Phys.*, 15, 6367-6378, doi:10.5194/acp-15-6367-2015, 2015.
- Gupta VK, Waymire E, Wang CT. 1980. A representation of an instantaneous unit hydrograph from geomorphology. *Water Resources Research*, 16, 855–862.

- Gupta, J.P., Wasi Ullah and V.C. Issac. (1975) A note on some soil moisture changes under permanent vegetative cover. *Indian Forester*, Sept., 523-526.
- Haigh, M., Rawat, J., Bisht H. (1990) Hydrological impact of deforestation in the central Himalaya. *Hydrology of Mountainous Areas (Proceedings of the Strbské Pleso Workshop, Czechoslovakia, June 1988)*. IAHS Publ. No. 190.
- Hiremath, A. J., & Sundaram, B. (2005). The fire-lantana cycle hypothesis in Indian forests. *Conservation & Society*, 3, 26-42.
- Jha, C. S., Dutt, C. B. S., & Bawa, K. S. (2000). Deforestation and land use changes in Western Ghats, India. *Current Science*, 79(2), 231-237.
- Kallarackal, J., & Somen, C. K. (1997a). An ecophysiological evaluation of the suitability of *Eucalyptus grandis* for planting in the tropics. *Forest Ecology and Management*, 95(1), 53-61.
- Kallarackal, J., & Somen, C. K. (1997b). Water use by *Eucalyptus tereticornis* stands of differing density in southern India. *Tree Physiology*, 17(3), 195-203.
- Kannan, R., Shackleton, C. M., & Shaanker, R. U. (2013). Reconstructing the history of introduction and spread of the invasive species, Lantana, at three spatial scales in India. *Biological Invasions*, 15(6), 1287-1302.
- Kohli, R. K., Batish, D. R., Singh, H. P., & Dogra, K. S. (2006). Status, invasiveness and environmental threats of three tropical American invasive weeds (*Parthenium hysterophorus* L., *Ageratum conyzoides* L., *Lantana camara* L.) in India. *Biological Invasions*, 8(7), 1501-1510.
- Krishnaswamy J, Mehta VK, Joshi P, Rakesh KN, Suparsh PN. 2006a. Comparative hydrology in forested South India: methodological approaches to unique challenges. In *Hydrology and Watershed Services in the Western Ghats of India. Effects of Land Use and Land Cover Change*, Krishnaswamy J, Lele S, Jayakumar R (eds). Tata McGrawHill: New Delhi; 265–295.
- Krishnaswamy J., Bonell M., Venkatesh B., Purandara B. K., Lele S., Kiran M.C., Reddy V., Badiger S. & Rakesh K. N. (2012), "The rain–runoff response of tropical humid forest ecosystems to use and reforestation in the Western Ghats of India", *Journal of Hydrology*, Vol. 472–473, pp: 216–237
- Krishnaswamy J., Bonell M., Venkatesh B., Purandara B. K., Rakesh K. N., Lele S., Kiran M.C., Reddy V. & Badiger S. (2013), "The groundwater recharge response and hydrologic services of tropical humid forest ecosystems to use and reforestation: Support for the "infiltration–evapotranspiration trade-off hypothesis"", *Journal of Hydrology*, Vol. 498, pp: 191–209
- Krishnaswamy J., Milind Bunyan, Vishal K. Mehta, Niren Jain & K. Ullas Karanth (2006b), "Impact of iron ore mining on suspended sediment response in a tropical catchment in Kudremukh, Western Ghats, India", *Forest Ecology and Management*, Vol. 224, pp: 187–198
- Krishnaswamy, J.**, R. John and S. Joseph. (2014) Consistent response of vegetation dynamics to recent climate change in tropical mountain regions. *Global Change Biology*, 20, 203-215.
- Kumar, V. R. 2010. Colonizing Greens: Political Economy of Deforestation in Colonial South India 1800-1900. *A Biannual Journal of South Asian Studies*, 226.
- Laurance, W.F. (2007) Forest destruction in tropical Asia. *Curr Sci* 93, 1544–1550.
- Lynch, O. J., & Talbott, K. (1995). *Balancing acts: community-based forest management and national law in Asia and the Pacific*. World Resources Institute.
- Mehta, V. K., Sullivan, P. J., Walter, M. T., Krishnaswamy, J., & DeGloria, S. D. (2008). Impacts of disturbance on soil properties in a dry tropical forest in Southern India. *Ecohydrology*, 1(2), 161-175.

- Menon S and Bawa, K.S. 1997. Applications of geographic information systems, remote sensing and a landscape ecology approach to biodiversity conservation in the Western Ghats. *Current Science*, 73: 134 – 136.
- Menon, S., Pontius, R. G., Rose, J., Khan, M. L. and Bawa, K. S. (2001), Identifying Conservation-Priority Areas in the Tropics: a Land-Use Change Modeling Approach. *Conservation Biology*, 15: 501–512. doi: 10.1046/j.1523-1739.2001.015002501.x
- Negi G. C. S., Rikhari H. C. & Garkoti S. C. (1998), “The hydrology of three high-altitude forests in Central Himalaya, India: A reconnaissance study”, *Hydrological Processes*, Vol. 12, pp: 343-350.
- Pandey, A. N., Pathak, P. C., & Singh, J. S. (1983). Water, sediment and nutrient movement in forested and non-forested catchments in Kumaun Himalaya. *Forest ecology and management*, 7(1), 19-29.
- Pathak, P. C., Pandey, A. N., & Singh, J. S. (1985). Apportionment of rainfall in central Himalayan forests (India). *Journal of hydrology*, 76(3), 319-332.
- Pearson, R.S. (1907) The level of subsoil waters with regard to forest. *Indian Forester*, 33, 57-69.
- Putty M.R.Y. & Prasad R. (2000), “Understanding runoff processes using a watershed model—a case study in the Western Ghats in South India”, *Journal of Hydrology*, Vol. 228, pp: 215–227
- Putty M.R.Y. & Prasad R. (2000), “Runoff processes in headwater catchments—an experimental study in Western Ghats, South India”, *Journal of Hydrology*, Vol. 235, pp: 63–71
- Puyravaud, J. P., Davidar, P., & Laurance, W. F. (2010). Cryptic destruction of India’s native forests. *Conservation Letters*, 3(6), 390-394.
- Rai, S. C., & Sharma, E. (1998). Hydrology and nutrient flux in an agrarian watershed of the Sikkim Himalaya. *Journal of Soil and Water Conservation*, 53(2), 125-132.
- Ravindranath, N.H., N.V. Joshi, R. Sukumar and A. Saxena. (2006) Impact of climate change on forest in India *Current Science*, Vol. 90 No. 3, pp 354-361.
- Ravindranath, N H., R K Chaturvedi and I.K. Murthy. (2008) Forest conservation, afforestation and reforestation in India: Implications for forest carbon stocks. *Current Science*, Vol. 95, No. 2 / 25.
- Ruiz, L., Varma, M. R., Kumar, M. M., Sekhar, M., Maréchal, J. C., Descloitres, M., ... & Braun, J. J. (2010). Water balance modelling in a tropical watershed under deciduous forest (Mule Hole, India): Regolith matrix storage buffers the groundwater recharge process. *Journal of Hydrology*, 380(3), 460-472.
- Saberwal, V.K. (1999) *Pastoral politics*. Oxford Univ. Press.
- Samra, J. S., Sikka, A. K., & Sharda, V. N. (2001). Hydrological implications of planting bluegum in natural shola and grassland watersheds of southern India. In *Sustaining the Global Farm. Selected papers from 10th International Soil Conservation Organization meeting held at Purdue University* (pp. 338-343).
- Samraj, P., S. Chinnamani, and B. Haldorai. (1977) Natural versus man-made forest in Nilgiris with special reference to run-off, soil loss and productivity. *Indian Forester*, July, 460-465.
- Sekhar, M., Rasmi, S. N., Sivapullaiah, P. V., & Ruiz, L. (2004). Groundwater flow modeling of Gundal sub-basin in Kabini river basin, India. *Asian Journal of Water, Environment and Pollution*, 1(1), 65-77.
- Sharda V.N., Samraj P., Samra J.S. & Lakshmanan V. (1998), “Hydrological behaviour of first generation coppiced bluegum plantations in the Nilgiri sub-watersheds”, *Journal of Hydrology*, Vol. 211, pp: 50–60

Shrestha UB, Gautam S, Bawa KS (2012) Widespread Climate Change in the Himalayas and Associated Changes in Local Ecosystems. PLoS ONE 7(5): e36741. doi: 10.1371/journal.pone.0036741

Sikka A.K., Samra J.S., Sharda V.N., Samraj P. & Lakshmanan V. (2003), "Low flow and high flow responses to converting natural grassland into bluegum (*Eucalyptus globulus*) in Nilgiris watersheds of South India", Journal of Hydrology, Vol. 270, pp:12–26

Singh, J. S., Pandey, A. N., & Pathak, P. C. (1983). A hypothesis to account for the major pathway of soil loss from Himalaya. *Environmental Conservation*, 10(04), 343-345.

Singh, K. P. (2005). Invasive alien species and biodiversity in India. *Current Science*, 88(4), 539.

Singh, S.P., D.B. Zobel, S.C. Garkoti, A. Tewari & C.M.S. Negi (2006). Patterns in water relations of central Himalayan trees. *Tropical Ecology* 47, 159-182.

Sivaramakrishnan, K. (2009). Forests and the environmental history of modern India. *The Journal of Peasant Studies* 36.2: 299-324.

Venkatesh B., Lakshman N., Purandara B.K. & Reddy V.B. (2011), "Analysis of observed soil moisture patterns under different land covers in Western Ghats, India", Journal of Hydrology, Vol. 397, pp: 281–294

# Chapter 8. Forest Management and Water in Malaysia

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## 8.1 Introduction

The tropical rain forest of Malaysia is one of the most complex and unique ecosystems in the world. This richness is reflected in a number of ecological study plots established in the country. For instance, there are 814 species of trees enumerated in a 50-hectare plot in Pasoh, Peninsular Malaysia, and more than 1,200 species identified in a 52-hectare plot in Lambir, Sarawak. A large expanse of tropical rain forest primarily occupies the hills and mountains; this type of forest typically forms the protected spines of the country in both Peninsular Malaysia and East Malaysia, on the island of Borneo. Endemism in plant species is particularly high in montane habitats and edaphic habitats like limestone hills and ultra-mafic soils. Overall, for example, 746 of the 2,830 tree species found in Peninsular Malaysia are endemics. Malaysia is also rich in plant genetic resources.

Malaysia's forests are carefully managed according to the principles of sustainable forest management. The goal is to achieve a balance between development and conservation, so that the forest products and services can be obtained in perpetuity. The forests are also managed as a renewable resource on a sustainable yield basis and have contributed significantly to socio-economic development.

According to the Malaysian Timber Industry Board (MTIB), the Malaysian exportation of timber and timber products in 2014 was worth RM 20.5 billion, with furniture contributing RM 8.01 billion. The major timber products are logs, sawn timber, plywood, veneer, and moulding. Based on the Statistics on Commodities (2010), in 2009, Malaysia produced 18,307 x 10<sup>3</sup> m<sup>3</sup> of logs, 3,888 x 10<sup>3</sup> m<sup>3</sup> of sawn timber, 4,156 x 10<sup>3</sup> m<sup>3</sup> of plywood, 846,000 m<sup>3</sup> of veneer, and 301,000 m<sup>3</sup> of moldings. The earnings from the export of major timber products in 2009 were RM 1,967 million in Peninsular Malaysia, RM 2,377 million in Sabah, and RM 6,535 million in Sarawak, for a total of RM 10,879 million. In 2009, the forestry and timber sector accounted for 39,745 jobs in Peninsular Malaysia, 53,217 in Sabah, and 83,834 in Sarawak, for a total of 177,105 workers.

The development of the industry to date has been remarkable, as private sector innovations, backed by the government's facilitation, have enhanced the timber industrial base. Thus, the timber industry has shifted from primary processing to manufacturing (including R&D), so that the country's forest resources and wood-based industries could be developed in a sustainable manner.

Apart from its socio-economic role, the Malaysian forest also provides important environmental protection, including the maintenance of environmental stability, the minimization of damage to rivers and agricultural land by floods and erosion, and the safeguarding of water supplies. It should be emphasized that the success and development of the agricultural sector depend on the protective role of the forests.

Forestry management in Malaysia is committed to the "International Tropical Timber Trade Organization (ITTO)'s Objective Year 2000". The objective was for all trade in tropical timber to be from sustainably managed forests by the year 2000 (ITTO, 1992). ITTO defines sustainable forest management as "the process of managing permanent forest land to achieve one or more clearly specified objectives of management with regard to the production of a continuous flow of desired forest products and services without undue reduction of its inherent values of future productivity and without undue undesirable effects on the physical and the social environment."

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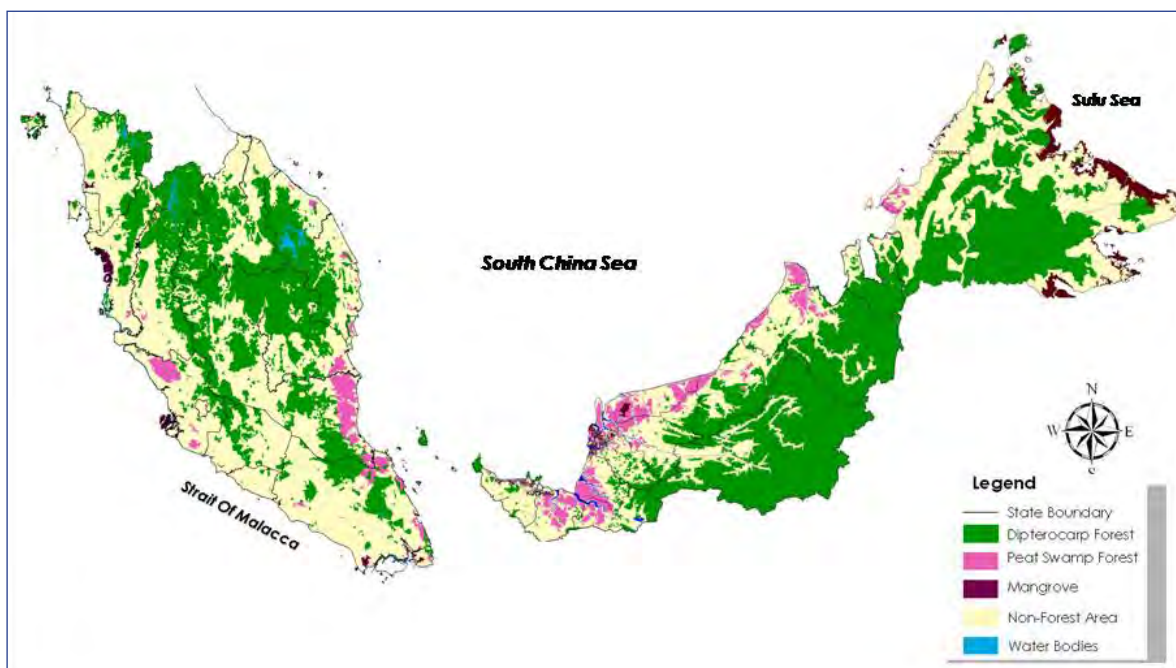
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### 8.1.1 Types of forest

All the three regions in Malaysia -- Sabah, Sarawak, and Peninsular Malaysia -- have rugged inland forest ranges that are mostly untouched due to their isolation and steep terrain. Mixed forests, as well as clearings for settlement and agriculture, are found in the lower areas. Generally, there are three main types of forest in Malaysia (Figure 1), but a more detailed categorization of forest types is provided below.

- 1) **Upper Montane Forest** covers the mountain peaks above 1,700 meters above sea level. There is an abundance of moss and lichen, both at ground level and on tree trunks. This forest type is perpetually damp; the main species are *Pierisovalifolia*, *Rhododendron*, and *Vaccinium*. Under-growth species include *Argostemma* and *Burmannia*.
- 2) **Lower Montane Forest** stretches from 800 meters to about 1,700 meters above sea level. This is less dense at the ground level, but has lush vegetation and rich bio-diversity. The common species are representative of the Fagaceae family, with many of the genera *Quercus*, *Lithocarpus*, *Castanopsis*, and *Lauraceae*.
- 3) **Hill Forest** occurs on the inland mountain ranges from 300 meters to 800 meters above sea level, and is dominated by a variety of dipterocarp species.
- 4) **Lowland Forest** can be found up to elevations of 300 meters above sea level, with thousands of species densely crowded together. The rich biodiversity of Malaysia's lowland dipterocarp forests is evident at all levels, from canopy to ground.
- 5) **Heath Forest** (also known as *kerangas*) is the product of infertile soils. This forest type looks stunted due to low productivity. The main species are *Cassuarina*, *Agathis alba*, *Dacrydium*, *Tristania*, and *Shorea albida*.
- 6) **Mangrove Forest** usually occurs along the coastal area, and is dependent on both saline sea water and mineral-rich fresh water. The mangrove forests are usually largely dominated by a single species of tree in a particular area. A distinctive feature of these trees is their large aerial roots.
- 7) **Peat Swamp Forest** grows on peat in certain coastal areas of Peninsular Malaysia and Sarawak. Peat is partly carbonized humus (decayed vegetation). The upper tree canopy is fairly level at up to about 30 meters, and ground plants are relatively sparse.



**Figure 1.** Forested areas in Malaysia (2010) based on forest type. Inland forest, peat swamp, and mangrove are located in the Permanent Reserves Forest (PRF).

### 8.1.2 Forest plantations

Plantation timber supply is expected to become increasingly important in the future, as the amount of timber from natural forests is expected to decline. Presently, the area approved for forest plantation development in Peninsular Malaysia is 324,417 ha (Forestry Statistics of Peninsular Malaysia, 2013), with substantial new areas at various stages of development. This is complemented by the 1.6 million ha of rubber plantations supporting a diversified industry, particularly furniture, medium density fiberboard, and particleboard.

Forest plantations in Peninsular Malaysia and Sarawak have been developed mainly by government agencies, while the majority of forest plantations in Sabah are being established by the private sector. Currently, the government is encouraging greater private sector participation in the establishment of new forest plantations by providing incentives to prospective developers.

In Peninsular Malaysia, a large-scale forest plantation program known as the Compensatory Forest Plantation Project (CFPP) was launched in 1982. The main objective was to supplement the expected shortage of natural forest timber supply. This project aimed to establish about 82,000 ha of fast-growing hardwood species, such as *Accacia mangium* (Akasia), *Gmelina arborea* (Yemane), and *Paraserianthes falcataria* (Batai), over a 15-year rotation period. However, by the end of 2000, only about 72,000 ha of such plantation forest were successfully established in various states of Peninsular Malaysia.

The Rubber Forest Plantation Project is a joint effort between the Forestry Department of Peninsular Malaysia (FDPM) and the Malaysian Rubber Board (MRB). It started in 1991, with the goal of identifying suitable rubber (*Hevea spp.*) clones that could be grown on a plantation basis for timber production. As of 1998, a total area of 1,667 ha of pilot rubber forest plantations were established in several forest reserves of Peninsular Malaysia.

In 2000, Sabah established about 140,000 ha of forest plantations, comprising approximately 117,000 ha of fast-growing timber species and 23,000 ha of mixed species, while Sarawak established about 30,000 ha forest plantations of mixed species on deforested areas.

### 8.1.3 Water resources and scenarios in Malaysia

There are eight mountain ranges in Peninsular Malaysia: Nakawan, Titiwangsa, Benom, Kedah-Singgora, Bintang, Pantai Timur, Keladang, and Tahan. These highlands originated in the Yunnan mountain high plain of inland China, which then formed a plateau crossing Thailand before extending from north to south in Peninsular Malaysia. These highlands are covered by tropical forests, and the river systems of Peninsular Malaysia flow down from them.

The major rivers in Peninsular Malaysia flow from the main range of Titiwangsa, which spreads across five states: Kelantan, Perak, Pahang, Selangor, and Negeri Sembilan. These are the most important catchment areas contributing to water resources in the western part of Peninsular Malaysia. River Muda, River Bernam, and River Linggi are the major rivers that flow toward Strait of Malacca, while River Pahang, River Rompin, and River Kelantan flow toward South China Sea.

Most inland areas of Sabah and Sarawak (i.e. West Malaysia) are also covered by the mountain ranges. There are combinations of four main ranges in Sabah, Crocker, TrusMadi, Maitland, and Brassey. The mountain ranges in Sarawak are along the border of Sarawak-Kalimantan and of Tama Abu, Kapuas Hulu, Kelintang ranges, and Mountains of Iran and Hose. River Kinabatangan (563 km) is the largest river basin in Sabah, while River Rajang (560 km) is the largest in Sarawak.

Based on the Review of The National Water Resources Study 2000–2050 (NWRS), conducted in 2011, of the total amount of rainfall received on Malaysia's land surface, 51% (1,500 mm) goes to surface runoff, 43% (1,250 mm) evaporates into the atmosphere, while another 6% (192 mm) contributes to groundwater recharge. When analyzed by region – i.e. Peninsular Malaysia, Sabah,

and Sarawak – the percentage of rainfall distributed to each result differs, as shown in Table 1.1 below. Surface runoff and groundwater recharge are highest in Sarawak, while evapotranspiration (ET) is highest in Peninsular Malaysia.

### 8.1.4 Water users in Malaysia

Rivers are the main source of fresh water. The country's rivers play a crucial role in agricultural development and productivity, domestic and industrial water supply, biodiversity, provision of food, transportation, hydropower, and recreation. The main categories of water users are 1) domestic and industry, 2) agriculture, and 3) hydropower; 97% of their combined water supply is from rivers.

**Table 1.1** Contribution of average annual rainfall to surface runoff, ET, and ground water recharge, by region (Source: NWRS 2000–2050, 2011).

Location	Surface runoff (%)	Evapotranspiration (%)	Groundwater recharge (%)	Annual rainfall
Peninsular Malaysia	43	51	6	330 BCM
	(141 BCM)	(170 BCM)	(19 BCM)	
Sarawak	59	34	7	453 BCM
	(267 BCM)	(155 BCM)	(29 BCM)	
Sabah	46	47	7	188 BCM
	(86 BCM)	(87 BCM)	(13 BCM)	
<i>Total</i>	<i>494 BCM</i>	<i>412 BCM</i>	<i>61 BCM</i>	<i>971 BCM</i>

BCM = Billion Cubic Meters per year

The domestic and industrial demand for water supply grew rapidly after 1980s, as industrialization, population and urban growth all increased. Analyzing the 10 years between 1980 and 1990, the agricultural sector was the main water-user, with 78% (1980) and 80% (1990) of the total water use (Table 1.2a). This is followed by the domestic and industrial sectors, with 18% (1980) and 20% (1990) of the total water use (Fauzi, 2000). Irrigation systems in rice paddies created demand, as river water is channeled into the fields through irrigation canals and dam construction.

**Table 1.2a** Water usage measured in 1980 and 1990 by domestic and industry, and agriculture sectors. (Source: NWRS 20-2050, 2011)

Year	Domestic and Industry Sectors	Agriculture Sector
1980	1,300 MCM (18%)	7,400 MCM (80%)
1990	2,600 MCM (20%)	9,000 MCM (78%)

The NWRS included simulations that predicted that demand for water supply in each sector will increase by the year 2020 (Table 1.2b). Besides paddy fields, livestock and aquaculture sectors are also important water users in the food production field. The total water demand for Malaysia in 2010 from The NWRS's study reported that total water demand in the country in 2010 was 14,783 million cubic meters (MCM), which was about 3% of surface runoff that was available (494,000 MCM).

There are 93 dams in Malaysia: 72 are located in Peninsular Malaysia, while another 21 dams are in Sabah and Sarawak. The largest electric utility company in the country, Tenaga Nasional Berhad (TNB), managed 13 dams, constituting 79,142 MCM of freshwater, for hydroelectric power.

### 8.1.5 Water Resource Issues

Malaysia faces several water resource issues, such as supply and demand, river pollution and sedimentation, floods and droughts, alteration of river systems by infrastructural projects, and destruction of highland catchment areas. River pollution is the largest threat to the water supply; the sources of pollution are domestic and industrial sewage, livestock farm effluents, suspended solids from mining, and heavy metals from industrial areas. The government allocated about RM1 billion for the “River Cleaning Project” in Kuala Lumpur to mitigate the polluted water downstream of the river basin. Operations of the water treatment plants located at Semenyih and Cheras were affected by river pollution.

**Table 1.2b** Water usage measured in 2010 and projected for 2020 for all sectors of water users (Source: NWRS 20-2050, 2011).

Sector	Water Usage	
	2010	2020*
Domestic/ Industry (MLD)	14,458	18,618
Paddy fields (MCM)	8,266	9,112
Agriculture other than paddy fields (MCM)	1,113	1,124
Livestock (MCM)	126	175
Aquaculture (MCM)	1,287	1,595

MCM = Million cubic meter per year. MLD = Million liters per day. \* = projected water demand

Another issue is the management of the water supply in relation to the extended period of drought that occurred unexpectedly in this country (1999, 2009, 2010, and 2014). The dry period started during the normally wet months of January to March and extended to early September, with less than normal rainfall during the Southwest Monsoon. This led to a water supply crisis. In the states of Perlis, Kedah, and Selangor there was a shortage of water needed to irrigate rice paddies. The shortage also affected the heavily populated and industrialized states of Pulau Pinang, Selangor, and the Federal Territories of Kuala Lumpur. Selangor has almost reached its maximum capacity for the production of treated water for industries and domestic consumption.

Flood events have also created problems for water supply because the floods have overwhelmed water treatment facilities. Floods due to extreme rainfall during the Northeast Monsoon of November and December, 2006, caused a major loss of usable water in Johor in December 2006 and January 2007. A similar situation occurred in Kelantan, Terengganu, and Pahang in 2014. It is ironic that even though there is an abundance of freshwater available in this country, there is still not enough treated water to meet demands.

In the highlands, especially in the main range areas, the clearing of forests for land development and agricultural activities has resulted in soil erosion and sedimentation downstream. This affects the quality and quantity of the water in rivers, and subsequently the water supply. The over-exploitation of formerly forested lands for agriculture in the Cameron Highlands has been identified as the reason for landslides and major flood events that occurred in 2013.

In Peninsular Malaysia, the Selective Management System (SMS) is applied to forest harvesting. There is a prescription for felling trees along rivers and streams. Forest harvesting is prohibited in water catchment forests at the higher altitudes, as these areas are most sensitive to physical disturbances. Forest harvesting is not allowed in areas at 1000 m or greater elevation or in areas with a slope of more than 40%. However, illegal logging and plantations that involve large areas in the region could be affecting the quality and quantity of water resources.

### 8.1.6 Shifting Water Demand Management in Malaysia

Freshwater is abundant in this country, with an average annual rainfall of 2940 mm. From the population perspective, the rainfall volume is 33,000 m<sup>3</sup>/capita, surface runoff is 17,000 m<sup>3</sup>/capita, and annual domestic use is 80 m<sup>3</sup>/capita (Hanapi, 2015). The domestic treated water supply tariff is considered low compared with many other countries, with the lowest in Pulau Pinang (RM 0.43/m<sup>3</sup>) and the highest in Johor (RM 1.36 /m<sup>3</sup>). According to Quarterly Water Services Statistics, in 2014 water consumption in liters per capita per day (l/c-d) in Peninsular Malaysia was high (230 l/c-d) compared to that for Singapore (140 l/c-d).

A paradigm shift is needed in water demand management. Malaysian consumers need to learn to utilize water resources in the most efficient possible way. In addition, there are other steps that can be taken to improve water usage:

1. Reduce non-revenue water;
2. Reduce loss in quantity and quality of water;
3. Shift water usage from peak to non-peak hours;
4. Improve recycling and recovery of water;
5. Reduce household water usage;
6. Adopt water reducing devices;
7. Harvest rainwater;
8. Improve in-stream and environmental uses; and
9. Restructure the water tariff system.

## 8.2 Literature review

### 8.2.1 Catchment research in Malaysia

Despite some limitations, paired catchment is still a robust approach for conducting hydrological impact studies, because it can minimize the variability of hydro-meteorological parameters while providing a fundamental scale for integration and modeling. In impact studies, the relationship between hydrologic and climatic variables is established during a calibration period. Thus, one or several catchments are treated or disturbed while leaving at least one control catchment untouched. The magnitudes of the treatment's impacts are measured in terms of the deviation from the predicted behaviour, as represented by the control catchment.

Earlier hydrologic research in Malaysia dealt mainly with land use impacts, addressing aspects of erosion and sediment yield (Douglas, 1972; Leigh, 1978; Salleh *et al.*, 1983), as well as rainfall and runoff relationships (e.g. Low, 1971). These studies, however, were mostly short-term (usually less than one year) and did not employ the paired catchment technique.



Comprehensive catchment research in Malaysia has taken place mostly between the 1980s and the 2000s. The Forest Research Institute of Malaysia (FRIM) had set up two experimental catchments to assess the hydrological impact of selective logging operations at Berembun in Negeri Sembilan and Jengka in Pahang (Rahmid and Blake, 1979). The Department of Irrigation and Drainage (DID) had established another experimental catchment in Sg Tekam, Pahang, aimed at quantifying the hydrological impact of clearing forests to convert the land to oil palm and cocoa plantations (DID, 1986). In 1990, FRIM set up another experimental catchment at Bukit Tarek Forest Reserve in Kerling, Selangor (Saifuddin *et al.*, 1991). The study addressed the effects of clear-felling secondary rainforest and subsequently converting it to a forest plantation. Specific topics covered under this research program included hillslope hydrological processes (Noguchi *et al.*, 1997b; 2003), sediment transport (Sammori *et al.*, 2004; Ohnuki *et al.*, 2010), the nutrient cycle (Yusop *et al.*, 1996; Yusop *et al.*, 2006), runoff generation from forest roads (Ziegler *et al.*, 2007; Negishi *et al.*, 2008) as well as preferential flow (Noguchi *et al.*, 1997a; Negishi *et al.*, 2007), rainfall interception in a young *Hopea odorata* plantation (Siti Aisah *et al.*, 2012), and the effect of clear felling on water yield (Siti Aisah *et al.*, 2014).

The impacts of a forest harvesting operation in steep and difficult terrain were examined in Hulu Langat and Sg. Lalang Forest Reserve in Selangor, focusing on erosion and sediment yield (Lai, 1993). The Sabah Forest Industry (SFI) and the Swedish University of Agricultural Sciences set up an experimental catchment at Mendolong, Sabah in 1985 (Malmer, 1993). The initial objective of this study was to compare the impacts of “normal practices” versus “non-burning” methods for the establishment of forest plantations. Another forest catchment study took place in Danum Valley, Sabah by the University of Manchester in 1987, with Yayasan Sabah as the main local counterpart (Douglas *et al.*, 1992). The inclusion of a much bigger catchment (>1000 ha) enabled the assessment of on-site and off-site impacts (Douglas *et al.*, 1993). The Danum experimental site is still active and provides an opportunity to assess long-term recovery from a selective logging operation (Walsh *et al.* 2011).

## 8.2.2 Hydrological impacts of forestry activities

### 8.2.2.1 Water yield

Despite differences in the nature of disturbances, forest type, climate, and geological setting, almost every study concurs that considerable removal of vegetative cover will often lead to an increase in water yield. The highest increase in water yield was registered at Sungai Tekam on a 100% clearing, amounting to 822 mm/yr or 470% (Table 2.1, Site 1). Such a large increase in water yield may reflect the tremendous extent of the evaporative processes of the dipterocarp forest (Abdul Rahim, 1988). Considerable increases in water yield following forest clearing were also observed in Sipitang, Sabah (Table 2.1, Site 3). Interestingly, in a catchment that was manually cleared in which the residuals left unburned (Table 2.1, W4), only a small increase in water yield was found. This suggests that the remaining undergrowth not affected by manual clearing was still capable of evapotranspiring a significant amount of water. In addition, the smaller water yield increases in W1+2 and W5 may reflect lower ET values from secondary vegetation and logged forest at Sipitang, compared to a more intact forest at Sg Tekam.

At Berembun Forest Reserve, the “commercial” logging that removed 40% of the standing volume increased the annual water yield between 55% and 70% (Table 2.1, Site 2). Smaller increases, between 28% and 44%, were observed following reduced impact logging (RIL), which removed about 33% of the forest stock. The Berembun data correspond to an average increase between 3 and 4 mm for every percentage point of forest removal.

Forest was clear cut in 2000 for the preparation of forest plantation at Bukit Tarek Experimental Watershed (BTEW), Selangor. The annual water yields based on water year in the small catchment (14.4 ha) were calculated according to the rainfall received in that particular year (1998–2004). In the year following forest clearance the water yield increased from 46.9% of rainfall (P=3177 mm)

to 57.5% of rainfall (P=2707 mm). The catchment was cleared again before tree planting occurred in 2004; three years after the *Hopea odorata* forest plantation was established, water yield in 2007 was 61.4% of rainfall (P=3475 mm). This is higher than the yield in 2004, which was 42.2% of rainfall (P=2886 mm)(Siti Aisah, *et al.*, 2014).

**Table 2.1** Effects of forest removal on water yields in Malaysia.

Location	Treatment/ disturbance	Annual Rainfall (mm)	Water Yield Increases (mm)	Year after disturbance	Reference
1. Sg. Tekam, Malaysi					DID (1986; 1989)
A	Secondary forest to cocoa plantation	1878	110–706	4	
B	Secondary forest to oil palm (60%) and cocoa (40%) plantation	1878	137–822	4	
2. Berembun, Malaysia					Abdul Rahim and Zulki-fli (1994)
C1	Selective logging removing 40% of the commercial stock	2126	113–188	7	
C3	Selective logging removing 33% of the commercial stock	2126	53–106	5	
3. Sipitang, Sabah					Malmer (1992)
(W1+2)	Secondary vegetation to <i>A. mangium</i> (normal practices)	3341	89–522	3	
(W4)	Logged-over forest to <i>A. mangium</i> (manual felling, manual wood extraction; no burning)	3341	80–197	3	
(W5)	Logged over forest to <i>A. mangium</i> (normal practices)	3341	262–468	3	
4. BTEW, Malaysia	Secondary forest to <i>Hopea odorata</i>	2707	68	1	Siti Aisah <i>et al.</i> (2014)

### 8.2.2.2 Water yield recovery

A crucial issue in assessing the possible benefit associated with additional water yield due to forest removal is the duration of the increase. Unfortunately, many of the experimental catchments in the tropics could not be sustained long enough to capture a full recovery period. In the Berembun study, the water yield increases showed a decreasing trend between five and seven years after logging, but the yield was still higher than the background level (Abdul Rahim and Yusop, 1994). This suggests that the catchment may still be accumulating new biomass and the transpiration rate was still lower than that under the original conditions.

Due to vigorous growth of younger commercial trees and the intrusion of vines and grasses, the removal of forest cover would only lead to a temporary increase in water yield (Chappell *et al.*, 2005). In Sabah, Kuraji and Paul (1994) determined an estimated ET rate of 1450 mm/yr from a catchment in the third and fourth years after selective logging. This ET estimate is very close to the ET average for undisturbed lowland forests in Southeast Asia (1465 mm/yr, Bruijnzeel, 1990). In

another catchment area that was clear felled and burned, the ET in the third and fourth years after disturbance was 1200 mm/yr. In his review, Bruijnzeel (2004) suggests a rapid return to previous water yields, typically three to five years after rainforest removal. As secondary forests are fast-growing ecosystems with a primary productivity rate double that of primary forests (Brown and Lugo, 1990), the water yield after forest removal could dip even below the background level before rising again when the ecosystem has reached full maturity or climax.

While the increase in water yield following forest harvesting is generally short term, converting tropical forest to another landuse may cause a permanent change in water yield. In cases where forest is converted to grassland and short agriculture crops, there would be permanent increases in water yield (Fritsch, 1993). The additional water in streams is the result of the reduced interception capacity of smaller canopies and limited ability of shallow roots to pull water from deeper parts of soils.

On the other hand, an extensive forest plantation may reduce water yield, especially when the introduced species is a heavy water consumer (Malmer *et al.*, 2009). However, little is known about the water use of major plantation species such as oil palm, rubber, and *Acacia mangium*. In Malaysia, Chong (2008) investigated the hydrological properties of three oil palm catchments of different ages, namely C1 (2 years old), C2 (5 years), and C3 (9 years) over eight months. Projected annual ET values based on catchment water balance were 1365 mm/yr for C1, 1201 mm/yr for C2, and 1098 mm/day for C3. The ET value for young oil palm (2 years) in C1 is reasonable when compared to an ET value of 3.84 mm/day, or 1401 mm/yr, derived using micro-meteorological parameters (Hensen, 1999). The lower ET values from mature oil palms in C3 were due to catchment leakage (Geoffery, 2013). In a study of the establishment of forest plantation of *Hopea odorata* species in a small forested catchment, there was an increase in water yield observed after forest clear-cutting, and it took about three years for the yields to gradually decline as the forest recovered (Siti Aisah *et al.* 2014).

More research in plantation ecosystems is necessary, especially in view of recent evidence of high ET rates from rubber plantations, as reported by Maite *et al.* (2010) in northern Thailand and Tan *et al.* (2011) in southwestern China. However, the sites in those studies receive much less rainfall than Malaysia.

### 8.2.2.3 Baseflow / dry season flow

Maintenance of baseflow is crucial to ensure that forestry and land-use operations do not disrupt water availability. One interesting finding from the Berembun's study is that the increase in water yield was associated with the augmentation of the baseflow, rather than the stormflow. This was substantiated by two observations: first, the disappearance of the zero flow events that had been recorded prior to the logging operation; and second, the increased proportion of lower discharge values (Abdul Rahim and Harding, 1992). The higher baseflow was attributed to the extensive nature of the selective logging operations, which disperse the impacts of logging over a larger area. Consequently, forest soils are not greatly affected and can still maintain a high infiltration rate.

At the Sungai Tekam Basin, the relative contribution of baseflow to the total streamflow rose from 68% during the calibration period to 86% in the first year after forest clearing (DID, 1986). The higher baseflow can be explained in two ways: first, the gentle slope of the catchment (ranging from 6-8°) could only withstand minimum soil compaction from the forest clearing, and this resulted in higher baseflow; and second, the rapid recovery of surface crop cover after the forest harvesting helped to improve soil properties, thus increasing infiltration capacity.

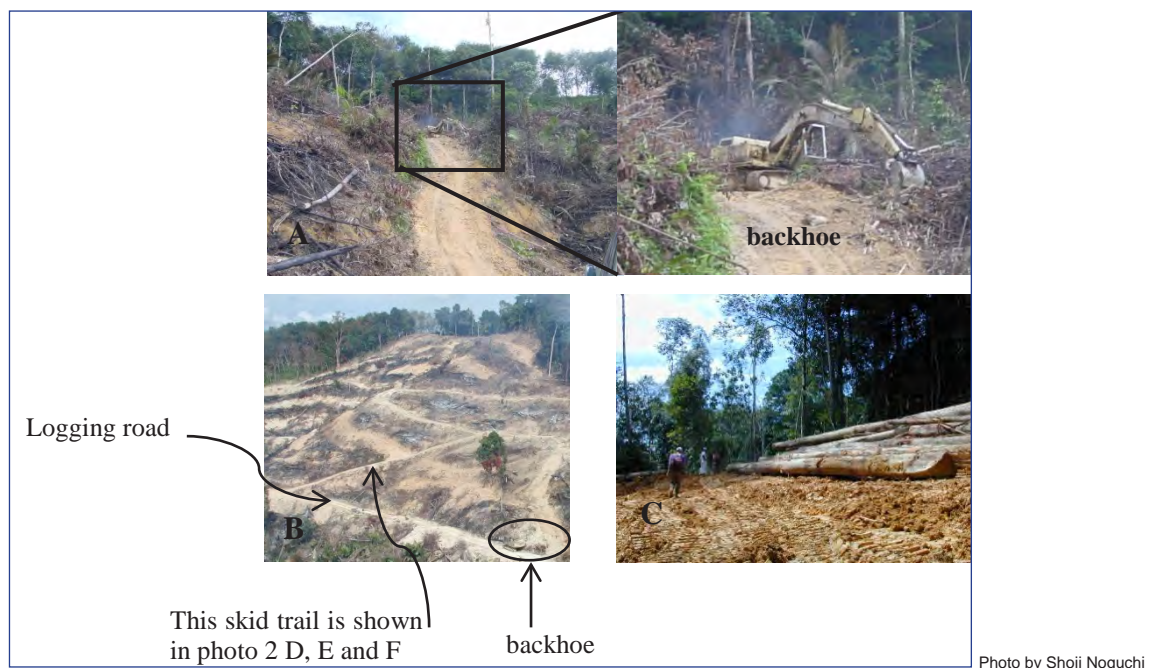
In general, the maintenance of baseflow levels entails limiting the ground disturbance so the opportunities for recharging soil moisture through infiltration are not significantly disrupted (Bruijnzeel, 1990). It is important not to exceed the threshold of acceptable ground disturbance during forest planning and operation. Compacted soil, mainly in the form of logging roads and landings, could

reduce infiltration and generate more overland flow. Diminished dry season flow occurs when infiltration is reduced so much that the increase in soil moisture associated with lower ET values from forest removal is not sufficient to compensate for losses to overland flow.

Based on the selective logging results from the Berembun study, Abdul Rahim and Yusop (1994) proposed a ground disturbance threshold of 10% to assure an undisrupted dry season flow, at least during normal weather conditions. Good forestry practices such as proper planning, construction, and maintenance of logging roads and careful extraction of logs could help reduce soil compaction. The alignment of roads far from water courses provides an opportunity for overland flow to infiltrate as it travels downslope. The ploughing of unused landings and roads could expedite revegetation and colonization of grass, an important initial step in the process of recovering soil infiltration properties (Baharuddin, 1995).

#### 8.2.2.4 Surface erosion and sedimentation

It is necessary for forest harvesters to establish logging roads, landings and skid trails in the forests (Sist *et al.*, 1998). In one study, soil losses during the first year after logging were  $13.3 \text{ t ha}^{-1} \text{ yr}^{-1}$  and  $10.1 \text{ t ha}^{-1} \text{ yr}^{-1}$  on logging roads and skid trails, respectively (Baharuddin *et al.*, 1995). The logging roads, skid trails, and landing areas (Figure 2) became the source of sediment after logging.



**Figure 2.** The logging road, skid trail and landing constructed in Bukit Tarek: (A) logging road, (B) a system of logging roads and skids, (C) log landing.

Well-preserved soil pedestals were observed on disturbed cutslopes, fillslopes, and skid trails (Figure 3A). In addition, overland flow occurred on the logging road (Figure 3B). Overland flow resulted in Hortonian overland flow (HOF) and intercepted subsurface flow (ISSF) along the logging road cuts that transformed it into surface runoff. ISSF plays a particularly important role in the additional road-generated sediment export and exacerbated HOF-driven erosion (Ziegler *et al.*, 2007; Negishi *et al.*, 2008). Total sediment export from the road surface ( $170 \text{ t ha}^{-1} \text{ yr}^{-1}$ ) and suspended sediment export from the logging-disturbed catchment ( $4 \text{ t ha}^{-1} \text{ yr}^{-1}$ ) were exceptionally high despite three years of recovery (Negishi *et al.*, 2008). It was reported that the riparian forest prevented eroded soil



originating from disturbed areas from directly entering the stream (Ohnuki *et al.*, 2010; Photo 2C), thus reducing sediment in streams (Gomi *et al.*, 2006).

Severe erosion is exacerbated on the extensively connected skid trails by runoff coming from upslope trails (Figure 3D, E, F). The maximum depth of the rill on skid trails was more than 1 m (Figure 2F). To reduce soil loss it is important to determine not only the proper density of logging roads and skid trails, but also their length and connectivity (Sidle *et al.*, 2004; Ziegler *et al.*, 2007). In addition, forest managers and engineers should carefully examine road placement, particularly when roads are constructed across hydrologically active areas such as zero-order basins (Negishi *et al.*, 2008) and riparian buffers (Gomi *et al.*, 2006).



**Figure 3.** Erosion features in Bukit Tarek: (A) pedestal erosion features, (B) overland flow on the logging road, (C) sediment deposition by forest buffer, (D) skid trail just established (ca. Jan 2004), (E) skid trail six months following logging, (F) skid trail 13 months following logging.

### 8.3 Politics

In Malaysia, the governance of water resources is under the jurisdiction of the state governments, e.g., the Selangor Waters Management Authority (Authority Enactment 1999) and the State Water Resources Council in Sabah (Water Resources Enactment 1998). Each state has its own laws, policies on water management, regulations, and developments. The areas covered are delineated in the legal framework, including canals, rivers, catchments and the land in their basins, and riparian reserves. In addition, the federal government has its policies under different ministries. The issue is that the administration of water resources involves many departments and agencies (Tables 3.1 and 3.2).



**Table 3.1** Agencies relevant to water resources and their roles in Malaysia  
(Source: Chan, 2002; Fauzi Abdul Samad 2003; Salam, 1999).

Category	Agencies
Federal Level	National Water Resources Council (NWRC) <sup>1</sup> , Department of Irrigation and Drainage (DID) <sup>1,2,3,4,5,6,8</sup> , Forestry Department (FD) <sup>6</sup> , Public Work Department (PWD) <sup>2,5,6</sup> , Department of Environment (DOE) <sup>3,4</sup> , Town and Country Planning (DCTP) <sup>6</sup> , Department of Mineral & Geoscience <sup>3</sup> , and Department of Fisheries <sup>4,9</sup> .
State Level	Local Authorities <sup>3,5</sup> ; Land Office <sup>6</sup> , Water Management Authority <sup>1,2,3,4,5,6</sup> , River Management Committees Under One-State One River Programme (DID).
Private Sector	Tenaga Nasional Berhad <sup>6,7</sup> .

Note: Area of focus: 1(water resource planning & development), 2(water supply), 3(water pollution control), 4(water quality management), 5(drainage and flood control), 6(water catchment), 7(hydropower), 8(irrigation), 9(fisheries).

As a result, the laws are fragmented to suit the sectoral management and use of land and water resources. The agencies responsible for the application of water resources legislation in Malaysia can be from the ministry and state levels, as well as private sectors. Any conflicts that arise in water resources management are resolved through adhoc inter-agency consultations. The National Water Resources Council was formed in 1998 for more efficiency in water resources management.

### 8.3.1 Integrated water resources management (IWRM)

The IWRM's approach was implemented in early 1990s, after urbanization and development in Malaysia caused problems in water resources management. The main concerns were river pollution and sedimentation, which can significantly stress water resources; water shortages and flood events due to climatic factors also needed to be addressed. In 1993, the Malaysian Water Partnership (MyWP) began implementation of the IWRM's approach in all land and water resource development and management efforts. In 1997, the pilot project began in the state of Selangor to assess the feasibility of establishing the Selangor Waters Management Authority (SWMA, also known as the Lembaga Urus Air Selangor or LUAS). This agency had administrative authority over the water quantity and quality of all the rivers in the state. However, after 18 years, the agency is not as effective as it should have been, suffering conflicts with the existing regulatory agencies and financing problems as well.

### 8.3.2 Integrated river basin management (IRBM)

The IRBM was implemented from 2002 to 2006 with the objective of balancing societal needs with conservation of resources to ensure sustainability. It was carried out based on coordinated management of resources in a natural environment, with the river basin as a geographical unit. The government established the SWMA in 1999, intending it to serve as a model for the integrated management of a river basin. The project was based on a cooperative program between the Government of Malaysia and Government Environmental Assistance Programs Denmark (DANIDA). Cooperation between federal agencies and the SWMA is important in the process of model development and river basin management. The Selangor River basin and Kedah River basin were selected as models in the application of IRBM. The Ministry of Natural Resources and Environment (NRE) was created in 2004, and at the moment is responsible for managing water resources in this country

### 8.3.3 The National Water Resources Policy (NWRP)

The NWRP of Malaysia was instituted in 2012 with strategies and action plans to address the challenges of sustainable water resources management in this country. The main objective is to ensure the demand for water from all user sectors – man-made and natural -- is met in terms of quantity and quality in a manner that is secure and sustainable. The NWRP addresses the increase in national water demand, water pollution, water availability issues at state level, and the effects of climate change.

### 8.3.4 The National Forestry Policy (NFP) 1978 (revised 1992) and National Forestry Act (NFA) 1984 (revised 1993)

Under the NFP, there are four classifications of forests that are designated as the Permanent Forest Estate: Protection Forest, Production Forest, Amenity Forest, and Research and Education Forest. Under Section 10(1) of the NFA of 1984, the Permanent Reserve Forest (PRF) is classified into 12 functional classes and should be managed by the respective states. In Peninsular Malaysia, 4.94 million ha of forest (Forestry Statistics, 2013) are dedicated for PRF; within this, 1.95 million ha is classified as Protection Forest and another 2.98 million ha is classified as Production Forest that should be managed sustainably. Soil Protection Forest (SPF), Water Catchment Forest (WCF), and Flood Control Forest (FCF) are categories of Protection Forest that are obviously crucial to water resources management in this country. Hence, the FDPM has designated a forested area of 880,538 ha within the PRF as WCF. The WCF should not be involved in commercial forest harvesting and should be maintained as a natural ecosystem.

**Table 3.2.** Parts of legislative framework related to water resources management (*Source: NWRP, 2012*).

Category		Legal Policy/Act/Enactment
<i>Ministry Level</i>	Ministry of Natural Resources and Environment	National Water Resources Policy, National Mineral Policy, National Forestry Policy, National Biodiversity Policy, National Wetlands Policy, National Environment Policy, National Policy on Climate Change, Water Act, National Forestry Act.
	Ministry of Agriculture and Agro-Based Industry	National Agricultural Policy, Food Security Policy.
	Ministry of Energy, Green Technology and Water	National Energy Policy, National Green Technology Policy.
	Ministry of Plantation Industries and Commodities	National Biofuel Policy, National Timber Industry Policy.
<i>State level</i>		State Water Enactments, Water Supply Enactments, State Forest Enactments, Local Government Act

### 8.3.5 Sustainable forest management (SFM) and Malaysian criteria & indicators (MC&I)

Achieving sustainable forest management (SFM) in Malaysia consists of ensuring that the natural forest resources (inland forest, peat swamp forest and mangrove forest) are managed not only for sustainable production of timber and non-timber products but also in ways that safeguard the water supply and promote climate stability. One parameter applied for river protection during forest harvesting activities is the establishment of buffer zone along the river (Table 3.3). The calculation of the buffer's width is based on land slope, using the formula of  $7.6 + (0.6 \text{ m} \times \% \text{ slope})$ ; the minimum

width of the buffer zone is 20 m. In addition, there is a set of rules that dictate when to fell the trees in the logging areas in order to avoid negative impacts to the river systems.

Road construction specifications also help to minimize the impact on water bodies. The maximum allowed road density is 40 m/ha, right-of-way cannot be more than 12 m, and roads should be less than 4 m wide. In addition, roadside construction near buffer zones is not allowed and roads cannot be constructed on slopes of more than 20%. Other specifications address drainage systems, culverts, and bridges.

**Table 3.3.** The width of river buffer zone applied in forest harvesting areas (*Source: Anonymous, 1999*).

Land Slope		Width of Buffer Zone (m)
Degree	%	
0–11	0–20	20
12–16	21–30	21–30
17–22	31–40	31–45
23–27	41–50	46–55
28–30	51–60	56–70
31–40	61–84	71–95
>40	>84	Protected area

**Table 3.4.** Water resource elements included in the Forest Management Certification Program (*Source: [MC&I (Natural Forest), 2011]*).

Principle	Criterion	Indicator
<i>Principle #5: Benefits from Forest</i>		
	5.5 Forest management operations shall recognize, maintain, and, where appropriate, enhance the value of forest services and resources such as watersheds and fisheries.	5.5.1 Implementation of guidelines and/or procedures to identify and demarcate sensitive areas for the protection of soil and water, watercourses, and wetlands.
		5.5.2 Implementation of management guidelines, where appropriate, to maintain and/or enhance the value of forest services and resources.
<i>Principle #6: Environmental Impact</i>		
	6.5 Guidelines shall be prepared and implemented to: control erosion; minimize forest damage during harvesting, road construction, and all other mechanical disturbances; and protect water resources.	6.5.1 Availability and implementation of harvesting procedures to protect the soil from compaction by harvesting machinery and erosion during harvesting operations.
		6.5.2 Implementation of reduced/low impact logging to minimize damage to the environment.
		6.5.4 Availability and implementation of guidelines for conservation of buffer strips along streams and rivers.

The Malaysian Criteria and Indicators for Forest Management Certification (Natural Forest) [*MC&I* (Natural Forest)] have been used as the standard for assessing forest management practices at Forest Management Units (FMUs) for the purpose of certification. The certification program was established in 2002 with *MC&I* (2002). There are nine principles in that version of the *MC&I*; Principle #1 was the requirement to comply with all relevant national and local laws, regulations, and policies related to forest management. Table 3.4 shows the criteria and indicators for the management of production forests that are closely related to the protection water resources.

In addition to the *MC&I* (Natural Forest) for forest management, the “*MC&I* Forest Plantation v2” was published in February 2015 as the standard for forest plantation management certification. The criteria and indicators applicable to water resource management are similar to those in *MC&I* (Natural forest).

## 8.4 Climate change and the future of forestry & forest research

### 8.4.1 Possible effects of climate change on water resources in Malaysia

The National Hydraulic Research Institute of Malaysia (NAHRIM) conducted a study in collaboration with the California Hydrologic Research Laboratory (CHRL) on the impact of climate change on the hydrologic regime and water resources in the country. The first part of the study was conducted for Peninsular Malaysia from 2002 to 2006, and the second part for Sabah and Sarawak from 2007 to 2010 (Nahrim, 2006). This study stemmed from the National Water Resources Study in 2000, which recommended the development of a regional climate model. The Regional Hydroclimate Model (RegHCM) developed from this study was used to predict the impact of climate change until the year 2050.

The RegHCM-PM of Peninsular Malaysia was validated by historical atmospheric data (rainfall and temperature) and hydraulic data (streamflow) for a 10-year period (1984–1993). The future hydroclimate simulations were carried out for two periods (2025–2034 and 2041–2050) and then compared with the corresponding data from the 1984–1993 periods. The parameters used in the assessment were air temperature, rainfall, ET, soil water storage, and river flow. The results were shown as graphic displays spatially distributed over Peninsular Malaysia at monthly and annual intervals, and also in terms of their areal averages over 11 defined subregions of Peninsular Malaysia at monthly intervals. An assessment was also conducted of the water balance of monthly river flows at selected watersheds in Klang, Selangor, Terengganu, Kelantan, Pahang, Perak, and Kedah of Peninsular Malaysia. The comparisons were also shown by graphic displays of monthly flow values. Then the statistical tests of significance were carried out for the periodic mean monthly flows corresponding to the historical and future periods.

The results of the analyses indicated an expected increase in inter-annual and intra-seasonal variability, with increased hydrologic extremes (higher high flows, and lower low flows) in the Kelantan, Pahang, Terengganu, and Kedah watersheds in the future. The statistical tests indicated that the differences between past and future in high monthly flows during October and November at watersheds located in Terengganu, Kelantan, Pahang, and Perak are statistically significant at the 95% level. In these watersheds the trend is toward higher flows during the already high flow months of October and November. The report noted the high reliability of these inferences due to the low signal to noise ratios obtained for the differences between future and past monthly periodic mean flows. The low signal to noise ratios were due to the shortness of the simulation period (20 years).

A similar study method was also applied for the implementation of the hydroclimate model (RegHCM-SS) in Sabah and Sarawak (Nahrim, 2010). The findings indicated that there will be an increase of about 4°C in air temperature throughout Sabah and Sarawak by year 2050. In terms of annual rainfall, Sabah was expected to experience some dry and wet years, but the trend was not clear for Sarawak. There were no clear differences between the historical and future periods identified in Sabah and Sarawak.

The study also suggested that the impact of global climate change on the streamflows in the Sabah and Sarawak regions would vary by location within the region. The impact is also predicted to vary with seasons and time intervals. Kinabatangan, Padas, and Kadamaian Watersheds in Sabah are expected to have water supply problems in the future, while a significant flooding problem is expected throughout Sabah and Sarawak.

#### 8.4.2 Effects of extreme weather events of flood and drought to water resources

In the past, the Northeast (NE) Monsoon (November – February) was a standard annual event in the eastern part of Malaysia. But in 2014, Malaysia experienced changes in the weather pattern that affected the water supply in the country especially in Selangor state. The drought started in January and continued to the end of March. In the Selangor Dam the water level gradually decreased from 206 to 190 m (16 m difference). Some rainfall was received in April (inter-monsoon) that increased the water level, but it slowly dropped in June because the Southwest (SW) Monsoon also brought less rainfall than usual. Water levels in the dam almost reached a critical stage (185 m) in September. The rainfall started to increase in October (due to the NE Monsoon), but extreme rainfall occurred in December causing severe floods in the northeastern areas of Peninsular Malaysia (Kelantan, Perak, Pahang, and Terengganu) and also in Sabah. The flood had a considerable impact on the people who lived near riverbanks in those states. A year before that, in October 2013, mud floods occurred in the Cameron Highlands following the release of water from the Sultan Abu Bakar Dam, which threatened to burst after heavy rainfall.

Scientists observed that the extreme weather events are modulated by natural climate phenomena such as El-Nino, La Nina, the Madden-Julian Oscillation (MJO), and cold surges (Fredolin, 2015). The Madden-Julian Oscillation contributed to the severe wet season during NE Monsoon of 2014. It is also predicated that the extreme weather events will be more frequent and severe as the climate warms due to anthropogenic climate change.

#### 8.4.3 Changes in natural forests and forest plantation areas in Malaysia

Based on forestry statistics from the FDPM, Sabah, and Sarawak (Statistics on Commodities 2010), the total forested area in Malaysia is 18.03 million ha, including the areas considered stateland, forest plantation, and wildlife reserve. Sarawak has the largest forested area of (7.86 million ha) followed by Peninsular Malaysia (5.87 million ha) and Sabah (4.30 million ha).

In 2012, the forested area designated PRF in Peninsular Malaysia covered 4.89 million ha, with 3.60 million ha in Sabah and 6.00 million ha in Sarawak. The PRF in Peninsular Malaysia at that time represented an expansion of 210 thousand ha from the previous eight years (Table 4.1).

**Table 4.1.** Forested area (ha) by land status -- PRF, stateland forest (SLF), wildlife reserve (WR), and outside forest reserve (OFR) -- between 2004 and 2012 in Peninsular Malaysia  
(Source: Forestry Statistics Peninsular Malaysia 2013).

Year	PRF	SLF	WR	OFR	Total
a) 2004	4,683,505	413,664	769,641	66	5,866,876
b) 2012	4,893,613	304,907	585,119	4,884	5,788,523
Changes from a) to b)	(+) 210,108	108,757	184,522	4,818	78,353

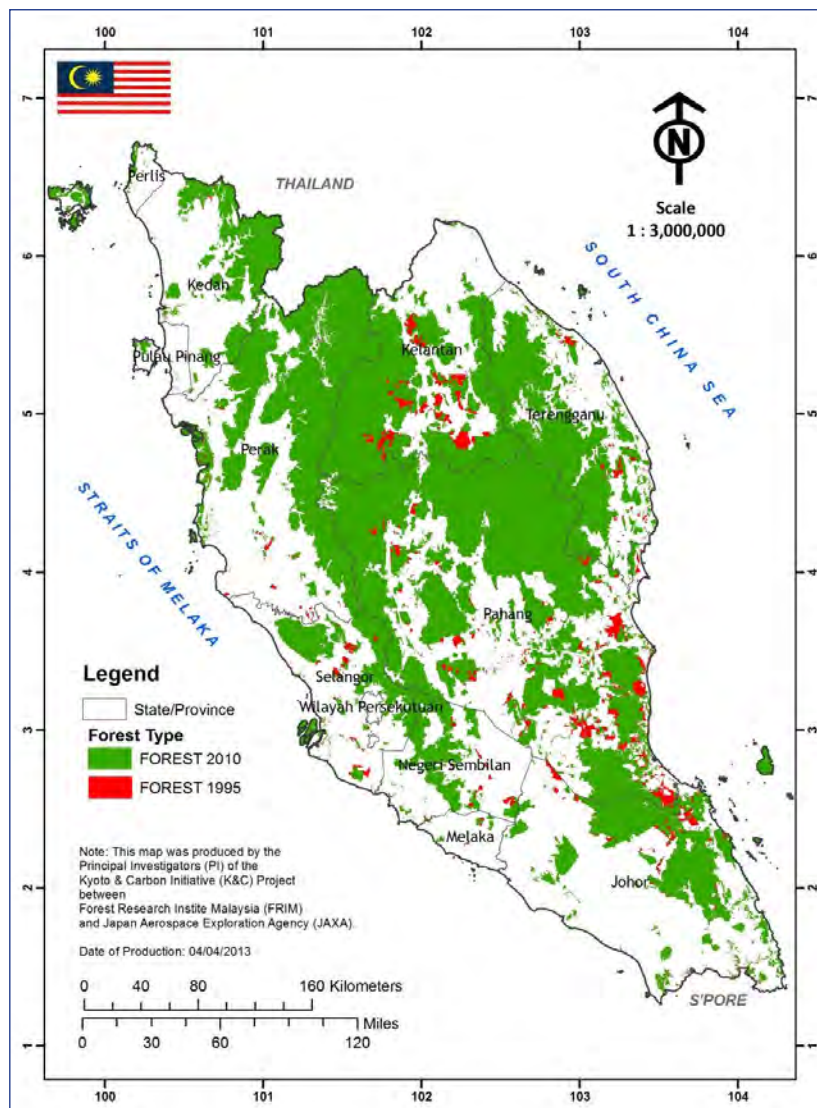
The FRIM conducted a project on forest change mapping in 2012 for Peninsular Malaysia using images datasets. It showed that within 15 years (1995–2010), the total forested area decreased by 28,498 ha/yr, which is equivalent to 0.44 % per year (Table 4.2). These changes in spatial distribution are shown in Figure 4.

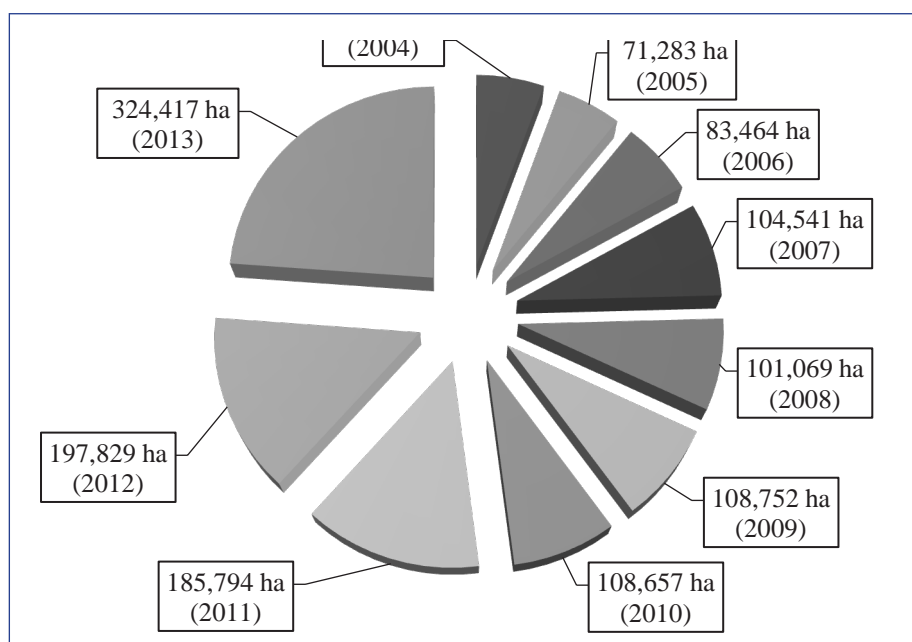


**Table 4.2** The changes in forested area (ha) based on forest types for a 15-year-period (1995–2010) in Peninsular Malaysia (Source: MFRD FRIM Annual Report 2014).

Forest Type	Year		Changes (ha) (c) = (a) – (b)	Rate of changes (ha/yr)	Rate of Changes (%/yr)
	1995 (a)	2010 (b)			
Inland forest	6,054,384.47	5,690,815.57	363,568.90	24,237.93	0.4
Peat swamp forest	336,959.15	290,038.47	46,920.68	3,128.05	0.93
Mangrove forest	132,168.76	115,180.60	16,988.16	1,132.54	0.86
Total	6,525,507.38	6,098,044.64	427,477.74	28,498.52	0.44

Based on approvals for forest plantation development, the forest plantation areas in Peninsular Malaysia increased from 75,055 ha in 2004 to 324,417 ha in 2013 (Figure 5). In 2013, Kelantan state had the largest area devoted to forest plantations (162,485 ha) followed by the states of Perak (56,503 ha), Johor (45,544 ha), Pahang (31,831 ha), and Selangor (11,381 ha). The other eight states have small areas, ranging from 36 to 9,131 ha.

**Figure 4.** Spatial distribution of changes in forest cover in Peninsular Malaysia between 1995 and 2010 (Source: MFRD FRIM Annual Report 2014).



**Figure 5.** Forest plantation areas in Peninsular Malaysia (hectares).  
Source: Forestry Statistics Peninsular Malaysia 2013.

Palm oil has become an important commodity for this country. Most oil palm plantations are planted in Sarawak, followed by Sabah and Peninsular Malaysia. Malaysia’s total land area is 32.996 million ha; oil palm plantations cover about 16.3%, while rubber plantations cover about 3.23%. As can be seen, the plantation areas are increasing over the last 5 years (2010–2014), and oil palm plantations and rubber plantations have increased about 9.98% and 3.53%, respectively (Table 4.3). One issue surrounding this change is the possible relationship between the conversion of land to oil palm plantations and climate changes.

**Table 4.3.** Area planted with tree crops (oil palm and rubber) in Malaysia (ha)  
(Source: Statistics on Commodities, 2010 and <http://www.kppk.gov.mywebsite>).

Year	2010	2011	2012	2013	2014
Oil palm	4,853,766	5,000,109	5,076,929	5,229,739	5,392,235
Rubber	1,028,000*	1,027,042	1,041,187	1,057,271	1,065,631

Note: \* = estimated.

The Water Catchment Forests (WCF) have been gazetted (i.e., approved by law) within the PRF by the FDPM. These forests function as water resources areas (Figure 6). Pahang has the largest area with 258,707 ha, followed by Perak with 159,866 ha and Johor with 85,598 ha. As of year 2014, 734,731 ha out of 880,538 ha identified have been gazetted as WCF (Figure 7).

For water quality monitoring, the FDPM has established monitoring stations in five states in Peninsular Malaysia. Kedah, Terengganu, Johor, and Pahang each established one station, and Pahang established five stations. The parameters observed are used to determine the Water Quality Index (WQI) from forested areas. The WQI is also monitored all over the country by the Department of Environment (DOE) Malaysia at the down-stream ends of the catchments. There are 464 rivers involved in the monitoring.

### 8.4.4 Climate change and the future of forestry & forest hydrology research in Malaysia

In Malaysia more than 50% of the total land area is still maintained as forest. Forestry Statistics 2013 shows that 44.23% or 5,831,101 ha of Peninsular Malaysia are still covered by forest. Values for Sabah and Sarawak are not available.

Under the Malaysian Constitution (Article 74(2)), land that includes forest is under the jurisdiction of the respective state governments. As such, each state has its own right to govern and manage its own forest resources. The forestry sector continues to contribute significantly to socio-economic development in Malaysia with emphasis on the practice of sustainable forest management. The current issue is that forest harvesting has moved to higher altitudes (>1000m). It is necessary to measure the impact of this shift to the hydrological parameters, as this is an environmentally sensitive area.

As the importance of climate change is realized, both international and national efforts to address it have increased, and forests are shown to be critical to alleviating the effects of climate change. Malaysia is involved in the establishment the program launched by the United Nations Framework Convention on Climate Change (UNFCCC), Reducing Emissions from Deforestation and Forest Degradation (REDD+). This program focuses on conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries (REDD+). The objective is to provide incentives to developing countries to protect, better manage, and wisely use their forest resources. Malaysia is in the process of developing its National REDD+ Strategy. The implementation of REDD+ in this country will result in the protection of water resources that originate from forested catchments. The Ministry of Natural Resources and Environment (NRE) has also proposed the establishment of National Climate Change Center, which will handle the issues of climate change and disaster risk management -- such as extreme floods -- in this country.

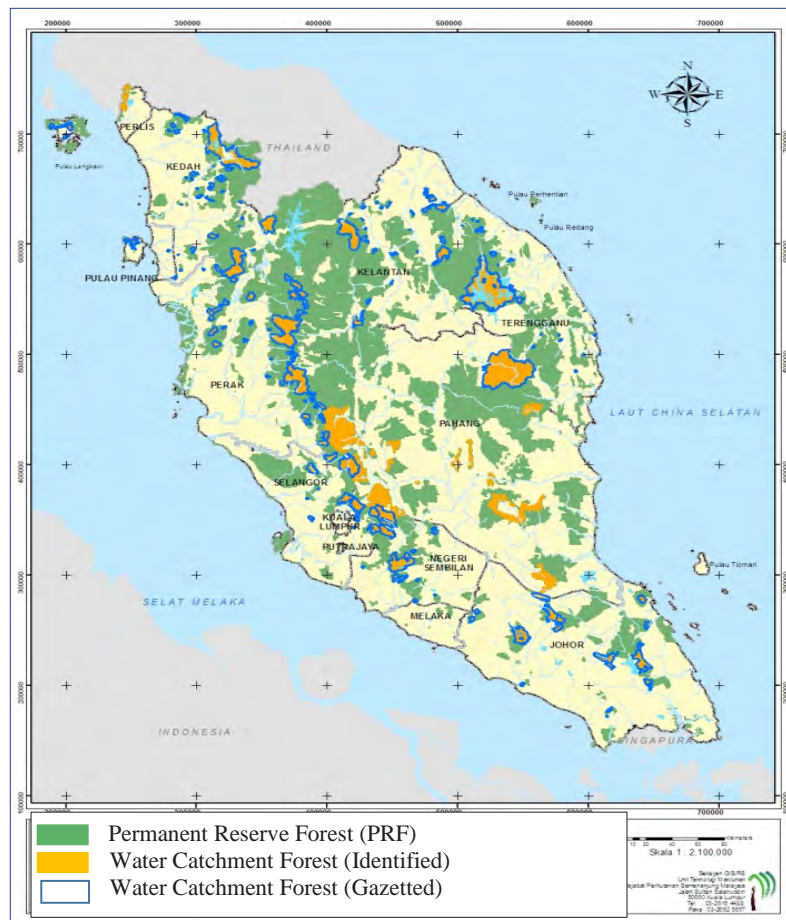
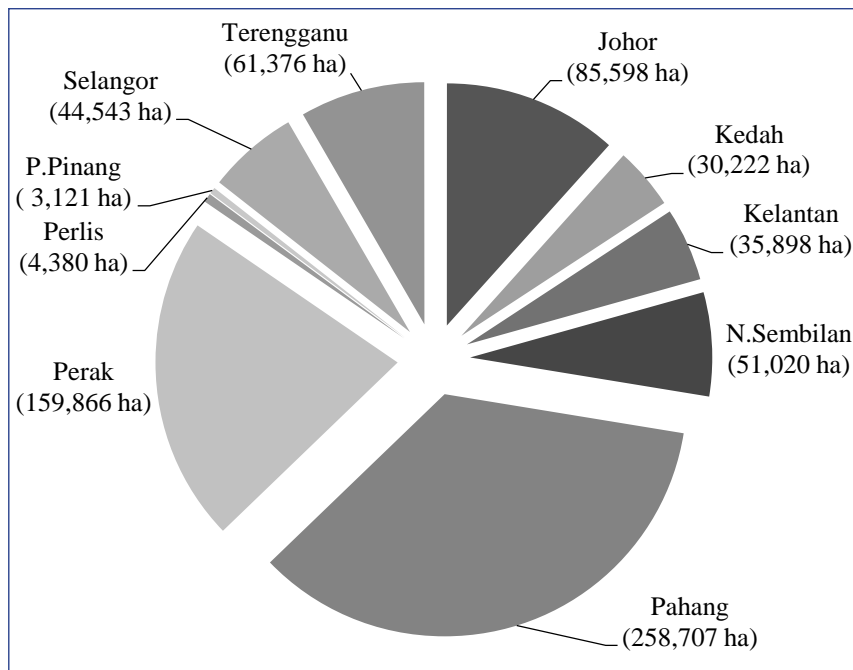


Figure 6 WCFs within the PRF (Source: Forestry Department, 2014).



**Figure 7.** WCFs (ha) that have been gazetted in Peninsular Malaysia (Source: FDPM, 2014).

The Management Plan of Water Catchment Forest is prepared by the forestry department for each respective state to ensure that the forest is managed for its resources. The states of Selangor and Perak have already adopted management plans, which focus on the management and conservation of forest resources, enforcement, activity control, monitoring of water quality and quantity, and water revenue. Research on hydrology, especially on water yields and discharge characteristics from this type of forest, can be conducted to assess the benefits of non-timber forest. Besides the state-based WCF management plans, the management of water bodies has been addressed in the Management Prescriptions for Non-Production Functional Classes of Forest (Shamsudin *et al.*, 2003).

Forest plantations were developed with the expectation of declining in timber supply from natural forests. The development of large-scale commercial forest plantations is under the Ministry of Plantation Industries and Commodities, which was mandated by the Cabinet in 2005. Under this program, 375,000 ha of forest plantation will be developed with an annual planting rate of 25,000 ha (<http://mtib.gov.my>). According to Forestry Statistics 2013, 324,417 ha have been identified for approved development as forest plantations, so only 50,583 ha more need to be identified. The private sector establishes the forest plantations; rubberwood and *Acacia* spp. are the two main species planted, in addition to other fast-growing timber species. A hydrological study needs to be conducted to assess how the large scale of forest plantation development effects water quality and quantity. The state governments should monitor and address the environment issues related to the establishment of forest plantations, and research components should be included in the planning and development processes. Research also can be conducted at the research stations and at other research sites established either in Peninsular Malaysia, Sabah, or Sarawak.

## 8.5 Acknowledgments

The authors would like to thank the HQ Forestry Department Peninsular Malaysia, for providing some of the current data used to write this chapter.



## 8.6 References

- Abdul Rahim, N. 1988. Water yield changes after forest conversion to agricultural land use in Peninsular Malaysia. *Journal of Tropical Forest Science*. 1(1): 67–84.
- Abdul Rahim, N. and Harding, D. 1992. Effects of selective logging methods on water yield and streamflow parameters in Peninsular Malaysia. *Journal of Tropical Forest Science*. 5(2): 130–154.
- Abdul Rahim, N. and Yusop, Z. 1994. Hydrological response to selective logging in Peninsular Malaysia and its implications on watershed management. In: *Proceedings of the International Symposium on Forest Hydrology*, Tokyo. pp. 263–274.
- Anonymous. 1999. Malaysian Criteria, Indicators, Activities and Standard of Performance (MC&I) for Forest Management Certification, Peninsular Malaysia. Forestry Department, Kuala Lumpur (Unpublished).
- Baharuddin, K. 1995. Effects of logging on soil physical properties and soil erosion in hill dipterocarp forest of Peninsular Malaysia. *Research Pamphlet* 119. Forest Research Institute Malaysia.
- Baharuddin, K., Mokhtaruddin, A.M., and Nik Muhamad, M. 1995. Surface runoff and soil loss from a skid trail and a logging road in a tropical forest. *Journal of Tropical Forest Science* 7: 558–569.
- Brown, S. and Lugo, A.E. 1990. Tropical secondary forest. *Journal of Tropical Ecology*, 6: 1–32.
- Bruijnzeel, L.A. 1990. *Hydrology of Moist Tropical Forests and Effects of Conversion: a State of Knowledge Review*. UNESCO IHP, Amsterdam.
- Bruijnzeel, L.A. 2004. Hydrological functions of tropical forests: not seeing the soils? *Agriculture Ecosystem and Environment*, 104: 185–228.
- Chan, N.W. 2002. *Review Paper on Chapter 18 of Agenda 21: Protection of the Quality and Supply of Freshwater Resources: Application of Integrated Approach to the Development, Management and Use of Water Resources*. Background Paper for NGO Perspectives for Advancing Sustainable Development in Malaysia, Malaysian NGO Forum Rio+10, Kuala Lumpur.
- Chappell, N., Tych, W., Yusop, Z., Abdul Rahim, N. and Baharuddin, K. 2005. Spatially-significant effects of selective tropical forestry on water, nutrient and sediment flows: a modelling-supported review. In M. Bonell and L.A. Bruijnzeel (eds) *Forests-Water-People in the Humid Tropics*. Cambridge Press. pp. 513-532. ISBN-10: 0521829534.
- Chong, M.H. 2008. *Comparison of rainfall runoff characteristics and evaporation in oil palm catchments*. M.Sc thesis, Universiti Teknologi Malaysia.
- DID. 1986. Sungai Tekam Experimental Basin. Transitional Report July 1980 to June 1983. *Water Resources Publication*, No. 16. Drainage and Irrigation Department, Ministry of Agriculture, Kuala Lumpur, Malaysia.
- DID. 1989. Sungai Tekam Experimental Basin Final Report, July 1977 to June 1986. *Water Resources Publication* No. 20. Drainage and Irrigation Dept., Ministry of Agriculture, Kuala Lumpur, Malaysia.
- Douglas, I. 1972. Impact of urbanization on the Klang River, Selangor, Malaysia. Paper presented at the 44th. Congress Australian and New Zealand Association for the Advancement of Science, Sydney, Australia.
- Douglas, I., Spencer, T., Greer, T., Bidin, K., Sinun, W. and Meng, W.W. 1992. The impacts of selective commercial logging on stream hydrology, chemistry and sediment loads in Ulu Segama rain forest. *Philosophical Transaction of Royal Society (London)*, B335: 397–406.
- Douglas, I., Greer, T., Bidin, K. and Spilsbury, M. 1993. Impacts of rainforest logging on river systems and communities in Malaysia and Kalimantan. *Global Ecology and Biogeography Letters* 3: 245–252.
- Fauzi, A. S. 2003. Water: Future Outlook. Paper Presented at the Dialogue on Food, Water and Environment, Sectoral Level. Organised by Malaysian Water Partnership, Putrajaya.
- Fauzi, A.S. 2000. Towards Realising the National Water Vision. Paper presented at the Workshop on Malaysian National Water Vision, 23–24 May 2000, Kuala Lumpur,
- Forestry Statistics Peninsular Malaysia 2012. Forestry Department Peninsular Malaysia. Ministry of Natural Resources and Environment Malaysia.
- Forestry Statistics Peninsular Malaysia 2013. Forestry Department Peninsular Malaysia. Ministry of Natural Resources and Environment Malaysia.
- Fredolin T., 2015. Coping with Greater Frequency and Severity of Weather Extremes (Especially Flooding). Paper presented at the Climate Change and Water Dialogue 2015, 22 May 2015, Petaling Jaya Selangor, Malaysia.



- MFRDB FRIM Annual Report 2014. Forest Research Institute Malaysia 2015. Ministry of Natural Resources and Environment.
- Fritsch, J. 1993. The hydrological effects of clearing tropical rain forest and the implementation of alternative land uses. *International Association of Hydrological Science Publication*. 216: 53–66.
- Geoffery, J. 2013. *Partitioning of rainfall and flowpath processes in small oil palm catchments*. PhD Thesis, Universiti Teknologi Malaysia.
- Gomi, T., Sidle, R., Noguchi, S., Negishi, J., Abdul Rahim, N. and Sasaki, S. 2006. Sediment and wood accumulations in humid tropical headwater streams: Effects of logging and riparian buffers. *Forest Ecology and Management*. 224: 166-175.
- Hanapi, M.N. 2015. Water and Industry. Paper presented at the Climate Change and Water Dialogue 2015, 22 May 2015, Petaling Jaya Selangor, Malaysia.
- Hensen, E. 1999. Note on oil palm oil productivity: Carbon dioxide gradients and fluxes and evapotranspiration, above and below the canopy. *Journal of Oil Palm Research*, 2(1): 30–40.
- Kuraji, K. and Paul, L.L. 1994. Evapotranspiration estimates of tropical rain forested watersheds using the short-time period water-budget method. *Proceedings of Annual Meeting Japan Society of Hydrology & Water Resources*. In 1994, pp. 588–598.
- Lai, F.S. 1993. Sediment yield from logged, steep upland catchments in Peninsular Malaysia. *International Association of Hydrological Science Publication*. no 216: 219–229.
- Leigh, C.H. 1978. Slope hydrology and denudation in the Pasoh forest reserve I. Surface wash; experimental techniques and some preliminary results. *Malayan Nature Journal*, 30: 179–197.
- Low, K.S. 1971. *Rainfall and Runoff on the Sungai Lui Catchment, West Malaysia*. Ph.D. Thesis, University of Hull.
- Maite G-C, Troch, P., Ziegler, A., Giambelluca, T., Durcik, M., Vogler, J. and Nullet, M. 2010. Hydrologic effects of the expansion of rubber (*Hevea brasiliensis*) in a tropical catchment. *Ecohydrology*. 3, 306–314. Doi: 10.1002/Eco.110.
- Malaysian Criteria and Indicators for Forest Management Certification for Natural Forest [MC&I (Natural Forest)]. 2011. Malaysian Timber Certification Council, Unit C-8-5, Block C, Megan Avenue 2, No. 12 Jalan Yap Kwan Seng 50450 Kuala Lumpur, Malaysia.
- Malaysian Criteria and Indicators for Forest Plantation Management Certification (MC&I Forest Plantation. v2). 2015. Malaysian Timber Certification Council, Unit C-8-5, Block C, Megan Avenue 2, No. 12 Jalan Yap Kwan Seng 50450 Kuala Lumpur, Malaysia.
- Malmer, A. 1992. Water yield changes after clear-felling tropical rainforest and establishment of forest plantation in Sabah, Malaysia, *Journal of Hydrology*, 134: 77–94.
- Malmer, A. 1993. *Dynamic of Hydrology and Nutrient Losses as Response to Establishment of Forest Plantation - a Case Study on Tropical Rainforest Land in Sabah, Malaysia*. Ph.D. Thesis, Swedish University of Agricultural Science, Umeå, Sweden, 181 pp.
- Malmer, A., Murdiyarso, D., Bruijnzeel, L. and Ilstedt, U. 2009. Carbon sequestration in tropical forests and water: a critical look at the basis for commonly used generalizations. *Global Change Biology*, Doi: 10.1111/j.1365-2486.2009.01984.x.
- National Water Resources Policy (NWRP), 2012. Ministry of Natural Resources and Environment Malaysia. ISBN 978-967-0250-08-3.
- National Hydraulic Research Institute of Malaysia (NAHRIM). Ministry of Natural Resources and Environment Malaysia. 2006. Study of the Impact of Climate Change on the Hydrologic Regime and Water Resources of Peninsular Malaysia. California Hydrologic Research Laboratory (CHRL).
- National Hydraulic Research Institute of Malaysia (NAHRIM). Ministry of Natural Resources and Environment Malaysia. 2010. Study of the Impact of Climate Change on Hydrologic Regime and Water Resources of Sabah and Sarawak. California Hydrologic Research Laboratory (CHRL).
- Negishi, J., Sidle, R., Ziegler, A., Noguchi, S. and Abdul Rahim, N. 2008. Contribution of intercepted subsurface flow to road runoff and sediment transport in a logging-disturbed tropical forest. *Earth Surface Processes and Landforms*. 33: 1174–1191.
- Negishi, J., Noguchi, S., Sidle, R., Ziegler, A. and Abdul Rahim, N. 2007. Stormflow generation involving soil pipes in a tropical zero-order basin of Peninsular Malaysia. *Hydrological Processes* 21: 789-806.
- Noguchi, S., Baharuddin, K., Yusop, Z., Tsuboyama, T. and Tani, M. 2003. Depth and physical properties of soil in forest and rubber plantation, Peninsular Malaysia. *Journal of Tropical Forest Science*. 15(4): 513–530.

- Noguchi, S., Abdul Rahim, N., Baharuddin, K., Tani, M., Sammori, T. and Morisada, K 1997a. Soil physical properties and preferential flow pathways in tropical rain forest, Bukit Tarek, Peninsular Malaysia. *Journal of Forest Research*, 2: 115–120.
- Noguchi, S., Abdul Rahim, N., Yusop, Z., Tani, M. and Sammori, T. 1997b. Rainfall-runoff responses and roles of soil moisture variations to the response in tropical rain forest, Bukit Tarek, Peninsular Malaysia. *Journal of Forest Research*. 2: 125–132.
- Ohnuki, Y., Abdul Rahim, N., Noguchi, S. and Sasaki, S. 2010. Sediment discharge through buffer zones in a tropical rainforest of Peninsular Malaysia. *Japan Agricultural Research Quarterly*. 44: 187-196.
- Quarterly Water Services Statistics, 2014. Suruhanjaya Perkhidmatan Air Malaysia (SPAN). Statistics on Commodities, 2010. 24<sup>th</sup> Edition. Ministry of Plantation and Commodities.
- Rahmid, K. and Blake, G. 1979. Forest hydrology study at Jengka and Berembun hill forest. Paper presented at the ASEAN Workshop on Watershed Conservation and Management Research Program, Kuala Lumpur, 3–7 September 1979.
- Sidle, R.C., Sasaki, S., Otsuki, M., Noguchi, S., Abdul Rahim, N. 2004. Sediment pathways in a tropical forest: effects of logging roads and skid trails. *Hydrological Processes* 18: 703–720.
- Saifuddin, S., Abdul Rahim, N. and Muhammad Farid, A. 1991. Watershed research in forest plantation: 1. Establishment and physical characteristics of Bukit Tarek Watershed. *FRIM Research Pamphlet* No. 110. FRIM, Kuala Lumpur.
- Salam, M. 1998. *Integrated Coastal and Estuarine Areas Management*. (Hand book 1–5). WWF-Malaysia, Selangor, Malaysia.
- Salleh, M., Abdul Rahim, N. and Mushrifah, I. 1983. The effect of logging on sediment yield in two forested catchment areas. In: Khamis, A., Lai, F., Lee, S., and Abd Rahman, M.D. (eds), *Regional Workshop on Hydrological Impacts of Forestry Practices and Reafforestation*. Serdang, Selangor: Universiti Pertanian Malaysia, pp. 61–69.
- Sammori, T., Zulkifli, Y., Baharuddin, K., Noguchi, S. and Tani, M. 2004. Suspended sediment solids discharge from a small forested basin in the humid tropic. *Hydrological Processes* 18, 721–738.
- Shamsuddin, I., Abd. Razak, O., Noor Azlin, Y., Samsudin, M., Safiah, M., Baharuddin, K. and Siti Aisah, S. 2003. *Management Prescriptions for Non-Production Functional Classes of Forest*. Forest Research Institute Malaysia, Malayan Forest Records No. 46. 154 pp. Doi.org/10.1155/2014/408409.
- Sist, P., Dykstra, D. and Fimbel, R. 1998. Reduced-impact logging guidelines for lowland and hill dipterocarp forests in Indonesia. Occasional paper 15. CIFOR 19 pp.
- Siti Aisah, S., Yusop, Z. and Noguchi, S. 2014. Influence of Pplantation establishment on discharge characteristics in a small catchment of tropical forest. *International Journal of Forestry Research*, Volume 2014, 10 pg. <http://dx.Doi.org/10.1155/2014/408409>.
- Siti Aisah, S., Yusop, Z., Noguchi, S. and Abd Rahman, K .2012. Rainfall partitioning in a young *Hopea Odorata* plantation. *Journal of Tropical Forest Science*. 24(2): 147–161.
- Tan, Z-H., Zhang, Y-P., Song, Q-H., Liu, W-J., Deng, X-B., Tang, J-W., Deng, Y., Zhou, W-J., Yang, L-Y., Yu, G-R., Sun, X-M. and Liang, N-S. 2011. Rubber plantations act as water pumps in tropical China. *Geophysical Research Letters*. 38, L24406: 1–3. Doi:10.1029/2011GL050006.
- Walsh, R., Bidin, K., Blake, W., Chappell, N., Clarke, M., Douglas, I., Ghazali, R., Sayer, A., Suhaimi, J., Tych, W. and Annammala, K.V. 2011. Long-term responses of rainforest erosional systems at different spatial scales to selective logging and climatic change. *Philosophical Transaction of Royal Society (London)*. B. 366, 3340–3353. Doi:10.1098/rstb.2011.0054.
- Yusop, Z. 1996. *Nutrient Cycling in Secondary Rain Forest Catchments of Peninsular Malaysia*. PhD. Thesis, University of Manchester.
- Yusop, Z., Abdul Rahim, N. and Douglas, I. 2006. Dissolved and undissolved nutrient loading from secondary forest catchments of Malaysia. *Forest Ecology and Management*. 224: 26–44.
- Ziegler, A., Negishi, J., Sidle, R., Gomi, T., Noguchi, S. and Abdul Rahim, N. 2007. Persistent of road runoff generation in a logged catchment in Peninsular Malaysia. *Earth Surface Processes and Landforms*. 32: 1947–1970. Doi: 10.1002/esp. 1508.

# Chapter 9. Forest Management and Water in Peru

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## 9.1 Introduction

### 9.1.1 Peru: main climate and physiological settings

Peru is the third largest country in South America after Brazil and Argentina; it is located in the central-western part of the sub-continent and occupies a land area of 1,285,215.60 km<sup>2</sup>. The Andes mountains, located longitudinally, divides the country into three “natural regions”: the Pacific coast (very arid, covering 10% of the territory), the high Andean range of mountains (semi-arid and sub-humid, 30%), and the Amazon jungle, the upper Andean Amazon and the lower plain (very wet and wet, 60%). From the hydrographic point of view, considering the continental divide and the drainage basins main stems end, there are three watershed systems: the Pacific Ocean system, with 53 basins (22 % of the territory), the Atlantic system with the only one and vast Amazon basin (74%), and the lake Titicaca system with 9 basins (and 4% of the Peruvian land area). Peru is one of the ten most biodiverse countries in the world, because of its wide diversity of species and ecosystems. It is as well a country geographically diversified with contrasting landscapes, local cultures, and abundant natural resources. The latitudinal range of Peru goes in between 0° and 18°, with elevations from 0 to almost 6,800 m.a.s.l. The position of the Andes and the high marine influence through cold and warm oceans currents along 3,000 km of coastline, create a variety of local climates and life zones, which characterize Peru. Figures 1 and 2 show the main geographical and climatic characteristics of Peru, and its basin systems.

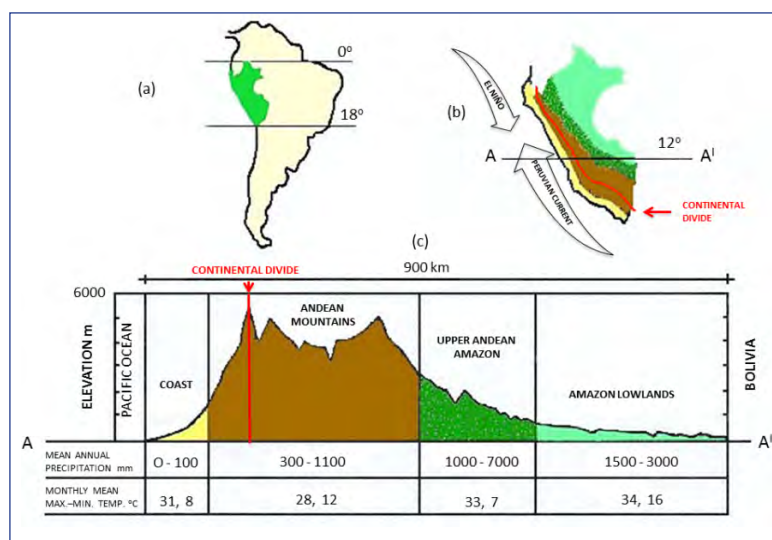


Figure 1. Geography and climate



Figure 2. Basin systems

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The Peruvian coast is extremely dry, especially from Ica (300 km south of Lima) to the south, due to the influence of the Atacama Desert, the driest in the world. In this region there is a clear and direct relationship between altitude and precipitation, and climate conditions are mainly identified by the variations in temperature and humidity. In the mountains, valleys, hills, and plateaus of the Andes rainfall is higher than in the coast. In the north, most mountains can even exceed 1,200 mm of annual rainfall. Temperatures in this region show a wider range. In the upper Andean Amazon jungle occur the highest rainfall records in Peru (7,500 mm/year), in the small city of Quincemil (Quispicanchis Province, Department of Cusco) on the Araza river basin. In much of this region, between 1,500 and 3,500 masl (*yungas*) there is also an important additional water supply from the mist condensation. The Amazon lowlands show relatively less precipitation values, shorter temperature ranges, but with higher maximum values. However, in this area annually some episodes of so-called *friajes* (cold spells) occur for a few days decreasing the minimum temperature as a result of icy winds originate in Antarctica. All this “normal” or natural climate variability, national climate performance is impaired when events “El Niño” occur (ENSO, El Niño Southern Oscillation) which in the most recent decades show higher frequency and intensity, apparently due to the climate change. In the mountains (especially in the eastern slopes of the Andes) and in the lower jungle, rainfall seasonality is marked with a dry period that take place depending on the site latitudinal and altitudinal variations, from May to October and a rainy one from November to April. These variations have a greater contrast in the lowlands. In the Amazon basin the rain depends on the forests.

### 9.1.2 Forests and forest resources of Peru

Peru forests cover more than 72 million hectares. Peru is the second Latin American country in forest area, the fourth largest one in tropical forests extension, and is among the 10 countries worldwide with more extensive wooded mass. This large area of predominantly woody natural Amazon vegetation cover, also include extensive palm dominated wetlands, and grasslands and bamboo association patches. In addition, legally and administratively are forest resources about 20 million hectares of high Andean prairies, located between the treeline and glaciers that correspond to the regional appellations of *paramo*, *jalca*, *puna*, and highlands moors. All these natural formations or naturalized extensive coastal, Andean and Amazonian areas produce timber, various other non-timber forest products (NTFP) and also provide important ecosystem services. Only the humid Amazon forests cover 67.98 million hectares while the dry and Andean forests reach 4.02 million hectares (MINAM 2010). Forest types differ in both, tree species composition and climatic conditions, especially seasonal water availability. Figure 3 shows the main locations of forest types described below. Table 1 shows Peru’s main natural forests and their extensions.

#### *Coastal dry forests*

Mostly located in northern Peru, the dry forests extend along the coast through the departments of Tumbes, Piura, Lambayeque, northern La Libertad, and along the lower Marañon basin valley, covering about 4 million hectares. The two areas are interconnected through the Porculla Pass (2,100 masl), the lowest Andean depression in Peru. The most conspicuous species in the dry forests at the lowest elevations is *algarrobo* carob tree or mesquite (*Prosopis* spp.), also known as *huarango* in Ica, of great local value in the rural economy for timber, fruits and other benefits, such as protection against desertification, beekeeping and providing shade for people and their domesticated animals. The higher areas the forest is dominated by the deciduous *ceibo* or kapok (*Ceiba* sp.) tree, which turns green with summer rains, and due to the shrubs and low vegetation it becomes almost impenetrable. These forests were strongly impacted by the high demand for firewood, charcoal, and other local wood uses, and fine hardwoods like *guayacán* (*Tabebuia* sp.) and *hualtaco* (*Loxopterygium huasango*), very appreciated for flooring, have been subjected in the past



decades to a logging ban which has allowed its partial recovery. All of these formations are heavily dependent on seasonal rains. Another important type of forest in the north of the country despite its small extension is mangrove, located at the mouth of the Tumbes River near the border with Ecuador. Mangroves are defined by the RAMSAR convention as an area of rich and productive wetlands, made up of islands and channels saturated by fine textured sediments carried by the river brackish water and controlled by the tides. They stabilize the accumulated sediment, prevent soil erosion and protect the valley of Tumbes of floods. These forests have been strongly affected and occupied by aquaculture ventures. Along the Pacific coasts and at the floodplains from the river mouth to higher elevations, there are also natural riparian forests mainly salix or *sauce* (*Salix humboldtiana*), and *molle serrano* (*Schinus molle*) overcoming the urban and agricultural development pressures. Several small green patches along the Pacific coast and feed by seasonal mist from the ocean are the hillocks or *lomas*, some of them legally protected due to their ecological and economical value.



**Figure 3.** Forest types.

Sources: <http://www.infobosques.com/bosques-del-peru.php>; Ministerio del Ambiente (MINAM 2012)



**Table 1.** Forest types(Source: <http://www.infobosques.com/bosques-del-peru.php>; Ministerio del Ambiente MINAM 2012)

Forest type	Area (ha)
Coastal dry forests	3,928,063
<i>Algarrobo</i> forests	2,627,031
Mountainl forests	163,629
<i>Ceibo</i> forests	1,137,404
Inter-Andean dry forests	335,688
Mangroves	4,918
Tumbes tropical forests	24,317
Upper Amazon forests	16,683,071
Lowland Amazon forests	50,928,757
Flooded forests	3,988,046
Alluvial forests	8,235,262
Hill forests	32,865,933
<i>Aguaje</i> wetland forests	1,529,400
<i>Paca</i> forests	4,320,708
High Andean forests	101,268
<b>Total</b>	<b>72,006,083</b>

### Andean forests

They are conformed by remaining relics of large tracts of two main species: *quinual* (*Polylepis* spp.) and *colle* (*Buddleia* spp.), probably the world's highest woodlands, as well as smaller stands of other species as *chachacomo* (*Escalonia resinosa*); *aliso* (*Alnus acuminata*); *molle* (*Schinus molle*), *pisonay* (*Erythrina edulis*), etc., adapted and distributed in the Peruvian Andes. These forests were strongly cleared for expansion of the agricultural frontier, firewood and charcoal production, and for extensive mining purposes since pre-colonial times. There are only about 101000 hectares of these forests left, at between 3000 and 4500 masl, and in remote areas protected by their inaccessibility and also as protected areas. Andean forests in the more humid and sheltered areas are often covered by epiphytes. In the undergrowth are species of grasses and herbs, wild potatoes, other Andean tubers and other species of the Andean flora. The *quinual* is a tree adapted to very cold weather, with an external bark in multiple thin layers. It plays an important role for protecting headwaters, streams upper reaches, and hillsides. It is locally used as firewood. The most important Andean forests are located in dispersed relic stands along the heights of the Andean region. The Andean species thriving in drier conditions are mostly located in the headwaters, hillsides and valleys of the following river basins: Marañon (Ancash, La Libertad, Cajamarca and Amazonas), Huancabamba (Piura), Chamaya (Cajamarca), Pampas (Apurimac and Ayacucho) and Pachachaca and Abancay (Apurimac).

### Upper Amazon forests

These Eastern Andean Amazon forests cover more than 17 million hectares in between 800 and 3500 masl. They are highly diverse, moist and mist forests, support a rich epiphyte population. High commercial value species such as walnut or *nogal* (*Juglans* spp.), cedar or *cedro* (*Cedrela montana*),

*ulcumano* (*Podocarpus oleifolius*), *romerillo* or *intimpa* (*Podocarpus glomeratus*), among others, are or have been presented in these forests, growing on sandy soils with a deep humus layer and high infiltration capacity. Rainfall is generally above 1000 mm/year at its driest areas, and may exceed 7000 mm/year. These forests have been felled and the land being occupied for many decades by migrant farmers and illegal *coca* (*Erythroxylum coca*) growers. At present there are important permanent crops in this region such as coffee (*Coffea arabica*), cocoa (*Theobroma cacao*), passion fruit or *granadilla* (*Passiflora ligularis*), some of them like *rocoto* (*Capsicum pubescens*), cultivated on steep slopes, induce to serious soil erosion problems. Because of their location at headwaters, its climate, and soils of high storage capacity, these forests are important suppliers of environmental services, especially clean water and more stable streams and river regimes that maintain steady streamflows during the dryer months at lower elevations.

### Lowland Amazon forests

Encompassing more than 50 million hectares, these forests are the largest in the country, very important as production forests. Its upper limit is around 800 meters and extend to the Peruvian Amazon eastern borders. Average rainfall values are in between 1500 to 3500 mm/year. Their terrestrial ecosystems show the dominance of trees at several layers and are formed by flooded, terraced, and hill forests. They present a great diversity of trees with presence of other plants such as shrubs, vines, bamboo or *paca* (*Guadua* spp.), ferns, and many palm trees, especially the *aguaje* (*Mauritia flexuosa*) predominant in hydromorphic soils, with very high carbon storage capacity. Aquatic ecosystems, lakes, ponds, oxbows or *cochas*, white and black water rivers, and wetlands are important components of the landscape and a large hydro-biological wealth. In more accessible areas these forests have been heavily exploited selectively since the rubber (*Hevea brasiliensis*) boom to extract from them the most valuable species as mahogany or *caoba* (*Swietenia macrophylla*), cedar or *cedro* (*Cedrela odorata*), rosewood or *palo rosa* (*Aniba rosaeodora*) *ishpingo* (*Amburana cearensis*), *tornillo* (*Cedrelinga catenaeformis*) *lupuna* (*Ceiba pentandra*), and lately high demand hardwoods, especially *shihuahuaco* (*Dipteryx* spp.) and others. Lowland forest are impacted by the establishment of industrial monocultures such as oil palm or *palmera aceitera* (*Elaeis guineensis*) over large areas, and land use and cover changes for agricultural purposes, as well as hydrocarbon and mining exploitation.

### Forest plantations

The first *Eucalyptus globulus* were planted in Peru about 1860, at a Franciscan monastery in Concepcion, Junin. Probably the first *Pinus* ssp. were planted during the decade of 1950 in marginal lands, in Sunchubamba, Cajamarca, on private grounds of the large *Hacienda Casagrande*, very important by its sugar cane production. Further plantations were tested and sponsored for protection and production purposes at small stands and agricultural land borders by the Forest Service and since the seventy's. international cooperation mainly from Belgium, Germany, Switzerland, Japan, USA, Netherlands and Finland, as well as FAO, supported several forestation efforts with public agencies as PRONAMACHCS, AGRORURAL, FONDEBOSQUE, INIA, IIAP, and private NGOs. During the last two decades private planting on relatively small properties has increased. At present, Cusco and Cajamarca are the departments with the largest areas of planted forests. And the new legislation pushed by private entrepreneurs, and institutions like INIA, CIP-CD Lima, UNALM, among others are trying to give new impulse to the commercial forest plantations.

Growing demand for forest products makes sense out of expanding planted forests. They may reduce pressure on natural forests, support biodiversity conservation, and contribute to climate change mitigation and adaptation actions. In Peru, planted forests for production or protection purposes contain mostly exotic species: eucalyptus (*E. globulus*) and pinus (*P. radiata* and *P. patula*). Among the most important native species in reforestation programs are *quinual* (*Polylepis* spp.) in the Andean region, and *tara* or *taya* (*Caesalpinea spinosa*) in the coastal and Andean region. *Bolaina blanca*

(*Guazuma crinita*), *capirona* (*Calycophyllum spruceanum*) and *tornillo* (*Cedrelinga catenaeformis*), among others, have been planted in the Amazon region.

The official statistics (2012) of planted forest in Peru exceeds 1million hectares. However, there are reasons to believe that such number is an overestimation because its calculation is based on the number of plants produced in the nurseries and taken to the field for final planting (at 3m x 3m), without considering the effective replacement of lost plants by a mortality rate which in some cases can exceed 50%. In addition, no information on the maintenance and monitoring actions to ensure planting survival is available. However, the extension suitable to be reforested in Peru is considered to be larger than 10 million hectares (INRENA 2005). At present we would be only using less than 10% of it, which makes only for about 14 % of the deforested area until 2005. During the past seven years less than 40000 hectares/year have been planted although the goals of the National Reforestation Plan 2005 indicated minimum annual targets for 2012 of 26500 hectares planted for commercial and industrial production and 32500 ha for environmental protection and watershed management purposes (INRENA 2005).

Porcón, Cajamarca, at the northern Andean region, with rainfall regimes of more than 1100 mm/year, is a project originated more than 30 years ago which became the most successful forest plantation model in Peru, with large timber resources in an originally area of 14000 hectares of prairies (*paramo* or *jalca*). The new Porcón beautiful landscape (see fig. 4), the microclimate, the restored infiltration capacity of the degraded prairie, the fungus production, and the added value given to its wood products, demand an important working force and provide important income to the local community. However, not all Andean watersheds are as Porcón. Most of the mountains in the central and southern Andes are located in semiarid zones with annual rainfall in between 200 and 700 mm, and more seasonal regime (short rains season and prolonged dry season), where the population and economic growth of the past years makes increasingly difficult to get water to meet other needs. New trees planted in these areas, depending on the chosen species, the forested area, its density, and the planting site, will increase the water demand to volumes still not calculated and could create social conflicts (Llerena *et al* 2011).

However, as it was stated before, there is an increased interest in Peru to invest in forest plantations looking for the best locations for this activity. New regulations have been proposed and enforced (September 2014) in order to facilitate and promote tree planting for commercial aims. It is expected to plant four million hectares of commercial plantations looking for reaching the first US\$ 1000 million in timber and wood exports in the short-term (*Gestión* newspaper, October 5<sup>th</sup> 2014, Economics section, e-version). In the same way, one of the objectives of the Strategic Action Plan for Adaptation and Mitigation presented by MINAM points out to the increase of forest cover for carbon sequestration. It is important to notice that beyond the initial watering demands of planted forests, water impacts are rarely an important issue when dealing with planting trees.



**Figure 4.** Porcón, Cajamarca (Photo: U. Pajares)

### 9.1.3 Forest management

This concept includes the use of social, environmental and economic criteria that help to maintain the long-term flow of forest goods and services without significant degradation over time and preserving natural capital. Forest management is encouraged by the presence of enabling conditions: national and regional legal, policy and institutional frameworks (FAO 2015). Decades ago Dourojeanni (1987) pointed out that there are few natural forests undergoing management and that the problem was not scientific or technical knowledge but social, political and institutional problems. The more conspicuous and successful management experiences seem to be those carried out in forests owned by native people (Gaviria and Sabogal 2013, Cossio *et al* 2014). Despite several studies, proposal and well-planned experiences looking for a more productive forest management in Peru this fundamental forestry activity is not developed as it should be in such a wooded country (Dourojeanni 1987, Figueroa *et al* 1987, Llerena 1989, Lombardi and Llerena 1991, Nalvarte *et al* 1993, Zarin *et al* 2004, Sabogal *et al* 2004, Sabogal y Casaza 2010, IICA 2012, Guariguata 2013).

The new forestry legislation in Peru defines several forest management practices according to forest type and land use, as follows: management of dry, Andean, Amazon, secondary, local (peasant and native communities), and planted forests as well as for agroforestry activities (Peru 2015a). Forest management plans are in some cases not implemented due to lack of compliance enforcement. Better control is expected with the new legislation, which has just been enforced. In the Peruvian forestry laws and operational rules, there are some points relating forest management and water, like riparian forests care, wetlands considerations, logging practices, and streams and forest roads crossings. There is also a general related review publication on hydrological impacts of forestry operations available (Stadtmuller 1994) and a Peruvian fieldwork guide (Sabogal *et al* 2004).

### 9.1.4 Deforestation and degradation impacts

Forest loss and degradation are the main threats faced by the Peruvian forests. The average annual deforestation in the Amazon rainforest since this process began to be measured is almost 175000 hectares. Between 75% and 90% of deforestation is due to the slash and burning of forests to agricultural activities of small scale (less than 5 hectares) and often is associated with low-income populations that migrate to the jungle. During the last decade opening of new roads and the improvement of old ones increased the accessibility to new forest and so the deforestation by expansion of rural settlements and entrepreneurs. Production of the goods demanded by the market, such as cocoa, coffee and palm oil, local alluvial mining and hydrocarbon exploitation are important deforestation drivers; as well as illegal logging activities which without destroying the whole forest cover, during the last decades has almost erased out of the accessible Amazon forests the most valuable species like *palo rosa* (*Aniba roseodora*), kapok or *lupuna* (*Ceiba pentandra*), cedar or *cedro* (*Cedrela odorata*), mahogany or *caoba* (*Swietenia macrophylla*). The highest deforestation pressure over the period 2000 - 2013 occurred in those forests that do not fit into any category of forest formal use and, therefore, do not have an authority to be responsible for its administration or care. As a result of decades of deforestation and degradation the extension of secondary forest in Peru at present reaches about 8 million hectares.

About the short term fate of the Peruvian Amazon region, Dourojeanni *et al* (2011) point out that the way political decisions are taken for the unplanned infrastructure development and the exploitation of the Amazonian natural resources is a serious threat to the future of the region and Peru. Instead of promoting good development, it is causing a situation in which everyone loses except those few who make profits from the unsustainable exploitation activities. The development of the region should be governed by a broad democratic planning and participatory process, which is yet to be created and improved in Peru. It is advisable to establish a moratorium on decisions for the start or implementation of new large projects. The issues of environmental and social responsibility must be much more elaborate and in the terms of reference of each project, the whole externalities and other costs should be clearly included. In addition, the role of the environmental sector in the process of



project approval needs to be enforced. Unfortunately this seems not to be the case in Peru where for the sake of facilitate investments some environmental rules have been weakened.

### 9.1.5 Water resources of Peru

Peru is among the ten countries with the largest reserves of water in the world, taking into account its potential surface water and groundwater. However, it is a country of extreme hydrological differences as shown in table 2 and figure 2. The Atlantic slope, the great Amazon basin, which represents more than 70% of the Peruvian territory, receives high annual precipitation and yield abundant water resources (about 98% of available water in the Peru), but has a low population density and little industrial development. On the other hand, the Pacific slope has 53 basins that concentrate less than 2% of water resources of the country, but is home of about 65% of the national population, the most populous cities of the country and the largest concentration of economic activity which provides over 80% of GDP. A third separate basin system is that of Lake Titicaca, which contains about 0.5% of available water in 9 basins, and provides to 5% of the population. That is why, despite the apparent abundance of water, Peru is among the five countries most vulnerable to climate change (ANA *et al* 2015).

**Table 2.** Distribution of Area, Population and Water Resources in Peru.  
Modified from Kuroiwa 2012, based on ANA 2009.

Basin systems	Area (10 <sup>3</sup> km <sup>2</sup> )	Population		Water availability		
		People	%	M m <sup>3</sup> /year	%	m <sup>3</sup> /person/ year
Pacific	279.5	18,315,276	65	37,363	1.8	2,040
Atlantic	958.5	8,579,112	30	1,998,752	97.7	232,979
Titicaca	47.2	1,326,376	5	10,172	0.5	7,669
Total	1,285.2	28,220,764	100	2,046,268	100	*72,510

\*National average

## 9.2 Literature review

According to Gilmour (2014), concerns about the hydrological impact of forest management go back more than a century and continue to the present day. These concerns have tended to focus on the effects of forests and forest management on various streamflow parameters (total water yield, low flows, flood flows), soil erosion, sedimentation, water quality, landslides and the water use of different vegetation types and species. There is now a solid body of scientific information for understanding and interpreting the relationships between forests and water in both temperate and tropical regions. However, there is also a parallel and deeply entrenched “popular narrative” that often runs counter to the consensus views of the forest hydrology scientific community. The same author (Gilmour 2014), points out that the primary general elements of this popular narrative are as follows:

1. Forests increase rainfall (conversely, removal of forests: decreases rainfall).
2. Forests increase water yield (removal of forests decreases water yield).
3. Forests reduce floods (removal of forests increases floods).
4. Forests increase baseflows (removal of forests decreases baseflows).
5. Forests regulate high and low flows (removal of forests unregulate streamflows).
6. Forests reduce erosion (removal of forests increases erosion).
7. Forests prevent/mitigate landslides (removal of forests increases landslides).

In Peru the forests-water issues are mostly dealt with only in academic circles and around some forestry and related schools. Most of the policy makers working on topics closely related to these themes and located in forested regions have not clear concepts about such relationships. Thus, the problem to face first is to improve the communication practices and facilitate the understanding of scientific knowledge, trying to increase the applied research in each Peruvian forest type if possible.

However, there is at least one interesting point to be emphasized considering the Peruvian reality (as well as others in Andean and Amazon countries), having in mind that the element 1 indicated above by Gilmour (2014) was originally developed for temperate forests. In Peru, accepting that “forests do not increase rainfall” would at least require an explanation for two exceptions to this rule. First, the case of the extensive and continuous Amazon dense forests (6.5 million km<sup>2</sup>, about 15% in Peru) whose evapotranspiration process puts some 20 billion tons of water into the atmosphere each day (Nobre 2014) and could generate more than 50% of its own rainfall which is kept in the catchment by the high Andean mountains. This huge volume of rain water even reaches other adjacent sub-basins of La Plata river watershed and influence the continent and the world as shown in figure 5 (Salati 1986, Victoria *et al* 1992, Marengo 2006, Makarieva and Gorshkov 2007, Nobre 2014). The second one is that well known mountain cloud forest scenario in which the “horizontal precipitation” is intercepted and the ever present mists condensed by the tree canopy on the hillsides and drips to the soil (Hamilton *et al* 1993, **Gómez-Peralta 2008**, Bruijnzeel *et al* 2010, Llerena *et al* 2010, Catchpole 2004, 2012). About the other Gilmour (2014) elements, from 2 to 7, the popular and not so popular confusion is still prevalent among much people.



Figure 5. Amazon rains

The natural cycle of the northern dry forests are strongly controlled by the seasonal regimes of rains and the fluctuations of the water table. These forests domain is defined by extreme events like the ENSO related floods after which the dry forests dormant natural regeneration thrive and increase their surface cover. The upper Andean natural and planted forests are strongly depending to its latitude and elevation which fairly correlate with rains and temperature. Northern latitude locations are much more watered than central or southern ones and the extended debate over planting trees and using native or exotic species (Hamilton and King 1983, Bruijnzeel 1990, 2004, Lima 1993, Farley *et al* 2005, Calder *et al* 2007, Buytaert *et al* 2007, Hamilton *et al* 2008, CIFOR 2012, Gilmour 2014) in Peru, arouse mainly in these areas. Trees adapted to higher elevations could reach more than 4000 masl, and grow on grass dominated areas, wetlands and peatlands. Main threats to these special ecosystems are associated to glaciers reduction and a warmer climate (Bradley *et al* 2006). At the eastern side of the Andes, going down from the high Andean prairies, the heath and the cloud forest benefit from abundant rains and the ever present fog. The lowlands are the realm of different types of riparian seasonal flooded, alluvial and hill forests along and around big meandering and braided rivers. Despite that there are a few spots of drier forest in the Peruvian Amazon region, water has not been a real problem. However the last big Amazon drought episodes during 2005 and 2010 followed by record flood events, meant a very serious problem to the Amazon flora and fauna (Nepstad *et al* 2007, Phillips *et al* 2009, Espinoza *et al* 2011, Lewis *et al* 2011, Marengo *et al* 2011, Gloor *et al* 2013, Bodmer *et al* 2014, Espinoza *et al* 2014, Meir *et al* 2015, Marengo and Espinoza 2015).

At present a promising approach to the forest-water relationship is the concept of ecosystem hydrological services (Dudley and Stolton 2003, FAO 2004, Llerena 2005, Hamilton *et al* 2008, Quintero 2010, Meier *et al* 2011, Hayek and Martínez de Anguita 2012, Gilmour 2014). Currently there are ventures and projects aimed at giving back to the people of the higher basins that conserve their wetlands, grasslands and forests, and by keeping them in good condition generate more and better water for downstream residents, who should reward such service. The main attempts to implement on forested watersheds what the concepts and the hydrological theory clearly support are mostly related to natural protected areas and are located in the following basins: Rumiayacu, Mishquiyacu and Almendra, Protected Forest of Alto Mayo, San Martín; Cañete, Nor Yauyos-Cochas Landscape Reserve; San Alberto, Yanachaga-Chemillén National Park, Oxapampa, Pasco; Cumbaza, Cordillera Escalera Regional Conservation Area, San Martín; Tilacancha, Private Conservation Area, Chachapoyas, Amazonas (Llerena and Yalle 2014).

During the last 40 years several institutions and projects, national and from abroad, individually and in association, have contributed in Peru to the forest and water knowledge. Some of these contributions are from UDEP (Tume *et al* 1989, Palacios y Tume 1991), which studied the dry forests; CONDESAN, IMHEA and ECOBONA (Buytaert *et al* 2007, Ochoa-Tocachi, in press, Tobón 2008) worked on Andean grasslands and forests. Important research at the upper and lower Amazon forests was or is done by: TROPISOILS (Elsenbeer 1989, Elsenbeer *et al* 1994, 1995); CAMREX (Aufdenkampe *et al* 2001, 2007); AARAM (McClain and Llerena 1998, Glauber 2001, McClain *et al* 2001, Molina 2001, Moll 2001, Ordoñez 2001, Sáñez 2001, Ramos 2002, Rodríguez 2002, McClain and Cossio 2003, Alemany 2004, McClain *et al* 2007); LBA (Werth and Avissar 2002, Llerena 2007a); HYBAM (IRD 2014, Espinoza *et al* 2014); RAINFOR (Malhi *et al* 2008, 2009, 2010, Brien *et al* 2015); UNALM (Ruiz 1985, Ormachea and Llerena 1992, Marmillod *et al* 1992, Velásquez 2002, Zanabria and Llerena 2003, Roncal 2006, Llerena 2007, Llerena 2007b, Llerena *et al* 2007, 2010, 2011, Llerena and Yalle 2014, Reyes 2014); UTU-ART (Salo 1988, Kalliola 1992).

### 9.3 Politics

In response to internal demands of forest stakeholders and international commitments, Peru is undergoing a reform process of its public forestry administration. There is a new national policy framework, the Forest and Wildlife Act, that has just been regulated and by which the National Forest and Wildlife Service (SERFOR) was created as the national forestry and wildlife authority,

governing body of the National System of Forest and Wildlife Management, constituting at a national level the technical-regulatory authority. However, at a regional level, the Regional Governments, through the Organic Law of Regional Governments, assume the responsibility of forest control and management, as well as granting access rights (authorization certificates) to forest resources within its scope of action. The new forestry administration includes new principles and approaches such as, the ecosystem, the landscape, the sustainability, and the climate change approach; by which it seeks an integrated management of forestry resources and wildlife, including ecosystems services and its contribution to relief and adjustment of ecosystems and populations faced with the impacts of climate change.

The National Forest and Wildlife Policy, adopted in August 2013, is another important tool within the reform of public administration. It establishes the core policy by honoring the treaties, international agreements and contracts ratified by Peru. The principles of the forestry administration include inter-sectoral approaches and incorporates the principles related to sustainability, competitiveness and ecology; understood as the integrated management of land, water and living resources, promoting conservation and sustainable use in an equitable way, recognizing the importance of wild ecosystems as a space of life, wildlife habitat and water source, and its contribution to food security and welfare of rural population who depend of it. For the implementation of the new approaches to the forestry administration, the direct and indirect causes of deforestation and forest degradation have been identified.

The forestry policy guides the lines of action towards conservation, protection, maintenance, improvement and sustainable use of the forest resources and wildlife of the nation, among them the different types of forests: Amazon Rainforest, dry forest, relict, bogs, moors, other threatened Andean ecosystems, and wild plant formations according to ecological characteristics and goods and services they provide. It also promotes the establishment of forest plantations on private or communal lands for multi purposes with public and private investment. To manage ecosystems that are threatened or in process of degradation lines of action and recovery options have been established, primarily using native species, especially in the basins headwaters and riparian strips. These actions consider the provisions in the Regulations of Water Resources Act, which establish coordinated work with the forestry and national wildlife authority and Regional and Local Governments, in its framework of action, and water user organizations for the promotion of programs and projects of forestation in marginal strips to avoid the erosive action of the water. The National Water Resources Plan recognizes the basin headwaters reforestation as a strategy to increase the availability of water resources, although the role of forest and tree plantations are not considered for water quality, it does consider the recovery and protection of the quality of water resources in natural sources and ecosystems.

In regards to forest plantations, 2014 saw the approval of the Board of Promotion of Forest Plantations for private land to promote private investment in the development of forest plantations on private land, dictating favorable measures and incentives for simplifying the registration procedure for forest plantations and for the transport of its products. Plantations in public land are governed by a different kind of law. However, some important issues remain to be addressed, such as legal security, tax incentives, financing mechanisms, technological innovation, among others already identified in the National Reforestation Plan, approved in 2006. It is important to note that in this plan it is indicated erroneously that forest plantations increase the river flow.

Moreover, Peru is developing the National Strategy for Forests and Climate Change and the national strategic document on REDD + in order to coordinate, integrate and complement existing sectoral and subnational approaches related to the conservation and sustainable use of forests including protected areas, indigenous lands, and all categories of the system of the forest heritage. It is intended to have involvement of the private sector for investment in forest plantation projects that involve mechanisms for environmental payment services; however, there are still barriers and constraints, such as property rights, illegal activities (mining, illegal crops), access to formal finance, value chain development, the technological gap, among others. The State recognizes that a substantial element, even though not shown in the economic figures, is the role of forests as providers of livelihoods



for rural people of the Amazon, as one of the major terrestrial drains of greenhouse gases (GHG) contributing to the removal of about 53 Gg of CO<sub>2</sub> equivalent per year; however, responsible for 40% of total GHG emissions, considering that the total net GHG emissions in the country is estimated at 138 million tons of CO<sub>2</sub> equivalent, mainly attributed to the change in land use. In this context, comprehensive intervention logic comprises transverse actions generating enabling conditions (governance, certification) which allow investments aimed at reducing the pressure on forests and restoring degraded areas, as well as investments aim to increase the competitiveness of the forests.

With these changes generated by the new administration, research plays an important role in all lines of action for forestry management, because it generates knowledge and scientific basis for decision-making within a framework of sustainable development that contributes to conservation, forestry management and wildlife and generating resources value for the welfare of the population. In this way the new structure involves the Studies and Investigation Research as part of the General Policy and Competitiveness Directorate, and General Management Knowledge Directorate, that cowork with other Directorates as well as with the National Institute for Agrarian Innovation (INIA), other research institutions like the Peruvian Amazon Research Institute (IIAP), universities; and maintain relations with national and international institutions involved in related activities to support and achieve the strategic objectives and functions of the SERFOR.

## 9.4 Climate change and the future of forestry & forest research

The impact of climate change on natural and forested ecosystems have been widely covered and well documented during the last years in the world and in the Americas (Llerena 1991b, Locatelli *et al.* 2009, Sebastian *et al.* 2011, Cuesta *et al.* 2012a, 2012b, Nobre 2014). In Peru the National Strategy on Forests and Climate Change has just been delivered for public opinion and criticism (Peru 2015b), and project reports, reviews and publications are due to the special biophysical complexity of its territory, projections beyond the general trends on future higher temperatures (i.e. precipitation projections) are difficult to point out. However, working on the perceptions of the senior local people, consulting with the regional authorities and checking their institutional awareness; looking at useful research, and consulting climate specialists Llerena *et al.* (2014a) were able to provide some insights on the present situation and its perspectives at dry forests in Piura, planted forests in Porcón, Cajamarca, and in an extensive lower Amazon forestry concession on the right border of the Ucayali river, near Atalaya, working with native people of the villages Galilea and Nueva Esperanza, sharing part of its communal lands.

Piura was the region with the best institutional framework, orderly teamworking with several regional and national organizations, public, private, and international, including universities, with a good climate database as well as instrumentation and even early alert systems, with good communication established with the general public and the rural communities. The leaders of the rural village visited were also well prepared persons able to deal with the demands of local people supported in great part by the carob tree, mesquite or *algarrobo* (*Prosopis pallida*) which are dominant forests; and mainly their goat herds. Local research carried out with international support, showed a clear trend towards a growing thermal amplitude of the maximum and minimum temperatures which seems to affect the carob trees and other local species (Cajusol 2013).

In Porcón, the community involved in the climate change exploration was more distant from the main city and more controlled by the local leaders under a strict religious regulation. The senior people could clearly see the differences the new planted forests had made in contrast to the original degraded, moist and windy grasslands. Their perceptions of the positive environmental, social, and economical influences of the new landscape with in between 20 and 30 years old, 12000 ha of planted forests (60% *Pinus patula*) were evident. They have a meteorological station but there were not visible interest in doing any kind of research or invest in additional instrumentation to face possible climate demands.

The native people at Galilea and Nueva Esperanza are, general speaking, the ethnic group with deeper roots in their lands. So, the perceptions of the senior citizens could be more clearly contrasted with the older times. Perceptions of the population indicate that the climate is changing in recent years. They felt that at present the temperatures are higher and rains more frequent. It is reported that during the last 10 years the dry season has been temporarily extended one month, beginning the month of June. Most people clearly remember that in previous years rains normally declined from July to October. Concerning flooding, it currently occurs between January and April and presented before between February and May. About the cold fronts or *friajes*, they used to present only in winter (July to September) and now they also occur in autumn (April to June) and much more frequently. There used to be a meteorological station at the forestry concession but since the company retired data gathering has been neglected. It is interesting to notice how the local people check and control their environment simply paying attention to the phenological stages of their local trees and shrubs.

These three different Peruvian cases provide interesting insights on each forest situation facing possible climate changes, taking advantage of the local knowledge. In addition, Espinoza (2015) briefly presents a very complete information about the impacts and projections in the Amazon basin, based upon modern research done during the last years. He points out that, consistent to the tropical region warming, the Peruvian Amazon has encountered an temperature increase of 0.09 °C per decade since 1965 (Lavado *et al* 2013), while recent studies show a decline in rainfall from 1970 (Espinoza *et al* 2009, Lavado *et al* 2012) with a significant increase of the dry season from 1980 (Fu *et al* 2013). In relation to this, more frequent and severe droughts have occurred in the past decade (Espinoza *et al* 2011, Marengo *et al* 2011) producing forest fires (Fernandes *et al* 2011) and it is estimated that tree mortality during these droughts increased 400% compared with normal years (Brando *et al* 2014). An increase in the mortality rate of the Amazonian biomass has been observed over the past three decades (Brienen *et al* 2015), consistent with a reduced capacity of the forest to absorb CO<sub>2</sub>. The authors suggest that climate variability, including extreme droughts, could be responsible for these changes (Brienen *et al* 2015, Lewis *et al* 2011). Just between 2005 and 2014 there have been two historic droughts and three catastrophic floods. Extreme droughts are mainly associated with warm conditions of the sea surface temperature of the tropical Atlantic Ocean and El Niño events, while severe floods are associated primarily (not exclusively) to La Niña events (Marengo *et al* 2015).

The projections of the models CMIP5 at a regional scale for the end of the twenty first century show a consensus on warming in the Amazon region. A possible increase of up to 2°C for RCP2.6 emissions scenarios and up to 5.2°C for RCP8.5 scenario is estimated (Blázquez *et al* 2013, Jones *et al* 2013). Precipitation projections range from +10% to -25% with a huge discrepancy of the models results. Recent studies project a slight increase in volume during high flows season and a significant decline of volume during low flows season (Guimberteau *et al* 2013), coinciding with a lengthier dry season in the future (Fu *et al* 2013). Warmer and drier conditions could result in irreversible impacts to the Amazon rainforest (Cox *et al* 2004, Nobre *et al* 2009), which reinforces the hypothesis of a possible “Amazonian savannization” (Oyama *et al* 2003, Salazar *et al* 2007, Malhi *et al* 2008). Indeed, the models linking climate with vegetation projected a shift from a tropical forest ecosystem to a savannah for the second half of the twenty first century (Oyama *et al* 2003, Salazar *et al* 2007).

Even though a possible collapse of the tropical rainforest, in terms of its intensity and extension is still highly uncertain; studies show that the projected increase of water stress during the dry season towards the end of the twenty first century and the increase of evapotranspiration could favor the Amazon region climate to be more conducive to the development of seasonal forest rather than tropical forest as we currently know it (Malhi *et al* 2009, Costa *et al* 2010). This is a high-risk scenario considering the important role of the Amazon rainforest in regulating moisture transport at a regional level (including the Andes) (Makarieva *et al* 2013, Zemp *et al* 2014) and in carbon balancing for the planet (Cox *et al* 2004). However, these projections could worsen by potential changes in land use in the Amazon induced by human activities such as deforestation, agricultural expansion, etc. (Nobre *et al* 1991, Sampaio *et al* 2007, Costa *et al* 2007, Coe *et al* 2009, Georgescu *et al* 2013, Moore *et al* 2007).

The diverse forests ecosystems including water resources are indeed threatened by climate change, but decades before this present threat arose, all the forests of the world have been seriously depleted by the human beings. So, it will not be too outrageous to say that we need to give each problem its right treatment and priority, while we find ways to clarify our doubts and uncertainties and made the best possible decisions on our forestry management and water practices. On this regard communication is very important as well as to take into consideration each kind of useful knowledge. Forestry practices alone are not any longer a good reply to the present situation. Now is very important, and maybe the only effective answer, to the more pressing land use problems to integrate forest management with other land uses, like on-farm conservation land management for preserving and enhancing ecosystem services in agricultural and forested landscapes together as Thorn *et al* (2015) point out now in the same way Lal and Russell (1981) did almost 35 years ago.

The Faculty of Forest Sciences of the Universidad Nacional Agraria La Molina (FCF UNALM) in Lima, is just dealing with a real life problem at the Dantas experimental forest (Marmillod *et al* 1992, Nalvarte *et al* 1993). This unit used to be a very active research and education center, until the years of socio-political unrest in the zone took everyone out of there. New people migrated into the premises, a new road was built, and part of the forest was destroyed and even converted to illegal crops. FCF UNALM wants to regain the property and the first steps with the local people were already taken successfully. At present, the organization of multidisciplinary teams with agronomists, economists, agricultural engineers, animal husbandry, fisheries, and food and social science specialists, among others, is underway in order to properly deal with the local demands and pressures, restore the ecosystem potential, improve the local livelihood and governance, reclaim the space, and share the experience.

## 9.5 Acknowledgments

To Beatriz Llerena and Adriana Hermoza, for their very important last minute support with English translations and review, as well as tables and figures design and improvement. To Michael Valqui for sharing useful information. To Pablo García-Chevesich, for his consideration, patience and kind support.

## 9.6 References

- Aleman N. C. 2004. Erosión hídrica y usos de la tierra en la cuenca del río Llamaquizú, Oxapampa, Perú. Trabajo de Fin de Carrera de Licenciado en Ciencias. Ambientales, Universidad Politécnica de Valencia - UNALM, La Molina, 45 pp. + anexos.
- Aufdenkampe A.K., Hedges J., Richey J.E., Krusche A.V., Llerena C.A. 2001. Sorptive fractionation of dissolved organic nitrogen and amino acids onto fine sediments within the Amazon Basin. *Limnology and Oceanography* 46 (8): 1921-1935.
- Aufdenkampe A.K., Mayorga E., Hedges J.I., Llerena C.A., Quay P.D., Gudeman J., Krusche A.V., Richey J.E. 2007. Organic matter in the Peruvian headwaters of the Amazon: Compositional evolution from the Andes to the lowland Amazon mainstem. *Organic Geochemistry* 38: 337-364.
- ANA. 2009. Política y Estrategia Nacional de Recursos Hídricos del Perú. Autoridad Nacional del Agua, Lima, 85 p.
- ANA, COSUDE, WWF. 2015. Huella Hídrica del Perú. Sector Agropecuario. Autoridad Nacional del Agua, Agencia Suiza para el Desarrollo y la Cooperación, Fondo Mundial para la Naturaleza, Lima, 58 p.
- Blázquez J., Nuñez M.N. 2013. Analysis of uncertainties in future climate projections for South America: comparison of WCRP-CMIP3 and WCRP-CMIP5 models. *Climate Dynamics* 41(3-4), 1039-1056.
- Bodmer R.E., Fang T.G., Puertas P.E., Antúnez M., Chota K. y Bodmer W.E. 2014. Cambio climático y fauna silvestre en la Amazonia peruana. Impacto de la sequía y de las inundaciones intensas en la Reserva Nacional Pacaya Samiria. Fundación Latinoamericana para el Trópico Amazónico (Fundamazonia). Lima, 254 p.
- Bradley R.S., Vuille M., Díaz H.F., Vergara W. 2006. Threats to Water Supplies in the Tropical Andes. *Science* 312: 1755-1756.

- Brando P.M., Balch J.K., Nepstad D.C., Morton D.C., Putz F.E., Coe M.T., Silvério D., Macedo M.N., Davidson E., Nóbrega C.C., Alencar A., Soares-Filho B.S. 2014. Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *Proceedings of the National Academy of Sciences* doi: 10.1073/pnas.1305499111.
- Brienen R.J.W., Phillips O., Feldpausch T.R., Gloor E., Baker T.R., Lloyd J., López-González G., Monteagudo-Mendoza A., Malhi Y., Lewis S.L., Vásquez-Martínez R., Alexiades M., et al 2015. Long-term decline of the Amazon carbon sink. *Nature* 519: 344-348. doi:10.1038/nature14283.
- Bruijnzeel L.A. 1990. Hydrology of moist tropical Forests and effects of conversion: a state of knowledge review. UNESCO, IAHS, Free University Amsterdam, 224 p.
- Bruijnzeel L.A. 2004. Hydrological function of tropical forests: not seeing the soil for the trees. *Agriculture Ecosystems & Environment* 104: 185-228.
- Bruijnzeel, L.A., Scatena F.N., Hamilton L.S. (edits.). 2010. Tropical Montane Cloud Forests. Science for Conservation and Management, Cambridge University Press, 740 p.
- Buytaert W., Iñíguez V., De Bievre B. 2007. The effects of afforestation and cultivation on water yield in the Andean paramo. *Forest Ecology and Management* 251 (1-2): 22-30.
- Cajusol C.G. 2013. Impactos del cambio climático y medidas de adaptación para la conservación del bosque seco y sostenibilidad de la cadena de valor de derivados de algarroba en la Región Piura. GIZ, PerúBiodiverso, Gobierno Suizo, Ministerio de Comercio Exterior y Turismo, GORE Piura.
- Calder I., Hofer, T., Vermont, S., Warren, P. 2007. Towards a new understanding of forests and water. *Unasylva* 58 (229): 3-10.
- Catchpole D. 2004 Ecology of vascular epiphytes on a *Ficus* L. host, Moraceae, in a Peruvian cloud forest, Tesis M.Sc. Geografía y Estudios Ambientales Universidad de Tasmania, 166 pp.
- Catchpole D. 2012. Orographic gradients in climate and forest cover at the cordillera Yanachaga, Peru, Tesis Ph.D., Geografía y Estudios Ambientales Universidad de Tasmania, 252 pp.
- CIFOR. 2012. Forests and water: What policy maker should know? Factsheet N°6.
- Coe M.T., Costa M.H., Soares-Filho B.S. 2009. The influence of historical and potential future deforestation on the stream flow of the Amazon River. Land surface processes and atmospheric feedbacks. *Journal of Hydrology* 369 (1-2): 165-174.
- Cossio R., Menton M., Cronkleton P., Larson A. 2014. Manejo forestal comunitario en la Amazonia peruana. Una revisión bibliográfica. Documento de trabajo 140. CIFOR, Lima, 25 p.
- Costa M. H., Yanagi S.N.M., Souza P.J.O.P., Ribeiro A., Rocha E.J.P. 2007. Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion, *Geophysical Research Letters* 34: L07706.
- Costa M.H., Biajoli L., Sanches A.C.M., Malhado L.R., Hutyrá H.R., da Rocha H., Aguiar R.G., de Araujo A.C. 2010. Atmospheric versus vegetation controls of Amazonian tropical rain forest evapotranspiration: are the wet and seasonally dry main forests any different?. *Journal of Geophysical Research* 115: G04021, doi: 10.1029/2009JG001179.
- Cox P.M., Betts R.A., Collins M., Harris P.P., Huntingford C Jones C.D. 2004. Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theoretical Applied Climatology* 78 (1-3): 137-156.
- Cuesta F., Bustamante M., Becerra M.T., Postigo J., Peralvo J. (Eds.) 2012a. Panorama andino de cambio climático. Vulnerabilidad y adaptación en los Andes tropicales. CONDESAN, SGCAN, Lima, 335 p.
- Cuesta F., P. Muriel, S. Beck, R. I. Meneses, S. Halloy, S. Salgado, E. Ortiz y M.T. Becerra. (Eds.) 2012b. Biodiversidad y Cambio Climático en los Andes Tropicales. Conformación de una red de investigación para monitorear sus impactos y delinear acciones de adaptación. Red Gloria-Andes, Lima-Quito, 180 p.
- Dourojeanni M.J. 1987. Manejo de bosques naturales en el trópico americano: situación y perspectivas. *Revista Forestal del Perú* 14 (1): 91-108.
- Dourojeanni M.J. 2009. Crónica Forestal del Perú. UNALM, UNMSM, Lima, 727 p.
- Dourojeanni M.J., Barandiarán A., Dourojeanni, D. 2009. Amazonia Peruana en 2021. Explotación de recursos naturales e infraestructura: ¿Qué está pasando? ¿Qué es lo que significa para el futuro?. ProNaturaleza, SPDA, DAR, ICAA, Lima, 162 p.
- Dudley, N., Stolton S. 2003. Running Pure: The importance of forest protected areas to drinking water. World Bank/WWF Alliance for Forest Conservation and Sustainable Use, Washington D.C., 112 p.
- Elsenbeer H. 1989. Hillslope hydrological processes and their controls in a tropical rainforest environment, Tesis Ph.D., NCSU, Raleigh, 207 p.



- Elsenbeer H., Lack A., Cassel D.K. 1995. Chemical fingerprints of hydrological compartments and flow paths at La Cuenca, western Amazonia. *Water Resources Research* 31 (12): 3051-3058.
- Elsenbeer H., Cassel D.K., Zúñiga L. 1994. Throughfall in the *terra firme* forest of Western Amazonia. *Journal of Hydrology* (NZ), 32 (2): 30-44.
- Espinoza J.C., Guyot J-L., Ronchail J., Cochonneau G., Filizola N., Fraizy P., Labat D., de Oliveira E., Ordoñez J., Vauchel P. 2009. Contrasting regional discharge evolutions in the Amazon basin (1974-2004). *Journal of Hydrology* 375 (3-4): 297-311.
- Espinoza J.C., Ronchail J., Guyot J.L., Junquas C., Vauchel P., Lavado W., Drapeau G., Pombosa R., 2011. Climate variability and extreme drought in the upper Solimões River (western Amazon Basin): Understanding the exceptional 2010 drought. *Geophysical Research Letters* 38 (13): L13406.
- Espinoza J.C., Ronchail J., Guimberteau M., Guyot J.L., Lavado W., Santini W. 2014. Eventos hidrológicos extremos en la cuenca amazónica peruana: presente y Futuro. In: El Perú frente al cambio climático. Resultados de investigaciones franco-peruanas. IRD, MINAM, Embajada de Francia. 47-57.
- Espinoza J.C. 2015. Finding observed impacts and future projections in the Amazon basin. Brief review about the state of the art on the Amazon and climate change for MINAM (unpublished) 4 p.
- FAO. 2004. Sistemas de pago por servicios ambientales en cuencas hidrográficas, Land and Water Discussion Paper 3, Roma 74 p. + CD.
- FAO. 2015. Global Forest Resources Assessment 2015. How are the world's forests changing?, Roma, 56 p.
- Farley K.A., Jobbágy E.G., Jackson R.B. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* 11:1565–1576.
- Fernandes K., Baethgen W., Bernardes S., DeFries R., DeWitt D.G., Goddard L., Lavado W., Eun Lee D., Padoch C., Pinedo-Vasquez M., Uriarte M. 2011. North Tropical Atlantic influence on western Amazon fire season variability. *Geophysical Research Letters*. 38: L12701, doi:10.1029/2011GL047392
- Figueroa C., Wadsworth, F.H., Branham S. 1987. Management of the Forests of Tropical America: Prospects and Technologies. ITF, UPR, USAID, USDA FS & OICD, 469 p.
- Fu R., Yin L., Li W., Arias P.A., Dickinson R.E., Huang L., Fernandes K., Liebmann B., Fisher R., Myneni R.B. 2013. Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *Proceedings of the National Academy of Sciences* 110: 18110–18115.
- Gaviria, A., Sabogal C. 2013. Sistematización de seis experiencias de manejo forestal comunitario en la Amazonia peruana. FAO, INF, MINAM, MINAGRI, Lima, 89 p.
- Georgescu M., Lobell, D.B., Field C.B., Mahalov A. 2013. Simulated hydroclimatic impacts of projected Brazilian sugarcane expansion. *Geophysical Research Letters* 40 (5): 972-977.
- Gilmour, D. 2014. Forests and water: A synthesis of the contemporary science and its relevance for community forestry in the Asia–Pacific region. RECOFTC Issue Paper No. 3. The Center for People and Forests, Bangkok, 30 p.
- Glauber A.J. 2001. Landslide effects on litterfall to Amazonian montane headwater streams, Tesis M.Sc. Universidad de Washington, Seattle, 42 p. + anexos.
- Gloor M., Brienen R.J.W., Galbraith D., Feldpausch T.R., Schöngart J., Guyot J.L., Espinoza J.C., Lloyd J., Phillips O.L. 2013. Intensification of the Amazon hydrological cycle over the last two decades. *Geophysical Research Letters* 40: 1–5.
- Gómez Z.P. 2001. Variabilidad espacio-temporal del nitrógeno e iones mayores en la cuenca del río Pachitea, Perú, Tesis M.Sc. EPG-UNALM, La Molina, 124 pp. + anexos.
- Gómez P.D. 2000. Composición florística en el bosque ribereño de la cuenca alta San Alberto, Oxapampa, Perú, Tesis Ing. For. UNALM, La Molina, 159 pp. + anexos.
- Gomez-Peralta D., Oberbauer S.F., McClain M.E., Philippi T.H. 2008. Rainfall and cloud-water interception in tropical montane forests in the eastern Andes of Central Peru. *Forest Ecology and Management* 255 (3-4): 1315-1325.
- Guariguata M. (Edit.) 2013. Avances y perspectivas del manejo forestal para uso múltiple en el trópico húmedo. CIFOR, Bogor, 281 p.
- Guimberteau M., Ronchail J., Espinoza J.C., Lengaigne M., Sultan B., Polcher J., Drapeau G., Guyot J.L., Ducharme A., Ciais P. 2013. Future changes in precipitation and impacts on extreme streamflow over Amazonian sub-basins. *Environmental Research Letters* 8 (1): 014035.
- Hamilton L.S., King P.N. 1983. Tropical forested watersheds, Hydrologic and soils response to major uses or conversions, East-West Center/UNESCO-MAB, Westview Press, Boulder, 168 pp.

- Hamilton L.S., Juvik J.O., Scatena F.N (Edits.). 1995. Tropical Montane Cloud Forests, Ecological Studies Vol.110, Springer-Verlag, Ann Arbor, 407 pp.
- Hamilton, L.S. 2008. Forest and water. FAO Forestry Paper 155. Roma, 78 p.
- Hayek F., Martínez de Anguita P. (Edits.) 2012. ¿Gratis?: los servicios de la naturaleza y cómo sostenerlos en Perú. Servicios Ecosistémicos Perú, Lima, 428 p.
- Herzog S., Martínez R., Jorgensen P., Tiessen H. (Edits.). 2012. Cambio climático y biodiversidad en los Andes tropicales. IAI, SCOPE, París, 426 p.
- IICA. 2012. Manejo Forestal Sostenible en la Región Andina. Catálogo de Proyectos del Programa MFS. Instituto Interamericano de Cooperación para la Agricultura, Ministerio de Asuntos Exteriores de Finlandia, Lima, 53 p.
- INRENA. 2005. Plan Nacional de Reforestación. Perú 2005-2024. Lima, 88 p.
- IRD. 2014. El Perú frente al cambio climático. Resultados de investigaciones franco-peruanas. MINAM, Embajada de Francia, Lima, 156 p.
- Jones C., Carvalho L.B. 2013. Climate change in the South American Monsoon System: present climate and CMIP5 projections. *Journal of Climate* 26 (17): 6660-6678.
- Kalliola R. 1992. Abiotic control of the vegetation in Peruvian Amazon floodplains: environment change and pioneer species. UTU-ART, Ph.D. thesis.
- Kuroiwa, J. 2012. Recursos hídricos en el Perú. Una visión estratégica. In: Diagnóstico del Agua en las Américas, B. Jimenez and J.G. Tundisi (Coords.), IANAS, FCCT, AC, Mexico DF, 405-219 p.
- Lal R., Russell E.W. (Edits.). 1981. Tropical Agricultural Hydrology. Watershed Management and Land Use. John Wiley & Sons Ltd., 482 p.
- Lavado W., Ronchail J., Labat D., Espinoza J.C., Guyot J.L. 2012. Basin-scale analysis of rainfall and runoff in Peru (1969-2004): Pacific, Titicaca and Amazonas drainages. *Hydrological Sciences Journal - Journal Des Sciences Hydrologiques* 57 (4): 625-642.
- Lavado W., Labat D., Ronchail J., Espinoza J.C., Guyot J.L. 2013. Trends in rainfall and temperature in the Peruvian Amazon-Andes basin over the last 40 years (1965-2007). *Hydrological Processes* 41: 2944-2957. doi:10.1002/hyp.9418
- Lewis S.L., Brando P.M., Phillips O.L., van der Heijden G.M.F., Nepstad D. 2011. The 2010 Amazon Drought. *Science* 331 (6017): 554-554.
- Lima W. de P. 1993. Impacto ambiental do eucalipto, Edusp, Sao Paulo, 301 pp.
- Llerena C.A. 1989. Antecedentes sobre Manejo del Bosque Húmedo Tropical. En: Experiencias de Manejo del Bosque Húmedo Tropical en Perú. FAO/Japón, Documento 20, Lima, 20-43.
- Llerena C.A. 1991a. Contaminación atmosférica, efecto invernadero y cambios climáticos: sus impactos forestales. *Revista Forestal del Perú* 18 (2): 101-135.
- Llerena C.A. 1991b. El manejo de Cuencas en el Trópico Húmedo del Perú, *Revista Forestal del Perú* 18 (1): 63-77.
- Llerena C.A. 2005. Conceptos sobre cuencas hidrográficas e hidrología forestal relacionados a servicios ambientales y producción de agua. Debate Interinstitucional: Enfoques y Mecanismos de Valoración Multidimensional del Agua y del Pago por Servicios Ambientales. Curso Gestión Integrada de Recursos Hídricos, CAMAREN-Ecuador, IPROGA-Perú, Lima, 11 p.
- Llerena C.A. 2007a. El Proyecto LBA, *Xilema* 19: 14-18.
- Llerena C.A. 2007b. El agua y la forestación en las cuencas de la sierra. *Xilema* 18: 7-13.
- Llerena C.A., Cruz Z., Durt E., Marcelo-Peña J.L., Martínez K. y Ocaña J.C. 2010. Gestión Ambiental de un Ecosistema Frágil. Los bosques nublados de San Ignacio, Cajamarca, cuenca del río Chinchipe, UNALM, Soluciones Prácticas ITDG, Lima, 130p.
- Llerena C.A., Hermoza R.M. 2010. ¿Cuántas cuencas hidrográficas hay en el Perú? *Xilema* 23: 24-26.
- Llerena C.A., Hermoza R.M. y Llerena C.M. 2011. Las plantaciones forestales y el agua en las cuencas, *Xilema* 24: 55-59 p.
- Llerena C.A., Hermoza R.M., Llerena L.M. 2007. Plantaciones forestales, agua y gestión de cuencas, *Debate Agrario* N° 42: 79-110.
- Llerena C.A., Yalle S.R. 2014. Servicios ecosistémicos en el Perú. *Xilema* 27: 62- 75 p.

- Llerena C.A., Yalle S.R., Sabogal C. 2014a. Aplicación de las directrices sobre cambio climático para los responsables de la gestión forestal. Planes de ejecución de acciones de adaptación y mitigación priorizadas frente a los impactos del cambio climático en tres áreas del Perú en Piura, Cajamarca y Ucayali. FAO, Lima, 77 p.
- Llerena, C.A., Yalle S.R., Silvestre E. 2014b. Los bosques y el cambio climático en el Perú: situación y perspectivas. FAO, Lima, 73 p.
- Llerena L.M. 2007. Evaluación del efecto de tubos protectores con capacidad de condensación de neblinas en el crecimiento inicial de plántulas de col de monte (*Tetrorchidium rubrivenium*) en Oxapampa, Perú, Tesis Ing. For. UNALM La Molina, 66 p + anexos.
- Locatelli B., Kanninen M., Brockhaus M., Pierce Colfer C.J., Murdiyarto D., Santoso H. 2009. Ante un futuro incierto. Como se pueden adaptar los bosques y las comunidades al cambio climático. Perspectivas Forestales N° 5 CIFOR, Bogor, 90 p.
- Lombardi I. y Llerena C.A. 1991. Recopilación y análisis de trabajos de Silvicultura y Manejo Forestal en el bosque húmedo tropical del Perú (Proyecto FAO/Japón).
- Makarieva A.M. and Gorshkov V.G. 2007. Biotic pump of atmospheric moisture as driver of the hydrologic cycle on land. *Hydrology & Earth Systems Science* 11: 1013-1033.
- Makarieva A.M., Gorshkov V.G., Sheil D., Nobre A.D., Li B.L. 2013. Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. *Atmospheric Chemistry and Physics* 13: 1039–1056, doi:10.5194/acp-13-1039-2013.
- Malhi Y., Roberts J., Betts R., Killeen T., Li W., Nobre C. 2008. Climate change, deforestation, and the fate of the Amazon, *Science*, 319: 169-172.
- Malhi Y., Aragão L., Galbraith D., Huntingford C., Fisher R., Zelazowski P., Sitch S., Mcsweeney C., Meir P. 2009. Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences* 106: 20610–20615.
- Malhi Y., Silman M., Salinas N., Bush M., Meir P., Saatchi S. 2010. Introduction: Elevation gradients in the tropics: laboratories for ecosystem ecology and global change research. *Global Change Biology* 16: 3171-3175.
- Marengo J.A. 2006. Mudanças climáticas globais e seus efeitos sobre a biodiversidade: caracterização do clima atual e definição das alterações climáticas para o território brasileiro ao longo do século XXI. Biodiversidade 26, Brasília, MMA, 212pp.
- Marengo J.A., Tomasella J., Alves L.M., Soares W.R., Rodriguez D.A. 2011. The drought of 2010 in the context of historical droughts in the Amazon region. *Geophysical Research Letters* 38: L12703.
- Marengo J.A., Espinoza J.C. 2015. Review Article. Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts. *International Journal of Climatology* 19 p. DOI: 10.1002/joc.4420
- Marmillod D., Nalvarte W. y Llerena C.A. 1992. La Unidad Modelo de Manejo y Producción Forestal Dantas. *Revista Forestal del Perú* 19 (1): 7-17.
- McClain M.E., Aparicio L.M., Llerena C.A. 2001. Water use and protection in rural communities of the Peruvian Amazon basin. *Water International* 26 (39): 400-410.
- McClain M.E., Cossio R.E. 2003. The use of riparian environments in the rural Peruvian Amazon. *Environmental Conservation* 30 (3): 242-248.
- McClain M.E., Galarraga R., Llerena C.A. y Ruiz J.E. 2007. Linking Global Change Research to Improved Policies and Management for Amazonian Rivers. En: *Communicating Global Change Science to Society*, editores: H. Tiessen, M. Brklacich, G. Breulmann y R. S.C. Menezes, Publicación SCOPE 68, Island Press, Washington DC, pp. 171-178.
- McClain M.E., Llerena C.A. 1998. El Manejo de Cuencas en Perú: de los Andes a la Amazonia. *Agua y Riego (IPROGA)*, vol. 12.
- Meir, P., Mitchell, A., Marengo, J., Young, C., Poveda, G., Llerena, C.A., Rival, L., Meneses, L., Hall, A., Betts, R., Farley, J., Fordham, S., Trivedi, M. 2011. Ecosystem Services for Poverty Alleviation in Amazonia. Global Canopy Programme y Universidad de Edimburgo, UK, 195p.
- Meir P., Wood T.E., Galbraith D., Brando P., Da Costa A.C.L., Rowland L., Ferreira, L. 2015. Threshold responses to soil moisture deficit by trees and soil in tropical rain forests: Insights from field experiments. *BioScience* 65 (9): 882-892.
- MINAM. 2012. Memoria Descriptiva. Mapa de cobertura Vegetal del Perú. Lima, 75 p.
- MINAM. 2014. Peru Kingdom of Forests. Lima COP20, CMP10. German Cooperation, Swiss Cooperation, Lima, 303 p.

- Molina J.A. 2001. Caracterización hidrológico-forestal de dos microcuencas con diferente cobertura vegetal en la cuenca del río San Alberto, Oxapampa, Perú, Tesis M.Sc. EPG-UNALM, La Molina, 91 p. + anexos.
- Moll M.E. 2001. Estudio de la infiltración en las dos microcuencas experimentales del proyecto AARAM-Perú (Wara y Killa) en San Alberto, Oxapampa, Ejercicio de Fin de Carrera de Ing. Técnica Forestal, Universidad Politécnica de Valencia, Gandía - UNALM, La Molina, 108 pp. + anexos.
- Moore N., Arima E., Walker R., Ramos da Silva R. 2007. Uncertainty and the changing hydroclimatology of the Amazon. *Geophysical Research Letters* 34 (14).
- Nalvarte W., Kroll B., Lombardi I. 1993. Plan Maestro. Unidad Modelo de Manejo y Producción Dantas. UNALM, 148 p.
- Nepstad D.C., Verissimo A., Alencar A., Nobre C., Lima E., Lefebvre P., Schlesinger P., Potter C., Moutinho P., Mendoza E., Cochrane M., Brooks V. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* 398: 505-508.
- Nepstad D.C., Tohver I.M., Ray D., Moutinho P., Cardinot G. 2007. Mortality of large trees and lianas following experimental drought in an Amazon forest. *Ecology* 88 (9): 2259-2269.
- Nobre, A.D. 2014. El Futuro Climático de la Amazonia. Informe de Evaluación Científica. In: Pan-Amazonia: escenarios y desafíos de la crisis climática. ARA, Lima, 14-65 p.
- Nobre C., Sellers P., Shukla J. 1991. Amazonian Deforestation and Regional Climate Change. *Journal of Climatology* 4: 957-988.
- Nobre C., Borma L.S. 2009. Tipping points' for the Amazon forest. *Current Opinion in Environmental Sustainability* 1: 28-36, doi: 10.1016/j.cosust.2009.07.003.
- Ochoa-Tocachi B. et al Impacts of land use on the hydrological response of tropical Andean ecosystems. *Hydrological Processes*, special issue on South American hydrology (in press).
- Ordoñez J. 2001. Análisis hidrometeorológico y aplicación del modelo IPH-MEN en la cuenca del río Pachitea, Tesis M.Sc. EPG-UNALM, La Molina, 145 pp. + anexos.
- Ormachea M., Llerena C.A. 1992. Erosión hídrica en el bosque húmedo tropical de Dantas. *Revista Forestal del Perú* 19 (1): 19-34.
- Oyama M.D., Nobre C., 2003. A new climate-vegetation equilibrium state for Tropical South America. *Geophysical Research Letters* 30: 2199.
- Palacios A., Tume P. 1991. Medición de la transpiración en árboles. *Revista Forestal del Peru* 18 (2): 45-54.
- Perú. 2015a. Reglamento de la Ley Forestal, 4 volúmenes: Gestión forestal; Gestión de la fauna silvestre; Gestión de plantaciones forestales y sistemas agroforestales; Gestión forestal y de fauna silvestre en comunidades nativas y campesinas. DS 018, 019, 020, 021-2015-MINAGRI. Diario Oficial El Peruano 30/09/2015, separata especial: 562528-562662.
- Perú. 2015b. Hacia una estrategia Nacional sobre Bosques y Cambio Climático. Documento preliminar. DS N° 011-2015-MINAM. Comisión Multisectorial: MINAM, MINAGRI, Ministerio de Cultura, MRREE, MEF, Lima, 112 p.
- Phillips O.L. et al (66). 2009. Drought Sensitivity of the Amazon Rainforest. *Science* 323: 1344-1347.
- Quintero M. (Edit.). 2010. Servicios Ambientales Hidrológicos en la Región Andina, IEP, CONDESAN, Lima, 252 pp. + 7 anexos.
- Ramos O. 2002. Pérdidas de nitrógeno del bosque de neblina en las subcuencas de San Alberto, Oxapampa, Perú, Tesis M.Sc. EPG-UNALM, La Molina, 89 pp + 7 anexos.
- Reyes R. 2014. Influencia de cuatro sistemas de uso de la tierra (Teca, cítricos y café bajo sombra manejado y en abandono) en la sortividad en el IRD Selva, Fundo La Génova, Chanchamayo, Junín, Tesis Ing. Forestal, UNALM, La Molina, 117 p.
- Rodríguez M.E. 2002. Estudio comparativo de la influencia de la vegetación en el ciclo hidrológico en dos microcuencas experimentales del río San Alberto, Oxapampa, cuenca del Pachitea, Proyecto AARAM-Perú, Ejercicio de Fin de Carrera de Ing. Técnica Forestal, Universidad Politécnica de Valencia, Gandía - UNALM, La Molina, 93 p + 7 anexos.
- Roncal W. 2006. Influencia de las plantaciones forestales sobre la escorrentía superficial y la erosión hídrica en Porcón, Cajamarca, Perú. Tesis M.Sc., EPG-UNALM, 138 p.
- Ruiz G.R.A. 1985. Evaluación de la influencia del bosque de protección en la conservación del suelo y agua en Oxapampa, Perú, Tesis M.Sc., EPG-UNALM, La Molina, 148 p.



- Sabogal C., Carrera F., Colán V., Pokorny B., Louman B. 2004. Manual para la planificación y evaluación del manejo forestal operacional en bosques de la Amazonia peruana. INRENA, CIFOR, FONDEBOSQUE, CATIE, Lima, 279 p.
- Sabogal C., Casaza J. 2010. Standing tall: Exemplary cases of sustainable forest management in Latin American and the Caribbean. FAO, Junta de Castilla y León, Rome, 276 p.
- Salazar L.F., Nobre C., Oyama M.D. 2007. Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters*. 34: L09708.
- Salo, J. 1988. Rainforest diversification in the western Amazon basin: the role of river dynamics. UTU-ART, Ph.D. thesis.
- Sampaio G., Nobre C., Costa M.C., Satyamurty P., Soares-Filho B.S., Cardoso M. 2007. Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion, *Geophysical Research Letters* 34, L17709
- Sánchez P.J.M. 2001. Use of the BMWP system for assessing water quality in San Alberto river (Oxapampa, Peru), Tesis M.Sc., IHE, Delft, 44 pp. + anexos.
- Saunders T.J., McClain M.E. y Llerena C.A. 2006. The biogeochemistry of dissolved nitrogen, phosphorus, and organic carbon along terrestrial-aquatic flowpaths on a montane headwater catchment in the Peruvian Amazon. *Hydrological Processes* 20: 2549-2562.
- Sebastian K. Herzog, S.K., Martínez, R., Jørgensen, P.M., Tiessen, H. (Edits.) 2011. Climate Change and Biodiversity in the Tropical Andes. Inter-American Institute for Global Change Research (IAI) and Scientific Committee on Problems of the Environment (SCOPE), 348 p.
- Stadtmuller T. 1994. Impacto Hidrológico del Manejo Forestal de Bosques Naturales Tropicales: Medidas para Mitigarlo, una revisión bibliográfica, CATIE-COSUDE, Colección Silvicultura y Manejo de Bosques Naturales N° 10, Turrialba, 62 p.
- Thorn J., Snaddon J. Waldron A., Kok K, Zhou W., Bhagwat S., Willis K., Petrokofsky G. 2015. How effective are on-farm conservation land management strategies for preserving ecosystem services in developing countries? A systematic map protocol. *Environmental Evidence* 4:. DOI 10.1186/s13750-015-0036-5
- Tobón C. 2009. Los bosques andinos y el agua, ECOBONA-INTERCOOPERATION, CONDESAN, Serie investigación y sistematización #4, Quito, 122 p.
- Townsend-Small A., McClain M.E., Hall B., Llerena C.A., Noguera J.L. y Brandes J.A. 2008. Contributions of suspended organic matter from mountain headwaters to the Amazon River: A one-year time series study in the central Peruvian Andes. *Geochimica et Cosmochimica Acta* 72: 732-740.
- Tume P., Cárdenas M., Calderón W. 1989. Efecto de la napa freática en el crecimiento y enraizamiento de *Prosopis pallida* en Piua. *Revista Forestal del Perú* 16 (19): 65-71.
- UNESCO. 1993. Hydrology and Water Management in the Humid Tropics, Edits.: M. Bonell, M. Hufschmidt y J.S. Gladwell, Cambridge University Press, 590 pp.
- Velásquez D.F. 2002. Estudio de la dinámica fluvial del río Ucayali y su influencia en la sucesión forestal en el área de Pucallpa, Tesis M.Sc., EPG-UNALM, 138 pp.
- Victoria R.L., Martinelly L.A., Mortatti J., Richey J. 1991. Mechanisms of Water Recycling in the Amazon Basin: Isotopic Insights. *Ambio* 20 (8): 384-387.
- Werth D., Avissar R. 2002. The local and global effects of Amazon deforestation. *Journal of Geophysical Research* 107D20, 8087, LBA 55, doi:10.1029/2001JD000717
- Zanabria P., Llerena C.A. 2003. Los bosques nublados de la Amazonia andina y su influencia en la precipitación neta: quebrada Torohuaca, San Ignacio, Cajamarca, Perú. *Revista Forestal del Perú* 26 (1-2): 37-49.
- Zarin D., Alavalapati J.R.R., Putz F.E., Schmink M. (Edits.). 2004. Working Forests in the Neotropics. Conservation through sustainable management. Columbia University Press, NY, 437 p.
- Zemp D.C., Schleussner C.F., Barbosa H.M.J., van der Ent R.J., Donges J.F., Heink J., Sampaio G., Rammig A. 2014. On the importance of cascading moisture recycling in South America. *Atmospheric Chemistry and Physics* 14: 13337–13359.

# Chapter 10. Forest Management and Water in Romania

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## 10.1 Introduction

Romania's relief is split threefold: 31% mountainous, 36% hills/plateaus, and 33% plains. The Carpathian ring is part of the Alpine chain, connected to the Alps in the west and the Balkans in the south. Beyond this are the Transylvanian Depression, which fills the Carpathian ring, hills, plains, and the Dobrogea Plateau, plus the plains of the Lower Danube and Banat-Crisana.

Romania's climate is mild, temperate-continental with four distinct seasons, most precipitation in the warm season and some Mediterranean influence to the south. Mean annual precipitation is 400-800 mm in the main agricultural area and over 1,200 mm in the Carpathians. Severe drought occurs every 15-25 years, especially in the plains.

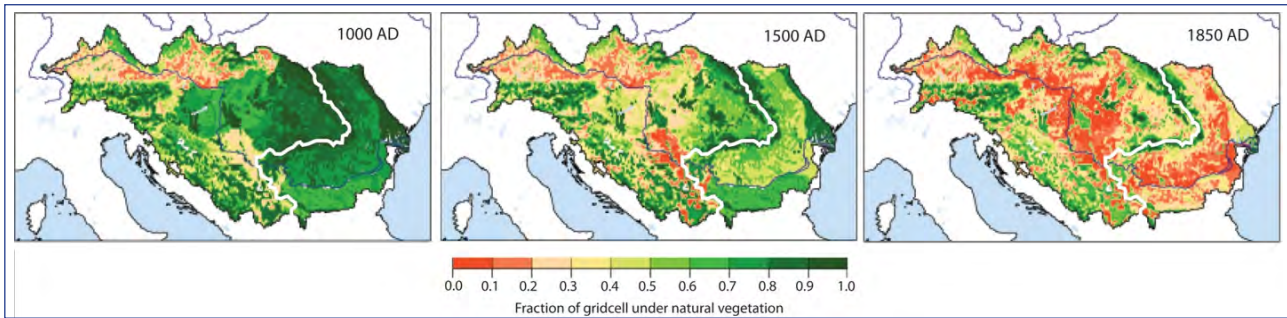
Total forest area in Romania consists of 6,339,000 hectares, from which 6,245,000 hectares are covered with forest vegetation (27% of total land area of the country). Forest composition is varied; conifers represent 31% of the total forested area (23% spruce, 5% fir-tree, and other conifers 3%), beech 31%, oaks 18%, other hard broad-leaves 15% and soft broad-leaves 5% (Giurgiu, 2010). In terms of tree cover, the area is larger (approximately 8 million hectares), being the difference given mostly by reforestation of abandoned agricultural land.

The Romanian forests have a very interesting history due to the influences of different policies from the neighboring empires (Austrian-Hungarian, Ottoman, and Russian). This history revealed drastically changes in landscapes, especially in the portion of forests lost for agricultural land (Figure 1). Cutting age research results showed that *“Over the last century humans have altered the export of fluvial materials leading to significant changes in morphology, chemistry, and biology of the coastal ocean. Here we present sedimentary, paleoenvironmental and paleogenetic evidence to show that the Black Sea, a nearly enclosed marine basin, was affected by land use long before the changes of the Industrial Era. Although watershed hydroclimate was spatially and temporally variable over the last ~3000 years, surface salinity dropped systematically in the Black Sea. Sediment loads delivered by Danube River, the main tributary of the Black Sea, significantly increased as land use intensified in the last two millennia, which led to a rapid expansion of its delta. Lastly, proliferation of diatoms and dinoflagellates over the last five to six centuries, when intensive deforestation occurred in Eastern Europe, points to an anthropogenic pulse of river-borne nutrients that radically transformed the food web structure in the Black Sea”* (Giosan et al., 2012).

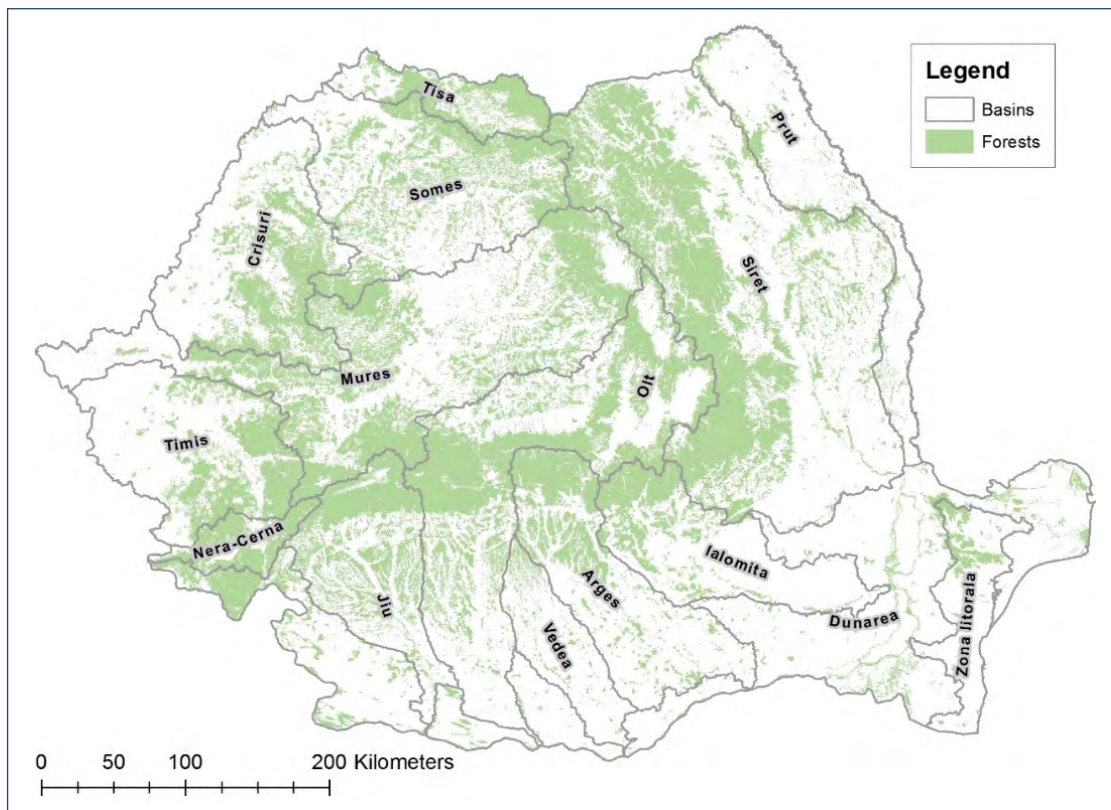
Between 1864 and First World War, the increasing agricultural business in Romania put pressure on forests, causing losses up to 25% of forest cover. Due to this drastic change of land use, the period between the two world wars is dominated by the “Land Reclamation Law” (1930), which governed the legal framework for inventory of degraded lands, establishing the perimeters for afforestation of degraded lands and torrents. Based on this law, Romania's politics intend to increase forest cover, but due to the lack of finance and focus, and constant pressure from societal needs, the approximate increase of forest cover with planted forests was 100,000 hectares, meaning a 2% increase (Figure 2).

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**Figure 1.** Forest cover evolution in Romania (Giosan et al., 2012)



**Figure 2.** Forest cover distribution in Romania's major basins.

In terms of priority functions performed by forests, according to forest management plans drawn up in recent years, forests coverage with special protection functions (functional group I) is 53.1%. The forests in this category are assigned with an important role in stopping and, especially, preventing degradation phenomena and the occurrence of torrential floods. Managed as living shields against soil degradation and pollution of water sources, 24.1% of the forests are primarily managed for soil protection, and 14.5% are designed with water protection functions (Table 1).

**Table 1.** Forest protection functions on basins and utilizable water resources

Basin Name	Protection Forests (%)				Usable Water Resources (BCM/year)
	Water protection	Soil protection	Other protection	Total	
Tisa	9.4	22.6	10.6	42.6	6.24
Someș	7.4	13.5	14.3	35.2	
Crișuri	11.5	13.8	8.1	33.4	2.87
Mureș	8.2	21.3	16.9	46.4	5.77
Timiș	9.7	19.4	16.7	45.8	3.56
Nera - Cerna	7.5	32.8	29.6	69.9	
Jiu	9.5	34.8	9.4	53.7	3.47
Olt	26.9	22.8	10.6	60.3	5.3
Vedea	2.5	52.4	15.3	70.2	2.39
Argeș	19	44.2	21.1	84.3	
Ialomița	18.9	28.4	32.6	79.9	1.39
Siret	13.9	23.6	11.4	48.9	7.54
Prut	5.3	11.5	8	24.8	1.76
Dunăre	34.8	30.2	25.7	90.7	-
Litoral	0	19.6	20	39.6	0.11
<b>Total</b>	<b>14.5</b>	<b>24.1</b>	<b>14.5</b>	<b>53.1</b>	<b>40.41</b>

The main forest products in Romania are represented by roundwood (Figure 3), which increased up to 18 million cubic meters in 2013. This increasing wood production yielded a higher demand in the market, putting pressure on forest resources.

**Figure 3.** Wood production (Source: Eurostat)

Romania's surface water endowment consists of internal river basins as well as the Danube, which is a trans-boundary river basin shared by 19 countries. The natural surface water potential of Romania is 127 Billion Cubic Meters (BCM)/year, with the internal river basins contributing 40 BCM and the Danube contributing 87 BCM per year. The groundwater endowment is estimated to be 10 BCM/year (Stanciu et al., 2011).



### *Water resources*

- Reservoirs: 1,449 from which 400 are very important
- Accumulated volume: 13,070 million cubic meters

### *Main water uses*

- 3,110 drinking water intakes with an installed flow of 171 cubic meters/second, from which 67 cubic meters/second are ground sources intakes.
- 3,838 industrial water intakes with an installed flow of 1082 cubic meters/second, from which 49 cubic meters/second are intakes from ground sources.
- 363 hydroelectric power stations in function, with 692 power groups.

With a current population of 20.2 million, the average water availability in Romania is about 2,000 cubic meters per capita per year. While this value is above the thresholds generally defined for water stress (1,700 cubic meter per capita per year) (Falkenmark, 1989), it is lower than the average value for Europe (4,500 cubic meters per capita per year), and underscores the need for good management to ensure resource conservation and sustainability.

Water demands have steadily decreased in Romania since the 1990s, mainly due to structural changes in the economy:

- Economically unviable irrigation schemes have closed.
- Industrial production has reduced, and the remaining industries have significantly reduced water consumption in production processes.
- Utilities have reduced losses and introduced tariffs, which have helped reducing water consumption in the domestic sector, even though the provision of water supply and sanitation services has expanded to an increasing fraction of the population.

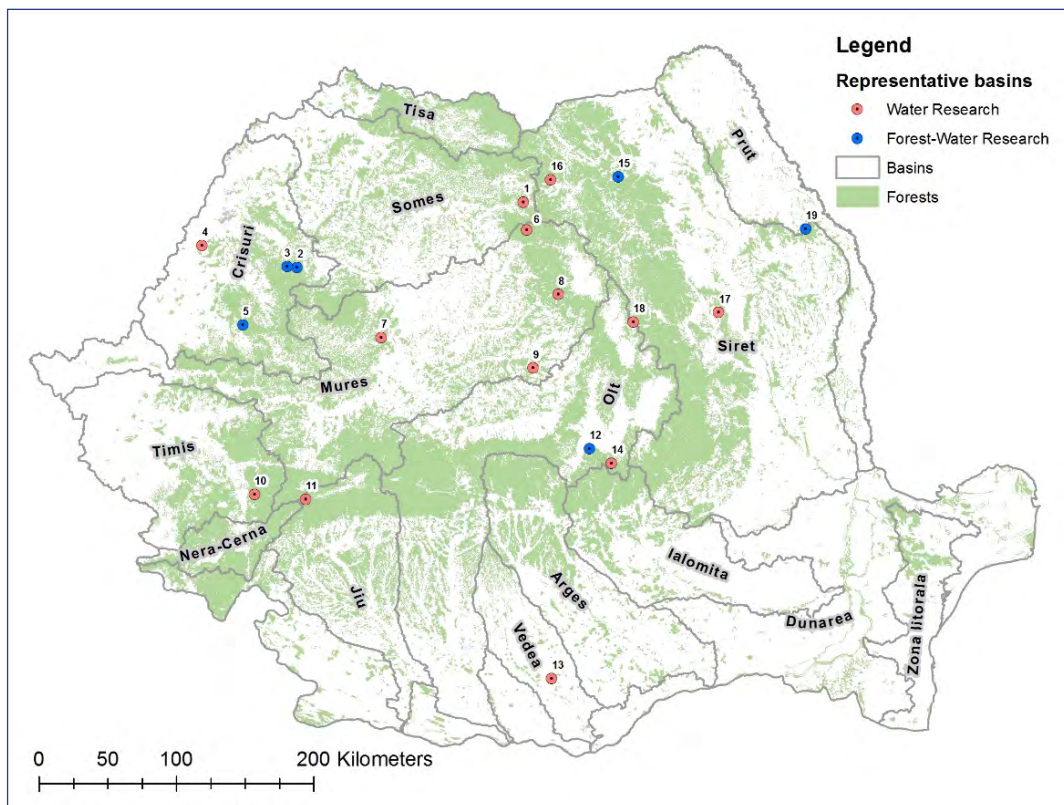
### *Water resource key issues directly related to the forest changes*

- *Flash Floods:* The high-intensity and short-duration floods (flash floods) are also becoming increasingly common in the mountain areas, mainly due to increasing frequency of high-intensity precipitation events, but also exacerbated by land use changes, especially forest loss and gain on high slopes. Even though the National Meteorological Administration and Institute of Hydrology developed new warning systems for floods, the warning time for small mountainous catchments, which are prone to flash floods, is about 2 hours, leaving the communities in these areas highly vulnerable to risk.
- *Drought:* Due to increasing temperature and decreasing river flows (see the following section on climate change) the frequency of droughts is increasing in Romania.
- *Climate change:* regional and local studies revealed that the climate in the country is shifting. It is uncertain whether the climate heads to a warming or cooling, but what is observable is the fact that the amplitude of the floods and droughts is increasing.

## 10.2 Literature review

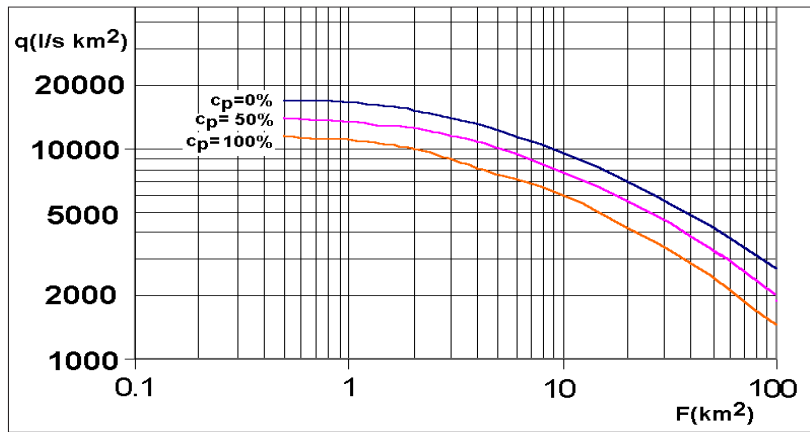
Research in forest hydrology started in 1969, when several representative basins have been equipped with a minimum of facilities specific to the study: pairs of rain gauges or pluviographs, in the open and under the canopy of trees, to study canopy retention as part of the fallen precipitation, devices for determining sap tree flows and evaporation. The main goal of this research was to determine the factors and how much they influence the water balance in forested basins (see Figure 5 ahead).

Using these basins, the researchers from National Institute of Hydrology and Watershed Management determined flow coefficients values in many river basins, with varying degrees of afforestation. Fund data accumulated through time created the possibility of determining the maximum flow of such probability rates, which led to the development of a relationship between specific discharge and watershed area (Giurgiu and Clinciu, 2008). Figure 5 shows this type of relationship for the Moldavian Central Plateau river; they were based on small areas, especially in peak flow values 1% exceedance probability, determined within the representative basin Tinoasa-Ciurea (no. 13 in Figure 4).



**Figure 4.** Geographic distribution of representative basins

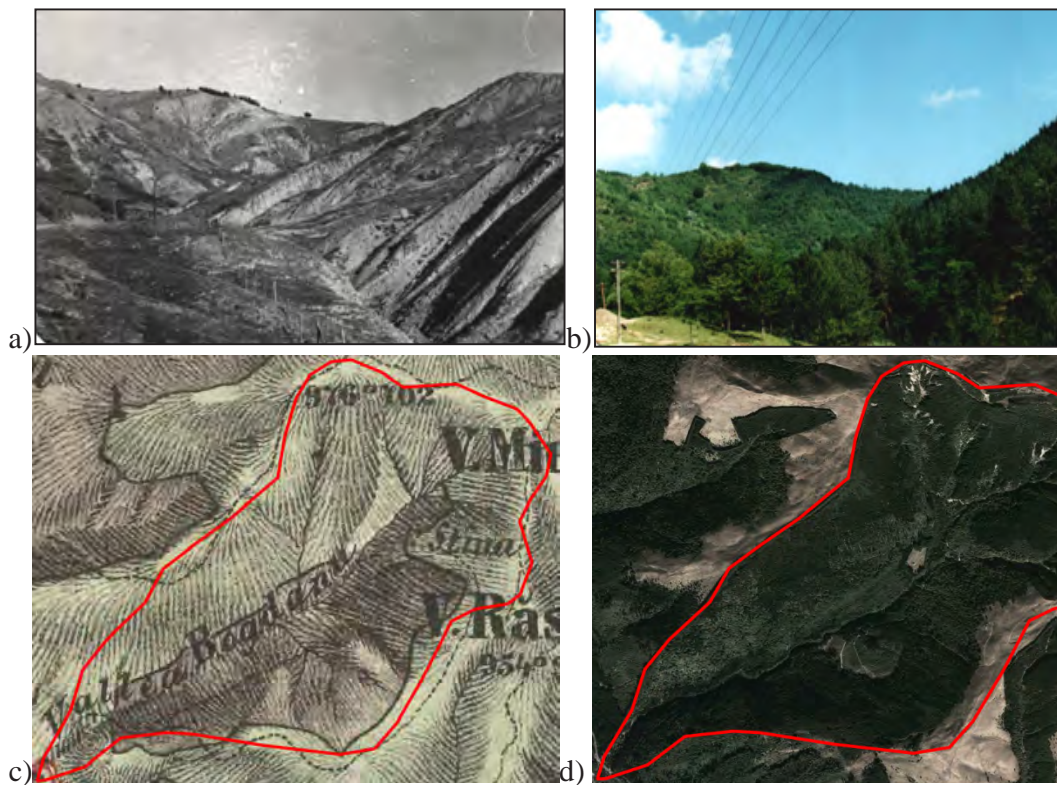
Due to the forest hydrology research in Romania is emphasized that maximum flow calculation at probability 1% in small watershedd can be done using a flow coefficient. The coefficient is based on data from representative basins, values depending on the variation coefficient of afforestation: 0% to 100%, in accordance with the amount of rainfall corresponding to various parts of the country, for this probability. These values were included in a summary table (Table 2), which is particularly useful in the practice of hydrology.



**Figure 5.** Relation between specific maximum flow and the basin area taking into consideration forest percentage.

**Table 2.** Flow coefficient (1% probability) based on Forest Coefficient (Cp) and Watershed slope (Ib)

	Cp(%)				
Ib(%)	0-20	20-40	40-60	60-80	80-100
10-May	0,55	0,53	0,51	0,49	0,47
20-Oct	0,57	0,55	0,53	0,51	0,49
20-30	0,59	0,57	0,55	0,53	0,51
30-40	0,62	0,60	0,58	0,55	0,53
40-50	0,64	0,62	0,60	0,57	0,55



**Figure 6.** Increasing water yield and quality by reforestation and watershed management Sării Valley – a) In 1954 (Photo:Costin); b) In 1997 (Photo:Untaru) and Bogdan Valley – c) Map of Romania 1864; d) GeoEye image 2014



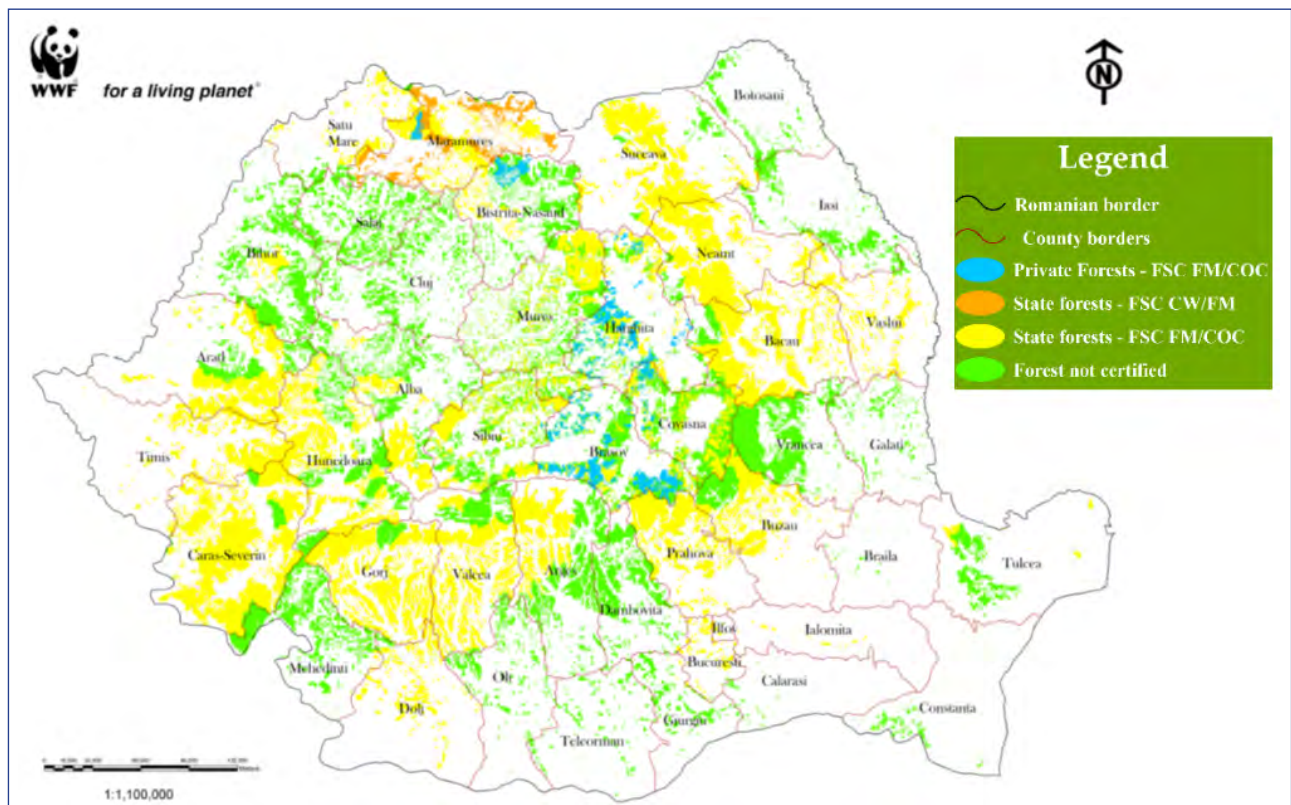
An important work for increasing water yield and improving water quality was the implication of forestry specialists in managing torrential valleys, where massive deforestation was produced in the past. At the beginning of the XIX century, more and more scientists demonstrated the benefits of forests for water and for flood regulation. Starting with that period, the Romanian forest engineers begun their campaign in developing and putting into practice mapping and restoring degraded lands and managing torrential valleys (Giurgiu and Clinciu, 2008). The benefits of that period can be seen nowadays in several watersheds like Bogdan Valley (Ialomita Basin) or Sării Valley (Siret Basin) (Figure 6).

### 10.3 Politics

In Romania, environmental laws are established through Acts of Parliament. These Acts provide the general framework for:

- Regulation of economical and social activities having an environmental impact;
- Protection of natural resources and conservation of biodiversity;
- Pollution control.

The responsibility for preparing more detailed requirements, regulations, and standards belongs to the Ministry of Waters, Forests, and Environmental Protection. The environmental legislative system has been revised according to the European legal system. It provides laws for different parts of the environment: air, water, and soil. It also provides laws related to these environments: dangerous substances, the fight against floods, forestry, food, and nuclear activity.



**Figure 7.** FSC Certified Forests in Romania (source: <http://www.certificareforestiera.ro>)



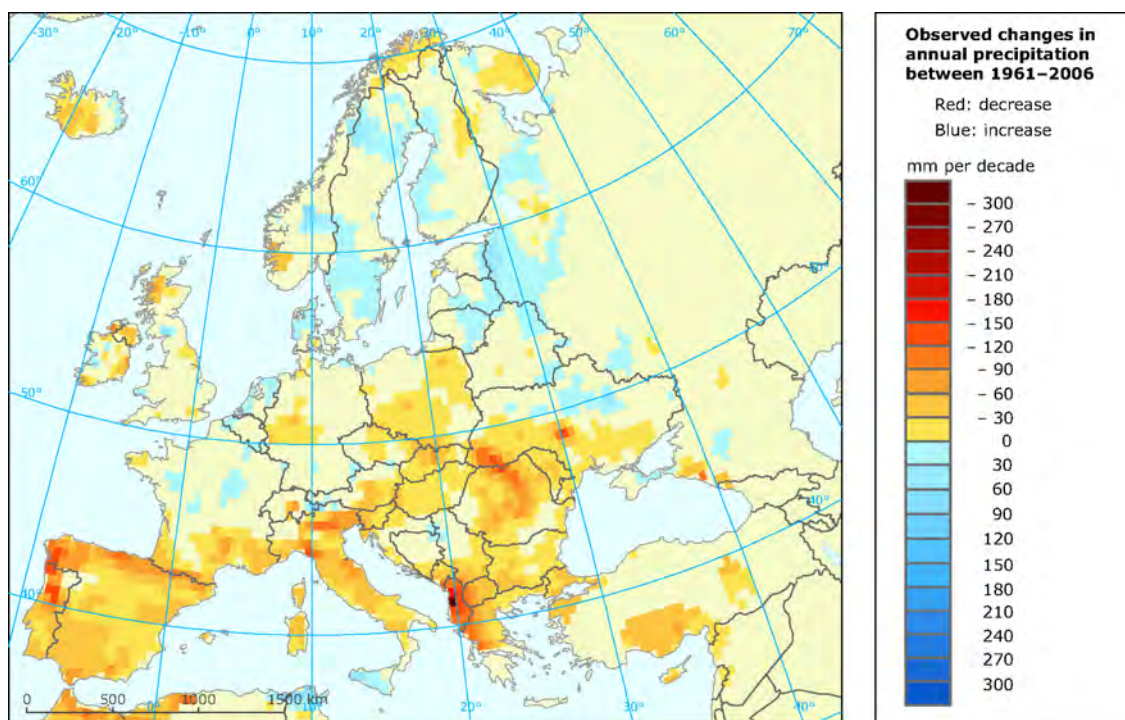
Today the Romanian environmental legislation is based on two fundamental laws that guide the whole environmental protection at the national level: the Environmental Protection Law (EPL) and the Water Law (WL). Both laws provide an excellent legislative frame for applying strong strategies to improve water yield and water quality. According to WL, all rivers have a buffer zone between 20 and 100 m, for protection. The protection of waters can be found in EPL and the same in the Forest Law, which defines a category of forests that should remain in basins stabilizing soil erosion and maintaining a constant water flow.

But from legal frames to facts there is a very long way with a lot of issues such as illegal extraction of sediments from riverbed, river contamination with garbage or industrial waste, intensive harvesting near large water storages, extracting logs using the watershed valley network, and intensive grazing.

Another important legal frame for protecting waters through forests is FSC standard implementation. Logging directly disturbs forests and waters, but the FSC standard requires operators to minimize forest damage during harvesting and road construction, as well as to protect forest ecosystems (Macicuca and Diaconescu, 2013). Romania has good implementation of FSC standards and approximately 50% of Romanian forests are certified (Figure 7).

## 10.4 Climate change and the future of forestry & forest research

There are quantitative estimates for Romania related to climate change, which come from two categories of sources (World Bank, 1999): (1) Climate change studies of Europe and (2) local studies aimed at assessing climate change impacts for specific selected river basins of Romania. The results of the continental-scale studies include relevant findings for Romania. Observed changes in climate over Europe in the 20th century show that Southern and South-Eastern Europe has experienced decreases in annual precipitation of up to 20%. Precipitation has decreased at a rate of about 30 mm per decade in Romania, between 1961 and 2006. Annual mean precipitation is projected to decrease by 5-20% in southern Europe and the Mediterranean in the period 2071-2100, compared to the period 1961-1990 (Figure 8).



**Figure 8.** Trends in annual precipitation across Europe between Jan 1960 and Jan 2012 (source: <http://www.eea.europa.eu/data-and-maps/figures/observed-changes-in-annual-precipitation-1961-2006>)

In line with the precipitation changes, annual river flows are increasing in the north and decreasing in the south, and this trend is projected to continue in the future. Large changes in seasonality are also projected, with lower flows in summer and higher flows in winter for Romania. As a consequence, droughts and water stress are expected to increase, particularly in summer. Flood events are projected to occur more frequently in many river basins, particularly in winter and spring, although estimates of changes in flood frequency and magnitude remain uncertain. In general, the range of climate change impacts across Romania includes a likely increase in cold spells, heat waves, heavy floods, landslides, formation of ice-dams on watercourses, damaging frost, and avalanches (World Bank, 1999).

In terms of climate change, the area occupied by forest plantations is slowly increasing, especially in the southern part of Romania. These are the efforts of community to stop the increase of desertification phenomena. The process is still slow due to the lack of funds and bureaucracy.

Future research and management practices should be incorporated in the management of forest to improve water quality and water yield, through increasing forest cover, especially in Southern and Eastern counties. Research should concentrate on the needs of forest managers, which converge into one point: increasing the forest cover by maintaining the harmony between economic needs and ecological demands.

## 10.5 References

- Falkenmark, 1989. The massive water scarcity threatening Africa-why isn't it being addressed. *Ambio* 18, 112-118.
- Giosan, L., Coolen, M.J.L., Kaplan, J.O., Constantinescu, S., Filip, F., Filipova-Marinova, M., Kettner, A.J., Thom, N., 2012. Early anthropogenic transformation of the Danube-Black Sea system. *Sci. Rep.* 2, 582. doi:10.1038/srep00582
- Giurgiu, V., 2010. Considerații asupra stării pădurilor României - partea I: Declinul suprafeței pădurilor și marginalizarea împăduririlor. *Rev. pădurilor*.
- Giurgiu, V., Clinciu, I., 2008. *Silvologie VI*. Romanian Academy Publishing House.
- Macicuca, A., Diaconescu, C., 2013. Forest Certification Effects on Sustainable Management of Romanian Forest Ecosystems. *Present Environ. Sustain. Dev.* 7.
- Stanciu, P., Oprisan, E., Tecuci, I., 2011. National Water Resources and their Evolution in the Context of Climate Change. National Institute of Hydrology and Water Management.
- World Bank, 1999. *Integrated Water Resources*.

# Chapter 11. Forest management and water in the Republic of South Africa

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## 11.1 Introduction

South Africa is a semi-arid country with a very limited area of natural forest. The early colonial governments encouraged the establishment of plantations to supply wood for local uses, and South Africa consequently has a long history of plantation forestry. However, the growth of the man-made forests soon led to conflicts with downstream water users, mainly farmers. The simmering debate about the positive and negative effects of plantations of introduced tree species became a high-level political issue, and this led to the establishment of a large and intensive forest hydrological research program in 1936. The results of the research program were incorporated, between 1970 and 1995 into management policies for these plantations and the humid mountainous catchment areas (watersheds). One policy element was that the extent of the plantations was regulated, based on the estimated effects of the plantations on regional water resources. More recently, a new National Water Act (1998) has further restricted the forest industry, with the result that there has been a stagnation of timber planting over the last twenty years.

This chapter outlines the history of the forest industry and associated forest hydrology research in South Africa, and describes the measures that have been taken to control the forest industry because of its effects on water resources.

### *Water resources in South Africa.*

South Africa is essentially a semi-arid country, with a mean annual precipitation (MAP) of roughly 460 mm (DWAF 2004), which is greatly exceeded by evaporative demand that ranges between 1400 and 3000 mm/year (Schulze, 2008). The distribution of precipitation though is highly variable, both in space and time, and there are small areas of the country with high rainfall (roughly 20% of the country has an MAP > 800 mm (Dye and Versfeld, 2007), which are largely responsible for sustaining much of the perennial streamflow. The high rainfall zones, known locally as mountain catchment areas, are responsible for 60% of the countries surface water production (Jacobson 2003). Groundwater resources are limited, so the country is dependent on surface water resources.

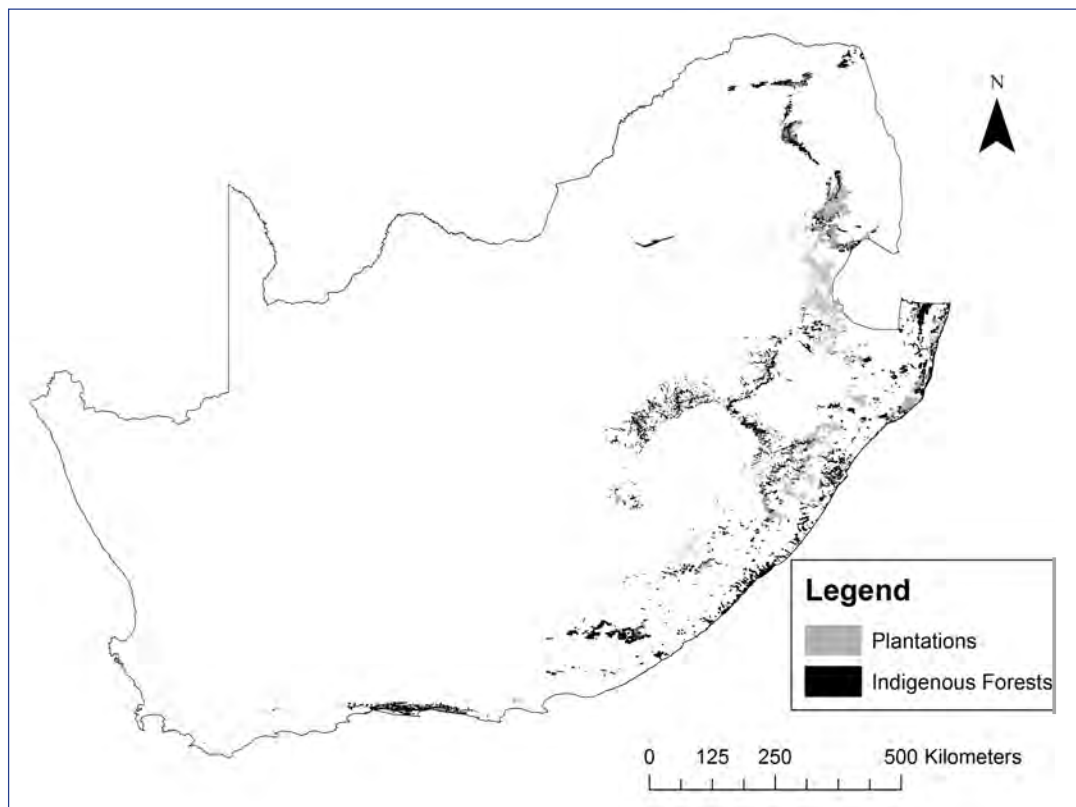
Within South Africa and the neighbouring mountain country of Lesotho, a large capacity to store water has been built to retain water for drier years, and there is a large reliance on inter-basin transfers of water. South Africa has a reservoir storage capacity of 32,412 million m<sup>3</sup>, which is the equivalent of 66% of the Mean Annual Runoff (MAR) (DWAF 2004). Most water is used by agriculture, with irrigation accounting for 62% of utilizable water. The next biggest user is municipal water use (27%), for residential (urban and rural), commercial and light industrial purposes. Other uses are mining, bulk industrial and power generation, which jointly account for another 8% of utilizable water (DWAF 2004).

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## Forest Resources

The humid parts of South Africa are scattered along the south and eastern seaboard and along the seaward escarpment that runs up the eastern part of the country. Within these well-watered regions there is a very small area of native forest, covering approximately 0.4% of the total land area (Figure 1). This restricted and scattered forest area produces a very small amount of high quality furniture wood, but the trees are slow-growing, the forests are difficult to regenerate, and the majority of the forest area is managed for conservation rather than production. The native forests are valued mostly for their aesthetic and ecological values, and they are not a significant part of the economy.



**Figure 1.** The distribution of native (indigenous) forest and timber plantations in the Republic of South Africa (GEOTERRAIMAGE, 2014).

Against this background of timber scarcity, the early governments in South Africa encouraged the planting of introduced tree species for timber, from as early as the late 19<sup>th</sup> Century (van der Zel, 1995; Kruger and Bennett, 2013). The earliest plantations were of eucalypts to supply fuelwood for trains and timber for railroad ties (sleepers). Another early crop was wattle, Australian *Acacia* species (mainly *A. mearnsii*), planted for the production of tannin from its bark. Mining became a major economic activity by the beginning of the 20<sup>th</sup> Century, and mining companies started planting introduced trees (mainly fast-growing eucalypts) to supply wood for mine props in the underground mines. Gradually, a saw-timber industry was developed based on plantations of pines that were thinned and pruned to produce a high quality timber.

Today, the country has a vibrant commercial plantation industry, based on approximately 1.27 million ha of plantations (Figure 2). These plantations are based on a limited number of pine, eucalypt and acacia species, but all are fast-growing, allowing for profitable production of forest products. Most of the saw timber comes from pine plantations which comprise 51% of the plantation area (mainly *Pinus patula*, followed by *P. elliotii*, *P. radiata* and *P. taeda*). A variety of eucalypt clones, mostly based on *Eucalyptus grandis*, are grown on short rotations (8-12 years), mostly for pulping and chipping (chips being exported to markets in the Far East are included in the pulpwood category in



Figure 3). These short-rotation eucalypts are also sawn for mining timber, though this market now makes up only 4% of production.

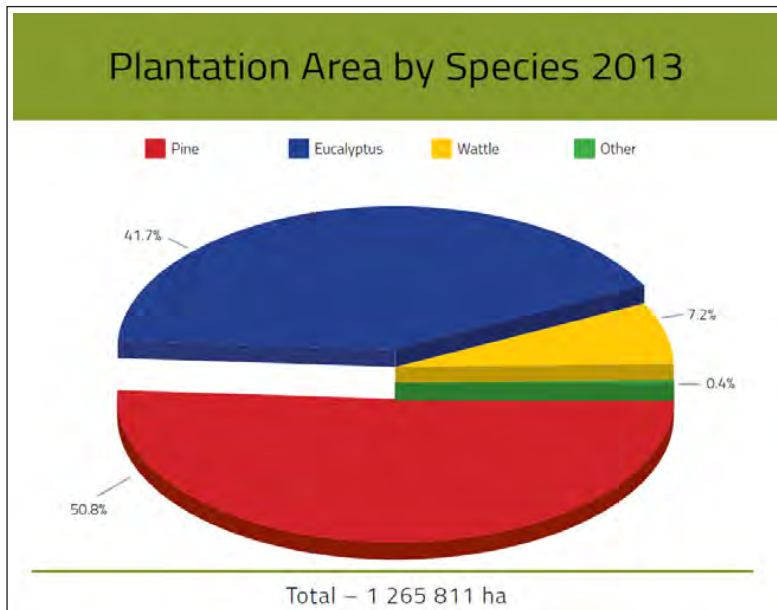


Figure 2. The area of South African plantations by tree type (FSA, 2014)

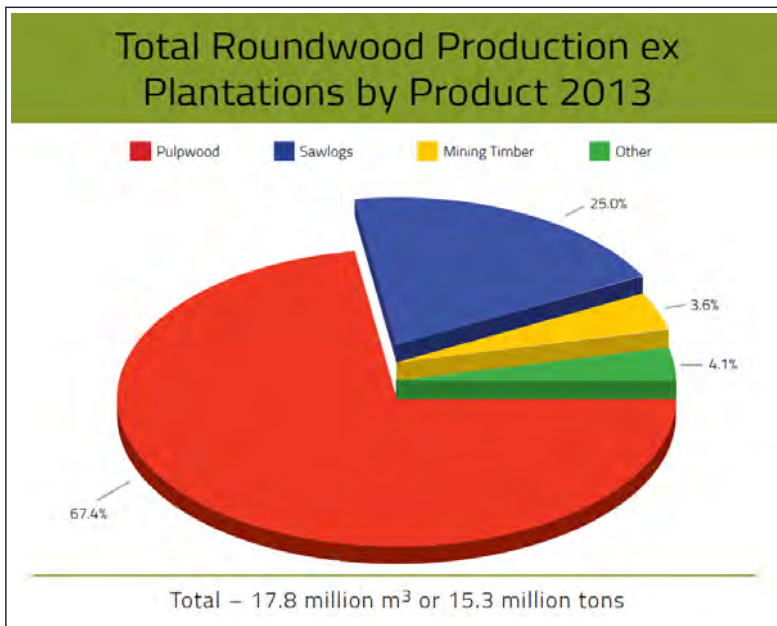


Figure 3. The main product categories of the South African forest industry (FSA, 2014)

### *The economic importance of the forest industry*

The national forest inventory estimates that the annual sustainable production of timber from the plantations is 20 million tons, at an average growth rate of 15.8 ton/ha for the whole industry (DAFF 2014). Exports of forest products in 2013 amounted to US\$1.7bn, which resulted in a positive trade balance with respect to wood products of \$380m (DAFF 2014). Perhaps most significantly in South Africa, the industry as a whole (including processing) employs 170,000 people of which 66,000 are involved in forestry operations (DAFF 2014). The forest industry based on plantations of introduced timber species is therefore an important part of the South African economy, and projections indicate

that it needs to grow in order to keep pace with future increases in demand for wood and fibre products.

## 11.2 Literature review

The commercial timber plantations are generally confined to areas where MAP exceeds 750 mm (van der Zel, 1995), and growth rates are generally positively related to rainfall. Although the current area of commercial timber plantations occupies only 1.04% of the land area, they are in the wetter parts of the country, and this lead to conflicts over their effects on water resources. As early as 1915 farmers were contesting the generally held view that forest cover would benefit the regional hydrology, and were complaining that their water supplies seemed to be negatively affected by upstream plantations (van der Zel, 1995). Forestry officials supported the spread of plantations for reasons of timber supply, control of erosion and for hydrological benefits, believing that trees would regulate flows and humidify their environment (Kruger & Bennett, 2013).



**Figure 4.** Plantation forests and water: A stream adjacent to a commercial pine plantation in the Magoebaskloof area, South Africa. (photo: M. Gush)

In 1935 the Empire Forestry Conference was held in South Africa. It brought the senior forest scientists from the British Empire together for an extended conference and tour of forestry sites in the country. At the time, South Africa had more plantations than any other country in the British Empire. Government ministers challenged the gathered foresters to advise them on the debate regarding the hydrological effects of plantations. As the then Minister for Agriculture and Forestry, Denys Reitz, said at the conference; “For more than a century we in South Africa have been planting trees, chiefly pines and eucalypts, under the impression that such plantations were valuable for the conservation of water. It has now been put to me that in this way we are decreasing the humidity and drying the soil.” (Bennett & Kruger, 2013). The conference recommended a serious scientific study to establish evidence of the hydrological influence of trees. In 1936, the Jonkershoek Forestry Research Station was established, under the direction of Dr CL Wicht, a forester with training from Germany and Oxford (Kruger & Bennett 2013). Additional gauged catchment studies that contrasted afforestation with introduced pines or eucalypts with a well-managed native vegetation, were added after the Second World War, at Cathedral Peak, Mokobulaan and Westfalia. As a result of the high political profile of the debate around plantations, there was strong government support for the research

programme, which maintained its funding and was able to stick to an ambitious research plan for close to five decades.



**Figure 5.** A mosaic of indigenous forest, commercial plantations and grassland in a landscape typical of South Africa forest growing areas. (photo: M. Gush)

The research programme involved planting gauged catchments to pine or eucalypts that were used in that region of the country, and applying standard silvicultural treatments for saw-timber crops, which included thinnings and pruning of the trees at prescribed intervals. Standard planting was at 3 m by 3 m spacing, giving an initial stocking of roughly 1360 stems per hectare (spha). Periodic thinnings would have brought stocking to below 400 spha in most experiments. Over time the experiments were analysed by a series of researchers, starting with Wicht (1967) who analyzed the first experiments with *Pinus radiata* planted into the sclerophyllous scrub (fynbos) in Jonkershoek. Nanni (1970) analyzed the experiments with *P. patula* plantings into montane grasslands at Cathedral Peak showing that the same trend found in the Mediterranean-type climate of Jonkershoek also occurred in the mountainous summer rainfall region. Van Lill et al. (1980) analyzed the early results of the first experiment with *Eucalyptus grandis* planted at Mokobulaan, showing a sharper and earlier reduction in flows than observed under pines. Bosch (1979) did more work on the catchments at Cathedral Peak, including the first analysis that showed that dry season flows were impacted to a greater relative extent than annual runoff. Van Wyk (1987) extended the analysis of the replicated experiments at Jonkershoek, confirming the general trend of streamflow reductions caused by the planting of pines. Smith & Bosch (1989) and Bosch & Smith (1989) analyzed the second experiment with eucalypts in sub-tropical Westfalia, showing that when the fast-growing eucalypts replaced mature native forest, there was a highly significant reduction in streamflows within three years of planting. Scott et al. (2000) provide a background and review of the main experiments in the gauged catchment network.





Photo courtesy of Wood SA and Timber Times

**Figure 6.** View of typical pine & eucalypt plantation in South Africa  
(source: <http://www.woodsa.co.za/2014/April/images/WaterUse3.jpg>)

It had long been standard practice for the riparian zones (a 20 m wide strip either side of streams) within timber plantations to be exclusion zones. This was done on the basis of early work that showed that riparian vegetation had a direct effect on streamflow (Rycroft, 1955). Subsequently, several experiments have shown that the practice of keeping the riparian zones under a native vegetation cover is justified from a water conservation perspective (Prinsloo & Scott, 1999; Scott 1999; Everson et al., 2007). Van der Zel (1970) and Lesch and Scott (1997) looked at the influence of thinnings on water yield. Although thinnings may remove as much as half the trees, the remaining plantation trees soon occupy the whole site so that any savings in water are of short duration (<2 years). During the 1990's a series of process studies were undertaken in the plantations (many summarized by Dye 1996), which have provided insight into how and when the fast-growing introduced tree species use more than the native vegetation they have replaced.

Scott et al. (1998) used empirical models derived from the catchment experiment results to estimate the impacts of forest plantations on streamflow at regional and national scales. The forest plantations cover 1.2% of South Africa, but are concentrated in areas of higher rainfall, which produce a disproportionately large share of total streamflow. Thus, regional catchments in which some degree of afforestation has occurred comprise only 14% of the country, yet produce 53% of the mean annual streamflow and 70% of the mean annual low flows (Scott et al., 1999). Commercial plantations were estimated by Scott et al. (1998) to reduce mean annual streamflow by 3.2% ( $1417 \times 10^6 \text{ m}^3/\text{year}$ ) but low flows by 7.8% ( $101 \times 10^6 \text{ m}^3/\text{year}$ ). This translates into an annual average reduction of 98.6 mm/year for planted areas. In a more recent assessment, the ACRU model, a physically-based process model, was used to quantify the effects of afforestation across the country based on the difference in water use between native vegetation and plantations (Gush et al., 2002). From this study, reductions in streamflow caused by plantations in all quaternary (forth-order) catchments where commercial forestry was deemed to be viable ( $\text{MAP} > 650 \text{ mm}$ ) averaged a more modest 74 mm/year for eucalypts, 57 mm/year for pines and 57 mm/year for wattle (*Acacia*). However, as the study was only designed as an estimation of potential streamflow reductions across all viable forestry areas (including a large number of drier / marginal catchments where impacts would be lower in absolute terms), and not as a national water-use assessment, these estimates should not be considered representative of the



average water use by the commercial forestry sector. Despite the differences between the outputs of different models, it is clear that forest plantations have a significant effect on the available water resources of South Africa.

### 11.3 Politics

Following droughts in the 1960's, two government committees looked into water matters and addressed the role of forestry in water supply (Malherbe et al., 1968; van der Zel, 1995). Consequently, the Forest Act was amended in 1972 to regulate further afforestation for water conservation purposes. The Act put the Afforestation Permit System in place (van der Zel, 1995), which was administered by the central government's Department of Forestry. Catchments (drainage basins) were placed into one of three categories that would determine whether further forestry was possible or not. Category I catchments were considered already fully allocated (because of existing water use demands) and no permits were granted within these. Category II catchments had sporadic water shortages and afforestation would be capped so as to use no more than an estimated further 5% of mean annual runoff (MAR). In Category III catchments, over the bulk of the country, afforestation would be permitted to the extent that would use an estimated additional 10% of MAR. The scientific basis for the policy came from the long-term gauged catchment studies, and the estimates needed in the permitting system, specifically, came from a summary model developed by Nänni (1970) and modified by van der Zel (1995).

A major revision of the water law was undertaken after the democratization of South Africa in the 1990's leading to the National Water Act of 1998. This innovative legislation changed the basis for the regulation of forestry. Forestry is now classified as a "streamflow reduction activity" (SFRA), on the basis of its estimated effects on streamflow, which requires that it be licensed. On the surface, this new Act opens the prospect of other land uses, for example, dry land sugarcane or bamboo, also being included. However, at this time there is no other land use that has been classified as a SFRA. The licensing procedure is time-consuming and complex, and the implications of the licensing are yet uncertain (Dye & Versfeld 2007). This, together with the fact that South Africa is rapidly approaching the point at which all of its easily accessible freshwater resources are fully utilized (NWRS, 2013), has resulted in very little expansion of the forest industry in South Africa in the fifteen years since the National Water Act came into effect (Kruger & Bennett 2013).

### 11.4 Climate change and the future of forestry & forest research

The effects of climate change on the southern African sub-continent are uncertain. However, the South African forestry industry is sensitive to climate, as only 1.5% of the country is suitable for tree crops under the current climate (Fairbanks and Scholes, 2005). In addition, the relatively long period between planting and harvest makes tree plantations vulnerable to environmental change. Warburton and Schulze (2008) modeled the potential effects of climate change on main species of pines & eucalypts in South Africa. There is a convergence of predictions by different global climate models regarding temperature as all indicate an increase in temperature over the forestry regions of the country. Regarding precipitation though, predictions are more divergent though a rise in precipitation seems more likely in the eastern forestry areas. Using known prescriptions for the climatic suitability of major forestry species, Warburton and Schulze (2008) assessed the potential effects of plausible climate change possibilities on the forest industry. As might be expected, declining rainfall concomitant with rising temperature will have an especially negative effect on total area of optimal growth, while an increase in rainfall will offset all negative impacts of temperature, and increase the total area of optimal conditions for both pines and eucalypts. These changes will necessitate the issuing of appropriate water use licences and have associated impacts on water resources. Other emerging issues in South Africa which have a forests and water link include: a growing demand for bio-energy products; impacts of plantation species exchanges (genus exchanges) on streamflow reductions;

water use by agroforestry systems; reforestation and expanded use of indigenous tree species. With regard to the latter, recent studies have investigated the water use, growth rates and resultant water use efficiencies (WUE) of indigenous tree species in South Africa compared to introduced plantation tree species (Dye, et al., 2008; Gush and Dye, 2009; WRC, 2010). Results are showing that while biomass production is much lower for indigenous tree species, they also use much less water than introduced plantation species. Resultant WUE estimates showed substantial variation, even within a particular species, but on average results indicated that indigenous tree species appear to exhibit similar bio-physical water use efficiencies to introduced plantation tree species (WRC, 2010). The relatively low water-use characteristics of indigenous tree species suggests that they are promising for reforestation and expanding indigenous tree production systems in South Africa, maximizing benefits (goods and services) while minimizing resource impacts (water-use).

## Conclusions

In response to a shortage of native forest and an increasing need for timber, the early colonial governments encouraged the establishment of plantations to supply wood for local uses. South Africa thus has a long history of establishing and managing timber plantations using exotic tree species. However, the spread of the man-made forests soon led to conflicts with downstream water users, mainly farmers who claimed that, contrary to expectations, their stream water supplies seemed less reliable since the arrival of plantations. A simmering debate about the positive and negative effects of plantations of exotic tree species eventually became a high-level political issue, and this led to the establishment of a large and intensive forest hydrological research program in 1936. The research program was based on a series of paired catchment experiments around the timber growing areas of the country. These experiments produced unequivocal evidence that the fast-growing plantations had a negative effect on total and dry season streamflows. The results of the research program were incorporated into policy that regulated the extent and location of the plantations, based on their estimated effects on regional water resources. More recently, the National Water Act (1998) incorporated these restrictions by classifying commercial forestry as a streamflow reduction activity, and subject therefore to licensing and water use fees. As forestry is the only land use included under this restriction, and because of bureaucratic obstacles, the forest industry, despite its economic vitality and importance, is no longer expanding. The forest industry feels unreasonably disadvantaged by the fact that its hydrological effects are better understood than other land uses, and large forest corporations are now looking for growth opportunities in neighboring countries where investments in forest plantations are seen more favorably.

## 11.5 References

- Bennett, BM and Kruger, FJ, 2013. Ecology, forestry and the debate over exotic trees in South Africa. *Journal of Historical Geography* 42: 100 - 109
- Bosch, JM, 1979. Treatment effects on annual and dry period streamflow at Cathedral Peak. *South African Forestry Journal*, 108: 29.
- Bosch, JM and Smith, RE, 1989. The effect of afforestation of indigenous scrub forest with Eucalyptus on streamflow from a small catchment in the Transvaal, South Africa. *South African Forestry Journal* 150:7-17.
- Bosch, JM and von Gadow, K, 1990. Regulating afforestation for water conservation in South Africa. *South African Forestry Journal*, 153: 41 – 54.
- DAFF, 2014. Report on commercial timber resources and primary roundwood processing in South Africa. Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa.
- DWAF, 2004. National Water Resource Strategy, first ed. Department of Water Affairs and Forestry, Pretoria, South Africa.
- Dye, PJ, 1996. Climate, forest and streamflow relationships in Southern African afforested catchments. *Commonwealth Forestry Review*, 75: 31 – 38.

- Dye, PJ and Versfeld, DB, 2007. Managing the hydrological impacts of South African plantation forests: An overview. *Forest Ecology and Management* 251: 121–128.
- Dye, PJ, Gush, MB, Everson, CS, Jarman, C, Clulow, A, Mengistu, M, Geldenhuys, CJ, Wise, R, Scholes, RJ, Archibald, S and Savage, MJ, 2008. Water-use in relation to biomass of indigenous tree species in woodland, forest and/or plantation conditions. WRC Report TT361/08, Water Research Commission, Pretoria, South Africa.
- Everson, CS, Gush, MB, Moodley, M, Jarman, C, Govender, M and Dye, PJ, 2007. Effective management of the riparian zone vegetation to significantly reduce the cost of catchment management and enable greater productivity of land resources. Report to the Water Research Commission. WRC Report No 1284/1/07 (ISBN: 978-1-77005-613-8).
- Fairbanks, DHK and Scholes, RJ, 1999. South African country study on climate change: vulnerability and adaptation assessment for plantation forestry. CSIR Environmentek Report ENV/C/99. National Research Facility, Sustainable Development Program, Pretoria, South Africa.
- FSA, 2013. Abstract of South African Forestry Facts for the year 2012/2013. Forestry South Africa, report to Dept. Water Affairs and Forestry. Available from [<http://www.forestry.co.za>].
- GEOTERRAIMAGE, 2014. 2013 - 2014 South African National Land Cover Data. A commercial data product created by Geoterraimage for the Department of Environmental Affairs, South Africa.
- Gush MB and Dye PJ. 2009. Water-use efficiency within a selection of indigenous and exotic tree species in South Africa as determined using sap flow and biomass measurements. *Acta Horticulturae* 846: 323-330.
- Gush, M.B., Scott, D.F., Jewitt, G.P.W., Schulze, R.E., Hallows, L.A., Görgens, A.H.M., 2002. A new approach to modelling streamflow reductions resulting from commercial afforestation in South Africa. *S. Afr. For. J.* 196, 27–36.
- Kruger, FJ and Bennett, BM, 2013. Wood and water: an historical assessment of South Africa's past and present forestry policies as they relate to water conservation, *Transactions of the Royal Society of South Africa*, DOI: 10.1080/0035919X.2013.833144
- Le Maitre, DC, van Wilgen, BW, Chapman, RA and McKelly, DH, 1996. Invasive plants and water resources in the Western Cape Province, South Africa: modelling the consequences of a lack of management. *Journal of Applied Ecology*, 33: 161-172
- Lesch, W and Scott, DF, 1997. The response in water yield to the thinning of *Pinus radiata*, *Pinus patula* and *Eucalyptus grandis* plantations. *Forest Ecology and Management*, 99: 295-307.
- Malherbe, HLW, 1968. Afforestation and Water Supplies in South Africa. Report of an Interdepartmental Committee, Department of Forestry, Pretoria, South Africa.
- Nänni, UW, 1970. Trees, water and perspective. *South African Forestry Journal*, 75, 9–17.
- NWRS, 2013. National Water Resource Strategy. Department of Water and Sanitation, South Africa. Available from [www.dwa.gov.za/nwrs2013](http://www.dwa.gov.za/nwrs2013).
- Prinsloo, FW and Scott, David F, 1999. Streamflow responses to the clearing of alien invasive trees from riparian zones at three sites in the Western Cape Province. *Southern African Forestry Journal* 185: 1-7.
- Rycroft, HB, 1955. The effect of riparian vegetation on waterloss from an irrigation furrow at Jonkershoek. *Journal of the South African Forestry Association*, 26: 2-9.
- Schulze, RE (Ed), 2008. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/08, Section 18.3.
- Schulze, RE, 2010. Atlas of Climate Change and the South African Agricultural Sector: A 2010 Perspective. Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa. 391 pp.
- Scott, DF, 1999. Managing riparian zone vegetation to sustain streamflow: results of paired catchment experiments in South Africa. *Canadian Journal of Forest Research*, 29(7): 1149-1157.
- Scott, DF, Le Maitre, DC, Fairbanks, DHK, 1998. Forestry and streamflow reductions in South Africa: a reference system for assessing extent and distribution. *Water SA* 24, 187–199.
- Scott, DF, Prinsloo, FW, Moses, G, Mehlomakulu, M, Simmers, ADA, 2000. A Re-analysis of the South African Catchment Afforestation Experimental Data. WRC Report No. 810/1/00, Water Research Commission, Pretoria, South Africa.
- Smith, RE and Bosch, JM, 1989. A description of the Westfalia experiment to determine the influence of conversion of indigenous forest on water yield. *South African Forestry Journal* 151:26-31.
- Van der Zel, DW, 1970. The effect of thinning on flow in a Jonkershoek stream. *Forestry in South Africa*, 11: 41-43.

Van der Zel, DW, 1995. Accomplishments and dynamics of the South African afforestation permit system. *South African Forestry Journal*, 172: 49 – 58.

Van Lill, WS, Kruger, FJ and Van Wyk, DB, 1980. The effect of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. et Cham. on streamflow from experimental catchments at Mokobulaan, Transvaal. *Journal of Hydrology* 48:107-118

Warburton, ML and Schulze, RE, 2008. Potential impacts of climate change on the climatically suitable growth areas of *Pinus* and *Eucalyptus*: results from a sensitivity study in South Africa. *Southern Forests*, 70: 27–36.

Wicht, CL, 1949. *Forestry and Water Supplies in South Africa*. Department of Forestry, Union of South Africa. Pretoria, Government Printer, 58 pp.

Water Research Commission (WRC). 2010. Abridged Knowledge Review 2009/10 - Growing Knowledge for South Africa's Water Future. WRC, Pretoria. pp. 59-60.



# Chapter 12. Forest Management and Water in Spain

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## 12.1 Introduction

### 12.1.1 Territory and climate

Spain's total land area of 506,030 km<sup>2</sup> makes it one of the world's 50 largest countries and places it second in terms of size in the European Union (Figure 1). If river estuaries are included in the calculation, its coastline totals 10,099 km. In terms of topography, 57.7% of Spain's territory stands at over 600 m above sea level, making it the second-highest country in Europe (Huertas, 2011).



Figure 1. Location of Spain in Europe (Source: Google Maps)

Spain has a variety of climates, including oceanic, continental, and Mediterranean types. Temperatures vary greatly between inland areas, which have cold winters and hot summers, and the periphery, where winters are mild, particularly along the Mediterranean coast (Figure 2).

Autumn and spring see heavy rainfall, while rain is scarce during summers. Marked contrasts between areas also exist in terms of rainfall. The north and north-west of Spain are very rainy and do not have a clear dry season, while the rest of the country is predominantly dry, although some areas may receive exceptionally high rainfall. In parts of the south-east, rainfall is very scarce, creating a semi-desert landscape (Huertas, 2011).

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**Figure 2.** Spanish autonomous communities (Source: Huertas, 2011).

### 12.1.2 Brief history of Spanish forests

In regards to forest hydrologic restoration, the current Spanish forest situation can be described as a period of limited intervention, compared to previous stages as in the eighteenth century, with the Royal Instruction of December 7, 1748, which put an end to the unlimited powers of farm owners.

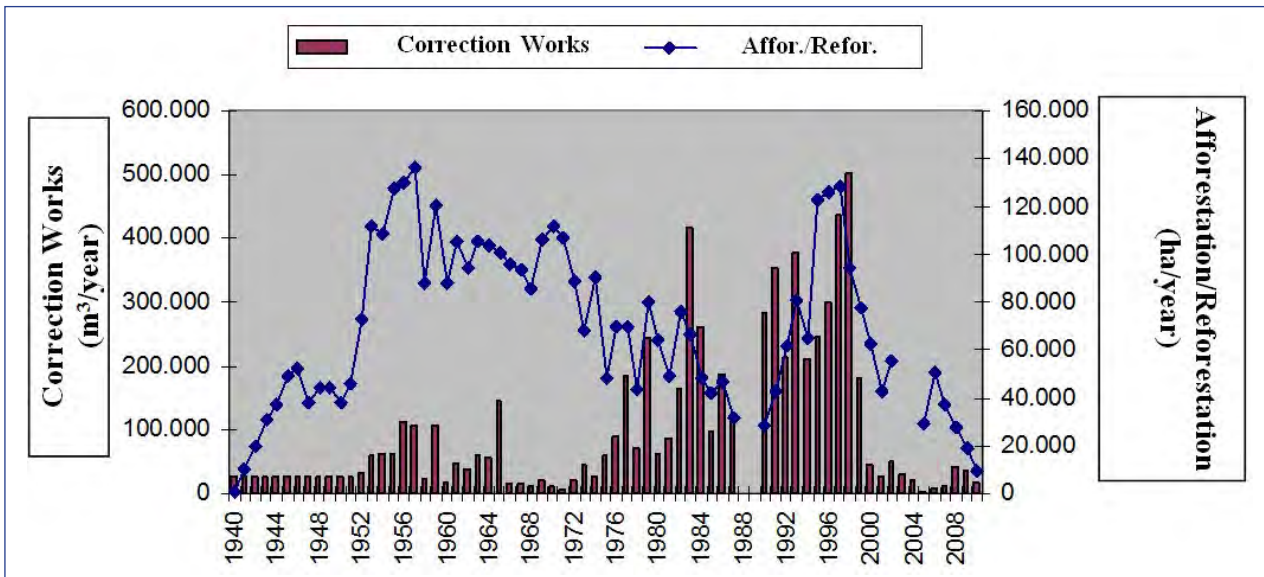
In the first half of the nineteenth century, the bourgeois liberal revolution began a process that led to disentailment measures, with terrible consequences for Spanish forests. Historians show that the destructive process of the forest, which is maintained throughout our history, reached an unprecedented intensity in the nineteenth century, causing an irreparable damage to Spanish forest. Between 1850 and 1900 there were cut down 2.7 M ha of trees on public lands and 7 M ha on private property (Del Palacio, 2014).

In the late nineteenth century and early twentieth, all works related to torrent control, precursors of forest hydrologic restoration, were due to works in countless headwaters with landslides problems, sediment transport and falling blocks attached to avalanches effects. In Spain, slope stabilization principles from France were essential in achieving a restorative doctrine. So, works from Surré and Thiery were adapted to the Spanish situation by Ayerbe, Azpeitia, Codorniú, and later by the professors García Nájera, López Cadenas de Llano, and Mintegui. In all restoration works, forest cover was considered absolutely necessary for erosion control in headwater, improving runoff water distribution and mitigation of extraordinary floods (García R., 2010).

In the twentieth century, before 1940, the quantification of the afforestation area is difficult to estimate, but according to Navarro (1975), it could be assessed in 40,000 ha. This area corresponds mainly to the afforestation/reforestation implemented under a forest hydrologic restoration plan, taking place since the creation of the Hydrological-Forest Divisions promoters of future reforestation activities.

In 1999, the Spanish Forest Strategy, adopted by the Environment Sector Conference, established the Spanish Forestry Plan, where 3.8 M ha had to be afforested or reforested with protective purposes (Del Palacio, 2014). Despite this, investments in reforestation/afforestation decreased, especially after 2006 (Figure 3), mainly due to the greater attention paid to the management of existing forests,

needed for major investments in conservation and maintenance, through silvicultural treatments and clearing forests for fire prevention.



**Figure 3.** Annual comparison between Afforested areas (ha/year) and quantity of correction works (m<sup>3</sup>/year), made by the Spanish Forest Administration since 1940 (From: Del Palacio, 2014).

### 12.1.3 Indicators for sustainable forest management

Spain’s forest, one of Europe’s largest and in constant growth for 30 years, plays an essential role in the conservation of biological diversity, the regulation of the hydrologic cycle, and the fight against desertification, as well as providing space for leisure and enjoyment for society as a whole. These qualities of forest ecosystems, however, are increasingly threatened by fire, climate change, and the abandonment and absence of management, among others (MAGRAMA, 2012).

#### 12.1.3.1 Forest Area

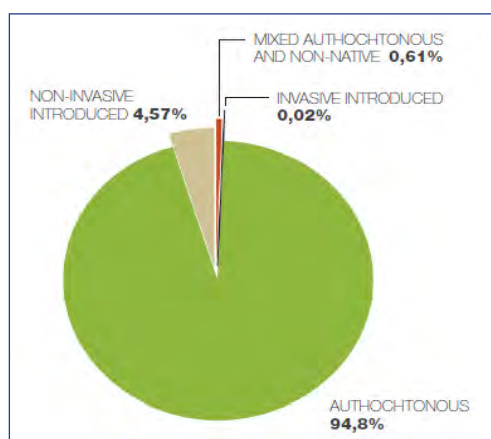
The current situation of forests and other wooded land areas in Spain is 27.67 M ha, which accounts for 55.6% of the total national area. Forests cover 18.27 M ha, while other wooded land area occupies 9.40 M (Figure 4).



**Figure 4.** Current situation of Forest and other wooded land area in Spain (extract from MAGRAMA, 2012; MFE, 2010)

The area of forest available for the supply of wood and firewood - not included in protected areas - is 14.92 M ha, equivalent to 82% of the forest area, and 29% of this evolution is based on natural regeneration of forest on abandoned agricultural areas since the rural exodus - from 1960 - and campaigns promoting the afforestation of agricultural and non-wooded land since 1990 (MAGRAMA, 2012). Other wooded land (OWL), complementary to the growth in forest area, fell by 20% (2.33 M ha) between 1990 and 2010.

Another aspect is that most Spanish forest area (Figure 5) comprises autochthonous species (94.80%). Non-native species account for 4.59% of the wooded area (5.2% taking into account mixed formations of non-native and autochthonous species). The main forest species introduced are eucalyptus (*Eucalyptus sp.*) and Monterrey pine (*Pinus radiata*), followed a long way back by other conifers like Douglas fir (*Pseudotsuga menziesi*) or larch (*Larix sp.*). Invasive non-native species occupy 3,681 ha (0.02% of the wooded area). These are principally broadleaved species like *Acacia sp.* and *Ailanthus altissima*, included in the Spanish Catalogue of Invasive Species. *Robinia pseudacacia* and *Gleditsia triacanthos* are on the list of non-native species with invasive potential (Royal Decree 1628/2011, of 14 November 2011) (MAGRAMA, 2012).



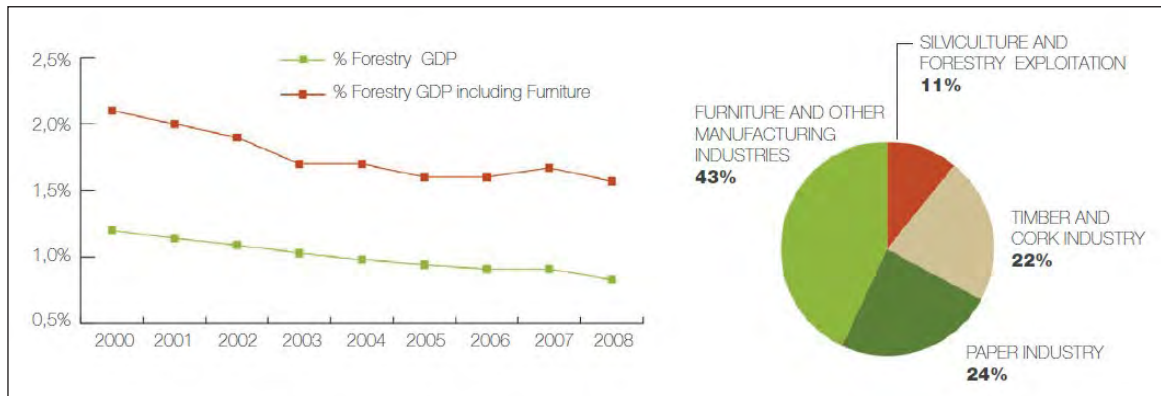
**Figure 5.** Distribution of Spanish forest formations (extract from MAGRAMA, 2012)

### 12.1.3.2 Contribution of the forestry sector to GDP

The forestry industry comprises the manufacture of timber products together with the paper, pulp, and cardboard industry. Furniture and other manufacturing industries have been calculated independently because, while in Spain they are considered as part of the forestry sector, European indicators don't include them (MAGRAMA, 2012).

In terms of the evolution of Gross Value Added (GVA) in Spain, between 2000 and 2008 it was broken down into sectors of activity (Figure 6): (1) the activities of the timber industry and the furniture industry showed an upward trend, and then (2) the sub-sectors of silviculture and exploitation and the paper industry showed a slightly downward trend. Between 2000 and 2008, the average contribution of the forestry sector was 1% of total Spanish GVA (1.76% including the furniture industry). The relative contribution of the forestry sector to total Gross Domestic Product showed a downward trend during this period (MAGRAMA, 2012).





**Figure 6.** Contribution of the forestry sector to the Spanish total Gross Domestic Product (extract from MAGRAMA, 2012)

### 12.1.4 Natural water resources

An analysis of water management plans in Spain can provide a general image about the characterization of Spanish water resources. Thus, it can be noted that in the twenty-five Spanish watersheds districts, there were defined 5,150 surface water bodies and 748 groundwater bodies.

Water management Plans also provide an estimation of how much water is used in Spain. Specifically, considering the traditionally consumptive uses (water supply, agricultural, industrial, and recreational), it is estimated an annual average of 30,000 hm<sup>3</sup> of water, of which 75% came from surface water (about 23,000 hm<sup>3</sup>) and the reminding 25% (7,000 hm<sup>3</sup>) comes from underground sources. For uses, it clearly stands agriculture (irrigation and livestock), consuming about 23,000 hm<sup>3</sup> (above 75% of the total), followed by urban supply (including industrial), with more than 5,000 hm<sup>3</sup>, i.e., around 17% (Ardiles, 2015).

## 12.2 Literature review

The absence of a national planning tool for the forest hydrologic restoration has prompted MAGRAMA to develop a general framework for the development of restoration works, conservation and enhancement of protective vegetation cover. This plan was called National Plan of Priority Actions (PNAP), related to forest hydrologic restoration, erosion control, and the combat against desertification.

To this end, projects such as LUCDEME (Acronym in Spanish, for Combating Desertification in the Mediterranean) were created in order to promote the implementation of several experimental stations integrated into a network called RESEL, consisting mainly of research centers and universities. The main objective of this network is to collect, store, and provide data on resources and natural processes linked to desertification. This network has worked on various research topics, among which can be highlighted the following (CONAMA, 2003):

- To get real rates of soil loss by water erosion, runoff, and sediment generation.
- Analysis of the role of Mediterranean forests in the production and quality of water and sediments.
- Reforestation trials using species and varied techniques, in relation to the improvement and protection of the soil from erosion processes.
- Effects of deforestation and fires.
- Calibration of rainfall-runoff-erosion models.

### 12.2.1 Spanish hydrology, in figures

Annual precipitation values vary widely, from 1,600 mm in large areas of the territory, sometimes even exceeding 2,000 mm, to 300 mm over the southeastern part of the Iberian Peninsula and less than 200 mm in some areas of Canary Islands. The average precipitation for Spain is 649 mm/year - equivalent to 346 km<sup>3</sup>/year. The rainiest month is December and July the least (MAGRAMA, 2000).

Moreover, the average annual potential evapotranspiration in Spain, applying Thornthwaite method, is 862 mm. The highest value is obtained on the southern part of the peninsula, the Canary Islands and on the central valley of Ebro River. The actual evapotranspiration presents a global average of 464 mm/year, being significantly lower than the potential evapotranspiration; under such value not always the optimum soil moisture for potential evapotranspiration occurs.

Due to the effects of climate variables combined with land characteristics, the total average annual runoff in Spain follows a similar pattern to that from spatial rainfall, although with greater variability (CEDEX, 2010). Total average annual runoff in Spain is 220 mm, equivalent to about 111,000 hm<sup>3</sup>. As for the spatial distribution, it shows clear regional differences, ranging from areas where runoff is less than 50 mm/year (southeast of Spain, La Mancha, Ebro Valley, Duero plateau and Canary Islands) to other areas where it exceeds 800 mm/year (Northern basins).

Regarding aquifers' water reserves, the volume of groundwater stored in Spain, down to 200 m below ground levels, it is estimated to be about 125,000 hm<sup>3</sup>. Approximately 120,000 hm<sup>3</sup> are in the Peninsula and 5,000 hm<sup>3</sup> in the Canary and Balearic Islands (MAGRAMA, 2000)

### 12.2.2 Case Study. Cover restoration-Sierra Espuña, Murcia (Espuña Hill, Province of Murcia)

The city of Murcia and other towns located near the Guadalentín River, a Segura River tributary, suffered from severe flooding, causing huge material and human losses. For this reason, in 1888 the government created the Reforestation Commissions, becoming later the Hydrological Forest Divisions. At that time, Guadalentín River had its hillsides almost bare of vegetation and also with high rates of soil erosion. Therefore, whenever a storm occurred, runoff mobilized a large volume of sediments and rocks that were dragged into the river, causing the raising of the bed and, consequently, its overflow. Thus, in 1890, by Royal Decree of November 5, the reforestation work in the scrubland called "Huerta Espuña", was approved, starting its implementation in June 1891 (Figure 7).

Preliminary works were focus in the stabilization of hillsides by implementing dry stone dykes, following the contour lines, in order to decrease and shorten the slopes. The next step was to plant frugal species, mainly Aleppo pine (*Pinus halepensis*). Also, beds were stabilized by transverse dams, built in order to decrease overland flow velocity and to promote sediment deposition. Thus, valleys had regained soil, allowing to plant hardwood and other riparian species.

Since the beginning of the restoration until today, reforestation has continued achieving near 7,000 ha, including the silvicultural treatments listed in the management plan (Del Palacio, 2014). This restoration has given to Sierra Espuña a natural forest aspect, which led in 1992 to be declared Regional Park (Figure 7).



Figure 7. Forest Hydrologic Restoration in Sierra Espuña (Murcia, Spain).  
Photographic comparison between 1895 and 2002 (Del Palacio, 2014).

## 12.3 Politics

According to MAGRAMA, for the elaboration of a forest hydrologic restoration plan, it is important to keep in mind all those sectoral plans affecting water planning, both regarding water use and soil, and especially those regarding irrigation and other agricultural uses (CONAMA, 2003). These plans are developed as sectoral plans, or programs under a special subject, addressing topics such as: supply, sanitation, purification, protection of resources, protection of natural areas, extreme events (floods and droughts), water-forestry relations, etc.

The integration of hydrological and forest restoration in several strategies and regional forestry plans has been a constant evolution. The Spanish Forestry Plan highlights the affinity between regional forestry plans in terms of joint programs to develop in their own territories, including in all plans and programs for the restoration and improvement of natural environments. Also, the Spanish Forestry Plan mentions that the top priority of the regional forestry plans aims for the maintenance and improvement of forest cover and infrastructures, where in terms of investment, means that 27% is dedicated to restoration actions of natural environments (Simon *et al.*, 1993).

Legislatively, it should be noted that both the Water Law 29/1985, and Royal Decree 927/1988, approving the Regulations of the Water Public Administration and Water Planning, indicate that watershed management plans should contain hydrological-forestry and soil conservation plans. This policy framework marks a new stage in the coordination between forest and water administrations, regarding actions in forest hydrologic restoration and reinforcing the existing coordination instruments before the promulgation of the Water Law.

Today and after the approval for the National Hydrological Plan in 2001, and the Spanish Forestry Plan in 2002, the foundation for a joint action in the management of forest hydrologic restoration actions has been laid (CONAMA, 2003).

### 12.3.1 Investment in the forestry sector

Public investment in the forestry sector has its origin principally in the General Administration of the State and in the Autonomous Regions. It is devoted to the creation of action like the prevention and extinction of forest fires, hydrological forest protection, subsidies to private woodland, forestry treatments etc.

Average public investment in the forestry sector was 1,228.6 M euros during the 2002-2008 period (3% of total public investment), which is the equivalent of 51 euros per wooded hectare and 20 euros per capita (Huertas, 2011).

## 12.4 Climate change and the future of forestry & forest research

Spain is highly vulnerable to climate change and, accordingly, an assessment of impacts and adaptations should be considered a priority. Spain was one of the first countries in Europe to develop an adaptation policy and, in 2006, approved the National Climate Change Adaptation Plan (PNACC in Spanish) and its First Work Programme (MAGRAMA, 2009).

In July of 2007, the European Union published the Green Paper Adaptation to Climate Change in Europe - options for EU action produced by the Commission and, in April of 2009, released the corresponding White Paper, which lays the foundations for Community policy on this matter.

The Second Work Programme reviews progress made since 2006 under the framework established by the PNACC, setting ambitious goals to address climate change adaptations in Spain. It is structured into the following four lines of action (MAGRAMA, 2009):

1. Sectorial assessment of climate change impacts, vulnerability, and adaptation. This lies at the core of the Second Work Programme, which maintains the focus of the First Programme. It continues to produce regionalized climate scenarios and sectoral assessments of water resources, coastal areas and biodiversity, and now extends its scope to include other relevant sectors, such as tourism, agriculture, health, forests, and soils/desertification.
2. Mainstreaming of climate change adaptation into sectorial legislation, by systematically and consensually identifying the legal instruments needed to achieve this goal.
3. Mobilization of key stakeholders (from the public, social, and private spheres) in the sectors included in the PNACC, to ensure that they participate actively in identifying adaptation measures.
4. Creation of a system of indicators for climate change impacts and adaptation in Spain in every sector, with the aim of developing a monitoring and assessment instrument to guide future implementation of the PNACC.

To complement the four lines of action mentioned above, the Second Work Programme is founded on two basic tenets (MAGRAMA, 2009): (1) strengthen R&D and Innovation to research, innovate, develop and implement adaptation technologies, and (2) reinforce coordination between national and regional government through the Climate Change Policy Coordination Committee (CCPCC - Comisión de Coordinación de Políticas de Cambio Climático) and its Impacts and Adaptation Working Group.

### 12.4.2 Water Resources

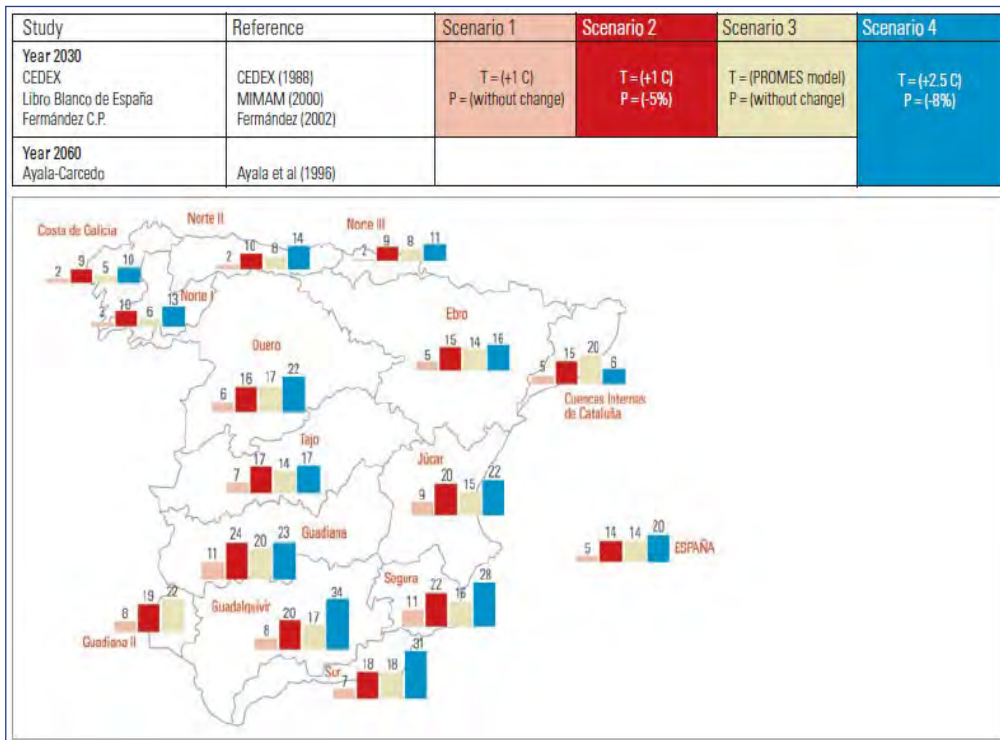
Climate change in Spain will be expressed by means of a general trend towards increases in temperature and decreases in precipitation, with the following effects (Figure 8) (MAGRAMA, 2006):

- A decrease of the general availability of water resources. Previous estimates for Spain as a whole - horizon 2030, considering temperature increases of 1 °C and 5% decreases in rainfall - estimate a 5 to 14% decrease in water supplies.
- Severe impacts are expected in arid and semi-arid areas (approximately 30% of the national territory), where water yields may decrease by 50%.
- Hydrological variability will increase in the Atlantic basins, while more irregularity is expected in flood patterns of the Mediterranean basin (CEDEX 2010).



### 12.4.2.1 First Action Lines in Water Resources

- Development of coupled climate-hydrology models to obtain reliable scenarios of all aspects of the hydrological cycle, including extreme events.
- Assessment of water management options in terms of the hydrological scenarios generated for the 21st century.
- Application of the foreseen hydrological scenarios to other sectors highly dependent on water (energy, agriculture, tourism, etc.).
- Identification of climate change indicators under the implementation scheme of the Water Framework Directive.
- Development of guidelines and regulations to incorporate the foreseen impacts of climate change into the processes of Environmental Impact Assessment and Strategic Environmental Assessment of Plans and Programmes, within the hydrological sector (MAGRAMA, 2006).



**Figure 8.** Long-term projections, as percentages, of total runoff decrease in Spain's main river basins, under several climate scenarios (Extract from: MAGRAMA, 2006)

### 12.4.3 Forests

The effects of climate change on forests will be accompanied by direct effects on plants species, as well as indirect ones, such as habitat regression, erosion, etc. (MAGRAMA, 2006).

- The physiology of species will be deeply affected.
- The decrease in water reserves in soils will be a major hydrological stress factor that will derive in a trend towards decreasing forest density and, in extreme cases, towards its substitution by shrubs.
- The flammability of forests will increase, and hence, the frequency, intensity and magnitude of forest fires.

- The impact of forest pests and diseases is expected to increase.
- The most vulnerable forest systems are found in high-mountain areas, dry ecosystems, and riparian woodlands.

#### 12.4.3.1 First Action Lines in Forests

- Drafting of guidelines and evaluation of techniques and models needed to implement an adaptive forest management to climate change.
- Development and application of forest growth models under different climate change scenarios.
- Assessment of the response of vegetation to a variety of adverse situations (draughts, fires, etc.).
- Evaluation of a system of climate change indicators for forests and implementation of an early warning system.
- Evaluation of the carbon balances for different types of forest ecosystems.
- Evaluation of above- and below-ground biomasses of Spanish species and forest systems (MAGRAMA, 2006)

## 12.5 Acknowledgments

We would like to thank the information provided by the Ministry of the Environment and Rural and Marine Affairs (MAGRAMA), through Eduardo Del Palacio and also José Nicolas from Tragsatec Company, who have been decisive in sharing their books about forest hydrologic restoration works in Spain. We also wish to thank professors Juan A. Mintegui and Jose Carlos Robredo for their contributions in this subject.

## 12.6 References

- Ardiles, L. S. 2015. LOS NUEVOS RETOS DE LA PLANIFICACIÓN HIDROLÓGICA. In Revista Ambienta nº 110. Marzo 2015.
- CEDEX. 2010. INFORME TÉCNICO: ESTUDIO DE LOS IMPACTOS DEL CAMBIO CLIMÁTICO EN LOS RECURSOS HÍDRICOS Y LAS MASAS DE AGUA. Centro De Estudios Y Experimentación De Obras Públicas (CEDEX) para el Ministerio de Medio Ambiente y Medio Rural y Marino (MAGRAMA).
- CONAMA. 2003. RESTAURACIÓN HIDROLÓGICO FORESTAL: PASADO, PRESENTE Y FUTURO. CONAMA VII. Grupo de Trabajo 8. Cumbre del Desarrollo Sostenible. Madrid
- Del Palacio, E. (2014). CIEN AÑOS DE RESTAURACIÓN HIDROLÓGICO-FORESTAL. Editorial Ministerio de Agricultura, Alimentación y Medio Ambiente. 197 pp
- García Rodríguez, J.L. 2010. LA RESTAURACIÓN HIDROLÓGICO FORESTAL, COMO HERRAMIENTA DE DISMINUCIÓN DE LA PRODUCCIÓN DE SEDIMENTOS. In Brea, D. and Balocchi, F (Eds.), *Procesos de erosión -sedimentación en cauces y cuencas-*, Vol. 1, PHI-VII / Documento Técnico N° 22, UNESCO
- Huertas García, J. 2011. THE ENVIRONMENTAL PROFILE OF SPAIN 2010. Ministry of the Environment and Rural and Marine Affairs.
- MAGRAMA 2000. LIBRO BLANCO DEL AGUA EN ESPAÑA. Ministerio de Medio Ambiente (Ministry of the Environment). Secretaría de Estado de Aguas y Costas. Dirección General de Obras Hidráulicas y Calidad de las Aguas.
- MAGRAMA 2006. NATIONAL CLIMATE CHANGE ADAPTATION PLAN. First Work Programme. Ministry of the Environment and Rural and Marine Affairs (MAGRAMA).

MAGRAMA 2009. NATIONAL CLIMATE CHANGE ADAPTATION PLAN. Second Work Programme. Ministry of the Environment and Rural and Marine Affairs (MAGRAMA).

MAGRAMA 2012. CRITERIA AND INDICATORS FOR SUSTAINABLE FOREST MANAGEMENT, IN SPANISH FORESTS 2012. Ministry of the Environment and Rural and Marine Affairs (MAGRAMA).

Navarro Garnica, M. 1975. Técnicas de forestación. Monografías, nº 9. ICONA. Madrid

Simón E., Mintegui, J.A, García, J.L. and Robredo, J.C. 1993. La Restauración Hidrológico-Forestal en las Cuencas Hidrográficas de la Vertiente Mediterránea. 325 págs. Información Técnica N° 22/93. Consejería de Agricultura y Pesca. Junta de Andalucía.

# Chapter 13. Forest management and water in the United States

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## 13.1 Introduction

This chapter outlines a brief history of the United States native forests and forest plantations. It describes the past and current natural and plantation forest distribution (map, area, main species), as well as main products produced (timber, pulp, furniture, etc.). Integrated into this discussion is a characterization of the water resources of the United States and the importance of forests for water uses. The chapter presents a review of the most extensive body of research on the relationships of water and forests that has been produced world-wide. Finally, the chapter concludes with a discussion of key forest and water issues, the principal one being a combination of water shortages and excess brought on by a changing climate and human population increases in vulnerable landscapes.

### 13.1.1 Importance of water

The value of forests in providing stable flows of good quality water was recognized by a number of civilizations (Greece, 1700 BC; India, 1000 BC; Rome, 312 BC; France, 1215 AD; Switzerland, 1535, etc.) (Neary, 2000). By the 19th century, the concept of catchment management and the relationship between forests and water supplies was well developed. For example, in 1849 the German naturalist Alexander Von Humboldt remarked that the concept of catchment management was well developed in European and American scientific circles. He further reflected: “How foolish do men appear destroying the forest cover of the world without regard to consequences, for they rob themselves of wood and water.”

In the 21st century, the mission of the US Forest Service, and forestry in as a profession, is in securing favorable water flows for human needs, and riparian and aquatic functions. It is now even more important than in the past two centuries. The population of the USA has expanded from 76 million at the start of the 20th century to 281 million people in 2000, the beginning of the 21st century (Hobbs and Stoops, 2002). Clean and accessible water remains one of the most important resources to sustain this expanding population. One resource that people need every day is water. And every day there are more people in the country that require water. Too often good quality water is taken for granted in developed countries. Across the developing world, the main cause of child mortality is still “dirty water” (Rutstein 2000).

### 13.1.2 Natural and plantation forest distribution

In 2005, forest land constituted 303.5 million ha of the USA total land area or about 33.3%, similar to both Canada and Mexico (Figure 1). The forests of the eastern USA are predominantly deciduous, while those of the west are mainly coniferous (U.S. Geological Survey 2015). The main eastern USA forest cover types are: white-red-jack pine, spruce-fir, longleaf-slash pine, loblolly-shortleaf pine, oak-pine, oak-hickory, oak-gum-cypress, elm-ash-cottonwood, maple-beech-birch, aspen-birch. Western forest cover types can be grouped into Douglas-fir, hemlock-sitka spruce, ponderosa pine, western white pine, lodgepole pine, larch, fir-spruce, redwood, chaparral, pinyon-juniper, and western hardwoods. Alaska has three cover types of spruce-birch, fir-spruce, and hemlock-sitka spruce. Hawaii’s forest cover consists of evergreen broadleaf tropical forest. The southeastern

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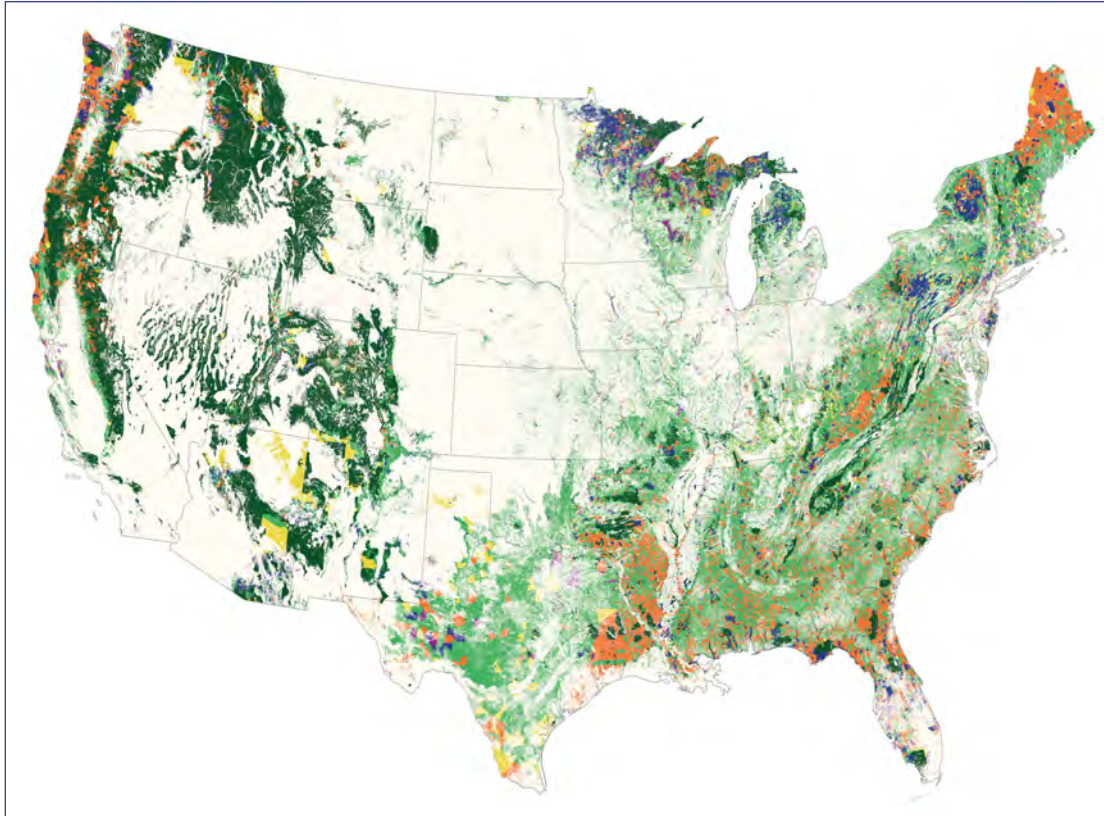


forests have a large component of yellow pines that form the backbone of the forest industry in that region. Plantation forests dominate the southeastern area forests. Uncolored areas (white in Figure 1) are urban, agriculture, prairie, tundra, ice, water, swamp, desert, or other miscellaneous cover types.



**Figure 1.** Dominant forest cover types of the USA (From: The National Atlas of the United States of America, US Geological Survey, 2015).

Forest ownership since 2005 is predominantly private in the eastern USA (78%) consisting of many smaller landownerships and fewer numbers of large ownerships (Figure 2). More than half the forest land in the United States (171.2 million ha) is owned and managed by some 11 million private forest owners. Of those private forest owners, 92% (10 million owners) are classified as small “family forest” owners with forest holdings of <4 ha. Industrial and government land holdings for vertically integrated forest products companies have declined in the past several decades in favor of forest management operations run by indigenous, local, or investment enterprises (White and Martin 2002). These private forests are managed under short rotations for sustained production of dimensional timber, pulp and paper feedstocks, furniture, bioenergy feedstocks



**Figure 2.** Dominant forest land ownerships of the USA: Dark Green = Federal, Yellow = Tribal, Light Green = non-industrial private, Orange = Industrial; Blue = State and Municipal, White = Non Forest. (From: The National Atlas of the United States of America, US Geological Survey, 2015).

### 13.1.3 History of forest use

Watershed management has been an integral part of forestry in the USA since the creation of the National Forests at the end of the 19th century and the beginning of the 20th century (Neary, 2000). The Forest Reserve Act of 1891 created the forest and grassland reserves that were to become the core of the National Forest system (Steen, 1976). During Congressional deliberations on the Forest Reserve Act, Secretary of the Interior John W. Noble personally intervened to include a provision authorizing the President to create forest reserves (Section 24). By the end of 1892, President Harrison had created/authorized 15 reserves totaling 5.3 million ha, primarily to protect water supplies. Additional reserves amounting to 2.4 million ha were added by 1896. The next president, President Cleveland, set off a land reservation furor by increasing the reserves by another 8.5 million ha in early 1897. That same year, the Pettigrew Amendment to the 1897 Sundry Civil Appropriations Bill more fully defined the purpose of the forest reserves (Steen, 1976), stating that the reserves were to be established only to: "...improve and protect the forest within the reservation, or for the purpose of securing favorable conditions of water flows..."

Clearly, by 1897, the interpretation of catchment management within the context of forestry was for water supply and flood prevention. The US Forest Service was established in 1905 with two primary missions, to: (a) manage the nation's forests, and (b) secure favourable conditions of water flow. Today an estimated 80% of the USA freshwater resources originate in forests, with much of the nation's drinking water originating in the 78 million ha that now constitute the National Forest System (Levin *et al.* 2002).



### 13.1.4 Multiple use forests: wood, water, range, wildlife and recreation

Forest management in the USA has been strongly influenced by the Multiple Use and Sustained Yield Act (MUSY) of 1960 (Cawley and Freemuth 1997). Although MUSY mandates that only National Forests be “administered for outdoor recreation, range, timber, watershed, and wildlife and fish purposes.” The broad directive was extended to other Federal agencies in 1976 by the Federal Land Policy and Management Act of 1976. Other forest land ownerships picked up the concept to some degree. The MUSY Act of 1960 codified the U.S. Forest Service’s management philosophy at the time and named a set of multiple uses: recreation, range, timber, watershed, and wildlife. The Act directed that no single use should be dominant and that resource outputs should be maintained without reductions in land productivity and sustainability. This broad guidance gave the Forest Service a considerable amount of leeway in land management. The objectives of land management under MUSY were community stability, jobs, sustainable supply of fiber, enhanced recreation and hunting opportunities, and sustainable supplies of high quality water for municipal use. These objectives were harmonious and initially there was very little resource conflict.

However, as Cawley and Freemuth (1997) argued, the multiple use concept eventually resulted in management gridlock as single-interest groups inserted their goals into the discussion regarding the management of public lands. They believed that MUSY created a zero-sum game, where the attitude of “*I must restrict or eliminate your use to protect my use*” has been the operative feature and that “*the logic of a zero-sum game encourages the various participants to concentrate their energies on the task of blocking the moves of their opponents rather than on seeking to establish a common ground upon which compromises could be constructed*”. The predictable outcome of a zero-sum game is gridlock (Cawley and Freemuth 1997). This has been a dominant feature of Federal land management decisions for the past half century. Fortunately, private forest land management has not been directly affected by MUSY politics. But, this conflict has resulted in a major shift of forest resource supply from public lands to private ones. The spotted owl dispute has been a major driver in this trend.

### 13.1.5 USA Water resources and uses



**Figure 3.** Major watersheds of the United States (From: The National Atlas of the United States of America, US Geological Survey, 2015).

The major drainage basins of the USA are shown in Figure 3 (U.S. Geological Survey 2015). The country has 3,069 km<sup>3</sup> of fresh water reserves, making it the third richest water nation behind Brazil (8,233 km<sup>3</sup>) and Russia (4,508 km<sup>3</sup>). The Great Lakes account for a large percentage of the USA water wealth. The eastern USA is predominantly humid with the western USA varying from arid and semi-arid to humid, depending wind patterns and topography. The central USA is occupied by the tall grass, middle grass, and short grass prairies that grade from wet to dry along east to west and south to north gradients.

Irrigated lands in the USA total 266,440 km<sup>2</sup>. Water withdrawals for all uses add up to 1,583 m<sup>3</sup> person<sup>-1</sup> yr<sup>-1</sup>. Forests provide drinking water for many municipalities and small water supply systems. In the USA, over 3400 towns and cities depend on National Forest catchments for their public water supplies (Ryan and Glasser 2000). An additional 3000 administrative sites such as campgrounds, picnic areas, and historical sites rely on the same or similar sources. It has been estimated that 25% of the people in the USA, predominantly in western regions where the bulk of the National Forest lands are located, rely on streams and groundwater emanating from National Forests for their public water supplies. Since 70% of the forest area in the USA is outside the National Forest System, particularly in the eastern USA, a conservative estimate is that 50–75% of the USA's population relies on forest lands to produce adequate supplies of good quality water.

### 13.1.6 Water resource issues in the 21<sup>st</sup> century

The direction of future water research using paired catchments will depend greatly on the important issues and governmental support for the science. Water research is expensive and it requires the commitment to the long-term that only government entities can afford. Water quantity and quality are going to be increasingly important topics as nations come to grips with water security problems (Vose *et al.* 2011). Human populations are increasing most in regions where the abundance of good quality water is being affected by climate change. The importance of long-term studies will loom large since these studies are good indicators of climate change and its effects (Archer and Predick 2008). Specific topics that require further water quality investigation include wildfire, fire retardant use, atmospheric deposition, trace organic chemicals, oil development, large-scale mining, inter-basin water diversions, and bioenergy.

Water is now an area of keen interest in bioenergy development because of its potential footprint on water supplies and its effects on water quality. Some recent publications have addressed the latter issue (Diaz-Chavez *et al.* 2011a, 2011b). Currently, BMPs offer the best solution to achieving the goal of energy production with biofuels that minimizes the impact on water quality. In some instances, sound research using the paired catchment approach will be needed to convince regulatory authorities that bioenergy feedstock production can co-exist with water quality goals and standards.

Over the span of the 20th Century, the perception of what constitutes watershed management and hydrologic science has grown considerably. At the beginning of the century, it was mostly concerned with the development and maintenance of water supplies. Water quality was a big issue then and it still is. At the beginning of the 21st Century, it is probably best defined as a comprehensive understanding of the components of watersheds and their physical, chemical, and ecological interactions to produce high quality water in sufficient supply to meet human demands (Reimold 1998). This definition also reflects thinking on the discipline at the end of the 20th Century that watershed management and hydrologic science incorporates the holistic approach to a watershed as an ecosystem, and not just manipulation of physical processes. The goal of watershed management is to assess the effects of current and future land uses on soil and water resources, determine the potential social and ecological impacts, and provide solutions to watershed problems.

As Rango (1995) pointed out, the increase in the world's human population (now at 7 billion) will cause the demand, scarcity, price, and need for high quality water to expand on a global scale into the foreseeable future. He forecast that, in this era of "Global Hydrology" for hydrologic science and watershed management, worldwide emphasis will be placed on large area assessments using



modeling, remote sensing, watershed management expertise, and the best hydrologic science. The technological tools and paired catchment infrastructure are in place. The key to the future success of these endeavors lies in watershed management professionals using their expertise and understanding of paired catchment science to develop positive outcomes for human populations of all countries.

## 13.2 Literature review

### 13.2.1 Water and natural processes

Although the initial focus of early catchment research was water yield, the adoption of the paired catchment approach set the stage for examining physical, chemical, and biological processes that controlled nutrient cycling and other water quality related functions of forest catchments (Bormann and Likens 1967). The untreated half of catchment study pairs provided the opportunity to study natural processes that controlled water yield and quality. However, the disturbances to these processes produced by practices such as harvesting, site preparation, road construction, fire, fertilization, herbicide use and insect outbreaks provided the real insight into natural catchment processes that affect both water quantity and quality.

### 13.2.2 Water yield

Forest harvesting affects many water cycle processes (Figure 4). The specific hydrologic effects are summarized in Table 1. Changes in baseflow and stormflow definitely affect the quantity of water delivered from forested catchments, and can ultimately alter water quality. The following discussion is a general summary of the effects, not a site-specific analysis. Remember, the occurrence and magnitude of these effects is a function of the general climate, precipitation, aspect, latitude, severity of disturbance, and the percentage of the watershed harvested.

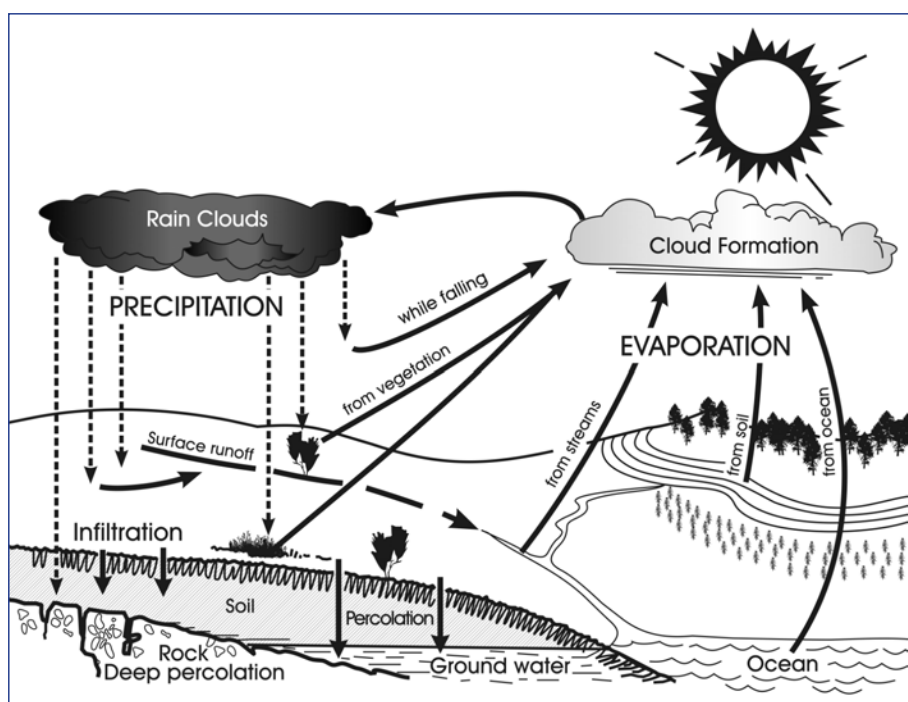


Figure 4. Hydrologic cycle processes (From Neary and Koestner 2012).

### 13.2.2.1 Water quantity – total yield

Watershed responses to forest harvesting are very ecosystem specific. Water quantity increases are normally the highest the first year after harvesting (Brooks *et al.* 2003). Thereafter water yields decline as vegetation recovers and leaf area index returns to levels that occurred before harvesting. This recovery period is very short (3-4 years; Brown *et al.* 1974) in forests with high evapotranspiration rates and low precipitation, and over 10 years in ecosystems with high rainfall and low evapotranspiration.

The amount of water yield increase after forest harvesting is a function of the proportion of a watershed that is cut, the amount of precipitation, and site factors such as aspect, soils, and vegetation cover (Neary and Koestner 2012). Aspect, which is a good indicator of potential evapotranspiration, has a strong effect on water quantity responses to forest harvesting (Figure 4). Slopes oriented normal to solar radiation receive the highest solar loadings and have the highest evapotranspiration. In general, mean annual streamflow increases as the percentage harvest of a forest stand or watershed approaches 100%. Streamflow is usually minimal at the low end of the precipitation range for forest ecosystems, but it is substantial in forests that occur in high precipitation zones.

**Table 1.** A summary of the changes in hydrologic processes after harvesting and other disturbances that change stand basal area, cover type, soil conditions, etc. (Adapted from Neary 2002).

Hydrologic Process	Type of Change	Specific Effect
1. Interception	Reduction	Moisture storage smaller
		Greater runoff in small storms
		Increased water yield
2. Litter Storage of water	Litter Reduced	Less water stored (0.5 mm cm <sup>-1</sup> )
	Litter Not Affected	No change
	Litter Increased	Storage increase
3. Transpiration	Temporary Elimination	Baseflow increase
		Soil moisture increase
4. Infiltration	Reduced	Overland flow increase
		Stormflow increase
	Increased	Overland flow decrease
		Baseflow increase
5. Streamflow	Changed	Increase in most ecosystems
		Decrease in snow systems
		Decrease in fog-drip systems
6. Baseflow	Changed	Decrease with less infiltration
		Increase with less transpiration
		Summer low flows (+ and -)
7. Stormflow	Increased	Volume greater
		Peakflows larger
		Time to peakflow shorter
8. Snow accumulation	Changed	Cuts <4 ha, increase snowpack
		Cuts > 4 ha, decrease snowpack
		Snowmelt rate increase
		Evaporation/sublimation greater

A considerable amount of research has been conducted in the past on the effects of forest harvesting for the purpose of increasing water supplies or determining the impacts on watershed hydrology (Tables 2 and 3). These studies have been very costly and required considerable dedication to their continuity. The earliest paired watershed experiments were installed in Switzerland, Japan, and the USA in the first decade of the 20th century (Neary 2000). Some have been in existence since the 1930s. Researchers in the USA have examined various intensities and harvesting configurations and timing. In doing so they have produced the largest body of works in existence on the relationships between forests and water quantity and quality.

With a 100% clearcut, first-year water yield increases reported in the literature generally range from 21 to 80%. One exception to this generalization occurs with high evapotranspiration and low rainfall (<480 mm) where harvesting has not produced increased streamflows (Clary *et al.* 1974). Another exception to this trend occurs in areas with high evapotranspiration and high rainfall. Increases in water yield of 0 to 280% have been reported after harvesting (Table 2; Clary *et al.* 1974, Neary *et al.* 1982). These higher values probably resulted from temporary removal of overstory and understory vegetation with high transpiration rates where rainfall was high. Although the absolute water yield increase the first year after harvesting increases with total precipitation, the percentage increase is not related to precipitation amount but the absolute amount is strongly related to the average annual rainfall.

**Table 2.** First year streamflow responses to forest harvesting in the United States, 450 to 1200 mm precipitation forest ecosystems. (Adapted from Neary 2002) .

Forest type	Location	Ppt. mm	Mean annual streamflow mm	Cut %	1st year increase mm	Percent increase %	Reference
Pinyon-juniper	Arizona USA	457	20	100	0	0	Clary <i>et al.</i> 1974
Aspen-conifer	Colorado USA	536	157	100	34	22	Reinhart <i>et al.</i> 1974
Ponderosa pine	Arizona USA	570	153	100	96	63	Brown <i>et al.</i> 1974
Oak woodland	California USA	635	144	99	33	23	Lewis 1968
Spruce-fir-pine	Colorado USA	770	340	40	84	25	Leaf 1975
Aspen - birch	Minnesota USA	775	107	100	45	42	Verry 1972
Slash pine	Florida USA	1020	48	74	134	280	Neary <i>et al.</i> 1982

In semiarid areas, where annual precipitation falls below 500 mm, forest cutting does not produce any additional increases in mean annual streamflow (Table 2; Clary *et al.* 1974). Evaporation is such a powerful factor in low precipitation climates, that basin-wide vegetation management or species conversion does not have much effect on streamflow.

The fact that harvesting of forest stands increases water yield has been used as the basis for municipal water supply augmentation (Bosch and Hewlett 1982, Brooks *et al.* 2003). The duration of the response is dependent on a number of factors. Generally, the increase in total water yield from harvesting is not of sufficient magnitude to produce adverse hydrologic or ecosystem effects. A more important parameter of concern is flood peak flows.

### 13.2.2.2 Water quantity – peak flows

Examination of the literature indicates that harvesting of forests produces a mixed peakflow response (Table 4). In locations where snowmelt runoff is an important component of annual hydrographs, declines in peakflows up to 35% have been reported after cutting (Pierce *et al.* 1970, Verry 1972). Some investigators have reported no peakflow response to harvesting (Kochenderfer *et al.* 1997). In other locations, watershed, vegetation, and climatic characteristics have produced peakflow increases of up to 1,400%. But that sort of response is rare, and more often produced by disturbances like wildfire. However, some combinations of terrain and geology may combine to create localized hazards (Neary and Hornbeck 1994).

**Table 3.** First year streamflow responses to forest harvesting in the United States, 1200 to 2600 mm precipitation forest ecosystems (Adapted from Neary 2002).

Forest type	Location	Ppt. mm	Mean annual streamflow mm	Cut %	1st year increase mm	Percent increase %	Reference
Coastal redwoods	California USA	1200	67		34		Keppler and Ziemer 1990
Mixed hardwoods	Georgia USA	1219	467	100	254	54	Hewlett and Doss 1984
Northern hardwoods	New Hampshire USA.	1230	710	100	343	48	Hornbeck <i>et al.</i> 1987
Loblolly pine	Arkansas USA	1317	214	100	101	47	Miller <i>et al.</i> 1988
Slash pine	Florida USA	1450	169	74	134	79	Swindel <i>et al.</i> 1982
Mixed hardwoods	W. Virginia USA	1524	584	85	130	22	Patric and Reinhart 1971
Mixed hardwoods	N. Carolina USA	1900	880	100	362	41	Swift and Swank 1980
Cascade Douglas-fir	Oregon USA	2388	1376	100	462	34	Rothacher 1970
Coastal Douglas-fir	Oregon USA	2483	1885	82	370	20	Harr 1976

Flood peakflow responses are important to understand from a watershed management and human health and safety viewpoint. Major changes in stream channel geomorphology and damage to cultural resources are a function of the magnitude of the peakflow. Peakflow responses from harvesting have been measured to be less than one order of magnitude greater than peakflows of undisturbed and forested lands (Table 4). They compare to the lower end of peakflow responses measured after wildfires (1 to 4 orders of magnitude increase) (DeBano *et al.* 1998). Floods after major, severe wildfires often produce significant channel degradation, sedimentation of reservoirs and low-gradient channels, damage to transportation systems, personal property damage, and can be a significant cause of human and livestock death and injury. Although peakflows increase after harvesting, they are not of the same level of concern as wildfire-induced peakflow increases.



**Table 4.** Effects of tree harvesting on peakflows ( $Q_{pt}$ ). (Adapted from Neary 2002) .

Forest Type	Location	Ppt. Mean	Peakflow ( $Q_{pt}$ ) Change 1-3 Years Post Harvest	References
Ponderosa pine	Arizona USA	570	Rainfall: $Q_{pt}$ +167%	Brown et al. 1974
Lodgpole pine, Engelmann spruce	Colorado USA	762	Snowmelt: -23 to + 50% change in $Q_{pt}$	Goodell 1958
Aspen	Minnesota USA	775	Rainfall: $Q_{pt}$ Doubled Snowmelt: $Q_{pt}$ -35 to +1,400%	Verry 1972
Loblolly pine	Georgia USA	1219	Rainfall: $Q_{pt}$ Tripled	Hewlett and Doss 1984
Northern hardwoods	New Hampshire USA	1230	Rainfall: -13 to +170% Rain +snowmelt: -21 to +23% change in $Q_{pt}$	Pierce <i>et al.</i> 1970
Loblolly and shortleaf pine	Arkansas USA	1317	Rainfall: $Q_{pt}$ increased +16 to +247%	Miller <i>et al.</i> 1988 Beasley and Granillo 1988
Slash pine	Florida USA	1450	Rainfall: $Q_{pt}$ increased six-fold	Swindel <i>et al.</i> 1983
Mixed hardwoods	W. Virginia USA	1524	Rainfall: No effect on $Q_{pt}$	Kochenderfer <i>et al.</i> 1997
Mixed hardwoods	North Carolina USA	1900	Rainfall: increased 9%	Hewlett and Helvey 1970
Douglas-fir and hemlock	Oregon USA	2300	Rainfall: $Q_{pt}$ increased 1% Snowmelt: $Q_{pt}$ -16%	Harr and McCorison 1979

### 13.2.3 Disturbance effects

Most of the forest catchment water quality studies reported in the literature deal with tree harvesting and post-harvest site preparation since much of the early interest in paired catchment science related to vegetation management to increase water yield. In addition, these practices were considered to produce the most disruptions to ecological processes and therefore the most influence on water quality. Since forest fertilization has been a basic feature of intensive forest management throughout the world, the impact of fertilizers on water quality has been an issue easily addressed by paired catchment research (Binkley *et al.* 1999). Paired catchments provided a sound basis for acid deposition research in the 1980s and 1990s (Likens *et al.* 1996), and continue to support scientific endeavors on climate change in the 21<sup>st</sup> Century (Bourauoui *et al.* 2004).

A number of water quality parameters are affected by disturbances, but only nutrients, sediments, and temperature will be discussed in the limited space available in this chapter. Other papers present a much more detailed discussion of these topics (Swanson *et al.* 2000, Neary 2002, Ice and Stednick 2004).

#### 13.2.3.1 Harvesting and site preparation – nutrients

Neary (2002) summarized a number of paired catchment studies looking at N losses in streamflow after harvesting and site preparation (Table 5). Nitrate nitrogen ( $\text{NO}_3\text{-N}$ ) dynamics are considered to be very susceptible to disturbance and  $\text{NO}_3\text{-N}$  concentration is a commonly accepted indicator of catchment health and water quality throughout the world since low levels ( $10 \text{ mg L}^{-1}$ ) can affect infant health (Neary 2002). For the most part, large increases in  $\text{NO}_3\text{-N}$  levels in streams draining harvested catchments have not been observed. Certainly there is no general indication that the World Health Organization (2006) water quality standard ( $10 \text{ mg L}^{-1} \text{NO}_3\text{-N}$ ) is commonly breached

by post-harvesting  $\text{NO}_3\text{-N}$  concentration increases. The largest increase reported (Pierce *et al.* 1970) was measured in an experiment where herbicides were used to suppress vegetation regrowth. Other causes of increased  $\text{NO}_3\text{-N}$  losses in forested catchments have been documented where severe fire occurred (DeBano *et al.* 1998), nitrogenous fertilizers were used during regeneration (Neary and Hornbeck 1994), or N saturation of ecosystems has reached a critical level due to atmospheric deposition (Aber *et al.* 1989). Paired catchments have been instrumental in demonstrating that, except in rare instances of delayed vegetation regrowth (e.g. Pierce *et al.* 1970) or forest ecosystems impacted by atmospheric deposition, forest harvesting does not significantly raise stream  $\text{NO}_3\text{-N}$  or other nutrient concentrations for long periods of time.

**Table 5.** Paired catchment comparison of the effects of forest harvesting on mean  $\text{NO}_3\text{-N}$  concentrations in streamflow in North America the year after cutting (Adapted from Neary 2002).

Forest Type	Location	$\text{NO}_3\text{-N}$		Reference
		Uncut	Cut	
		$\text{mg L}^{-1}$	$\text{mg L}^{-1}$	
Spruce, Fir	Colorado, USA	<0.1	<0.1	Stottlemeyer 1992
Slash pine	Florida, USA	<0.1	0.3	Riekerk <i>et al.</i> 1980
Loblolly Pine	Georgia, USA	0.1	0.1	Hewlett & Doss 1984
Mixed Conifer	Idaho, USA	0.2	0.2	Snyder <i>et al.</i> 1975
Aspen, Birch, Spruce	Minnesota, USA	0.1	0.2	Verry 1972
Mixed Conifer	Montana, USA	0.1	0.2	Bateridge 1974
Northern Hardwoods	New Hampshire, USA	0.3	11.9	Pierce <i>et al.</i> 1970
Mixed Hardwoods	North Carolina, USA	<0.1	0.1	Swank & Douglass 1975
Douglas-fir	Oregon, USA	<0.1	0.2	Fredrickson <i>et al.</i> 1975
Mixed Conifers	Oregon, USA	<0.1	0.2	Fredrickson <i>et al.</i> 1975
Oak-Maple	Pennsylvania, USA	0.1	5.0	Corbett <i>et al.</i> 1975
Loblolly Pine	South Carolina, USA	<0.1	<0.1	Van Lear <i>et al.</i> 1985
Mixed Hardwoods	West Virginia, USA	0.1	0.5	Aubertin & Patric 1974

### 13.2.3.2 Harvesting and Site Preparation – Sediment

After forest harvesting, forest catchments produce sediments yields that are highly variable depending on factors such as soils, climate, topography, ground cover, road networks, and catchment condition. Although sediment yields increase after harvesting due to the physical disturbance of soil, they are usually transient due to vegetation re-growth (Neary 2002). There is a large body of literature that reported using paired catchments to assess the effects of harvesting and site preparation on the sediment component of water quality (Binkley and Brown 1993, Neary 2002). The largest increases documented in the literature have been associated with post-harvest mechanical site preparation (Beasley 1979), slope instability (O'Loughlin and Pearce 1976), road construction and maintenance (Heede 1987), highly erosive soils (Beasley and Granillo 1988), and steep terrain (Beschta 1978) (Table 6).

**Table 6.** Effects of harvesting and related disturbances on sediment outputs from paired catchments (Adapted from Neary and Hornbeck 1994, Neary 2002, Diaz-Chavez 2011).

Forest Type	Location	Treatment	Sediment Increase Mg ha <sup>-1</sup> yr <sup>-1</sup>	Reference
Mixed Conifers	Arizona, USA	Clearcut	0.003	Heede 1987
Mixed Conifers	Arizona, USA	Cut, Road	0.081	Heede 1987
Loblolly Pine	Arkansas, USA	Clearcut	0.225	Beasley & Granillo 1988
Slash Pine	Florida, USA	Clearcut, Bed	0.033	Riekerk <i>et al.</i> 1980
Northern Hardwoods	New Hampshire, USA	Clearcut	0.323	Hornbeck <i>et al.</i> 1987
Douglas-fir	Oregon, USA	Clearcut	0.510	Beschta 1978
Loblolly Pine	South Carolina, USA	Clearcut	0.131	Van Lear <i>et al.</i> 1985

Sediment movement to and within stream systems is a constant environmental concern in managed forest catchments, but it also occurs naturally without management. Herein rests the importance of paired catchment analyses. Catchments can vary greatly in their natural suspended and bedload sediment characteristics (Trimble and Crosson 2000). Both natural and anthropomorphic erosion material can be re-entrained after initial deposition in ephemeral or perennial stream channels, and move downstream with streamflow for long time periods and distances. The cumulative effects of erosion and sedimentation that occurred centuries ago from agriculture or forestry can present forest managers with many challenges. Sediment is an important water quality parameter since it can harm aquatic organisms and habitats, and render water unacceptable for drinking water supply or recreation purposes (Table 6). However, adequate BMPs can significantly limit increases in sediment delivery to streams (Neary *et al.* 2011).

### 13.2.3.3 Harvesting and site preparation – temperature

Forest vegetation shades stream channels from solar radiation, thereby producing stream temperatures that are cooler and less variable than for unshaded sites. Increases in temperature that result from forest harvesting affect physical, chemical, and biological processes (Table 7). Thus, temperature is a critical water quality characteristic of many streams and aquatic habitats. Temperature controls the survival of certain flora and fauna in the water that are sensitive to water temperature. The removal of streambank vegetation by burning can cause water temperature to rise, causing thermal pollution to occur, which in turn can increase biological activity in a stream (DeBano *et al.* 1998, Brooks *et al.* 2003). Increases in biological activity place a greater demand on the dissolved oxygen content of the water, one of the more important water quality characteristics from a biological perspective.

In the USA there are no established national standards for the temperature of drinking water (Dissmeyer 2000). However, under the Clean Water Act, States are required to develop water quality standards to protect beneficial uses such as fish habitat and water quality restoration. The U.S. Environmental Protection Agency provides oversight and approval of these State standards. One of the problems with these standards is identifying natural temperature patterns caused by vegetation, geology, geomorphology, climate, season, and natural disturbance history. Also, increases in stream water temperatures can have important and often detrimental effects on stream eutrophication. Acceleration of stream eutrophication can adversely affect water quality by adversely affecting the color, taste, and smell of drinking water. Severe wildfires can function like streamside timber clearcuts

in raising the temperature of streams due to direct heating of the water surface (Neary *et al.* 2005, Table 7).

**Table 7.** Paired catchment studies of the effects of forest harvesting on stream temperature (Adapted from Binkley & Brown 1993, Binkley *et al.* 1999, Moore *et al.* 2005).

Location	Temperature			Time	Reference
	Control °C	Cut °C	Change °C		
<b>Clear Cut, No Buffer</b>					
New Hampshire, USA	16.0	20.0	4.0	Mean Daily 30 Days AUG	Likens <i>et al.</i> 1970
North Carolina, USA	18.3	21.7	3.4	Mean Daily 30 Days AUG	Swift & Messer 1971
Oregon, USA	13.3	15.6	2.3	1 Day - JUL	Brown <i>et al.</i> 1971
Oregon, USA	20.6	28.3	7.7	1 Day - JUL	Brown <i>et al.</i> 1971
Oregon, USA	14.4	22.8	8.4	Mean Daily 30 Days AUG	Levno & Rothacher 1969
Oregon, USA	12.2	22.2	10.0	Mean Daily 30 Days AUG	Brown & Krygier 1970
Pennsylvania, USA	17.8	25.0	7.2	Mean Daily 30 Days AUG	Rishel <i>et al.</i> 1982
<b>Clear Cut, With Buffer</b>					
Georgia, USA	21.1	25.0	3.9	Mean Daily 30 Days AUG	Hewlett & Fortson 1982
Oregon, USA	14.4	15.0	0.6	1 Day - July	Brown <i>et al.</i> 1971
Oregon, USA	16.7	18.3	1.6	1 Day - July	Brown <i>et al.</i> 1971
West Virginia, USA	14.4	16.1	1.7	Mean Weekly – Growing Season	Aubertin & Patric 1974
<b>Partial Cut With Buffer</b>					
Pennsylvania, USA	19.4	20.6	1.2	Mean Daily 30 Days AUG	Rishel <i>et al.</i> 1982
Oregon, USA	12.0	15.0	3.0	Mean Daily 21 Days AUG	Harr & Fredriksen 1988
Oregon, USA	12.5	14.4	2.0	Mean Monthly Max. (APR-OCT)	Harris 1977

### 13.2.4 Forest fertilizers

Forest fertilization is another management disturbance that has the potential to affect stream water quality because of the additions of N, phosphorus (P), cations, etc. to forest catchments (Binkley *et al.* 1999, Neary 2002). Streams originating in agricultural areas have about 9 times the load of N and P than forested catchments so the water quality of forested areas is highly valued. The growth of tree plantations in high production silviculture regions of the world is often limited by soil nutrient availability (Fox *et al.* 2007). Hence, fertilization is a common silvicultural practice in these high-intensity production forests. Fertilizer applications are rarely incorporated in stand management in slower growing forests due to economic limitations. Nitrogen and P fertilizers are the most frequently used but, in some locations, cations and micronutrients are applied to deal with local deficiencies. Here again, paired catchments have been invaluable in understanding the water quality implications of this management practice). Higher stream concentrations are usually associated with higher fertilizer application rates (e.g. >200 kg-N ha<sup>-1</sup>) or aerial applications that fly over or near monitored streams (Helvey *et al.* 1989). Nitrogen saturation of soils from atmospheric deposition (Aber *et al.* 1989) can predispose forest stands to leak highly mobile NO<sub>3</sub>-N if it is not utilized by vegetation (Pierce *et al.* 1970). Paired catchments provide investigators the ability to sort out fertilizer water



quality effects from those produced by other processes (e.g. herbicide suppression of vegetation regrowth, N saturation of soils, naturally high N soils, inputs from agricultural areas, etc.).

### 13.2.5 Roads

Best Management Practices for roads are most effective on minimizing sediment impacts to water quality when properly planned and implemented prior to, during, and after harvesting (Neary *et al.* 2011). Most of these guidelines relate to designing, constructing, and maintaining major access roads, logging roads, skid trails, and landings. Permanent roads and associated temporary roads are the primary sources for 90% of the sediment generated by harvesting (Swift 1988). The underlying principles of road BMP guidelines are to minimize disturbances in streamside zones, reduce the erosive power of runoff on bare road surfaces, and to maintain the normally high infiltration capacity of forest soils (Neary *et al.* 2011).

### 13.2.6 Fire

A major disturbance to catchment hydrology, geomorphology, and water quality in fire-prone regions like the western USA, the Mediterranean Basin, and Australia is wildfire (Shakesby and Doerr 2006). The random nature of wildfires and their characteristic severities rarely gives researchers the opportunity to use paired catchment techniques to assess impacts on water quality. Prescribed fires are much more amenable to paired catchment comparisons because they are easier to manage. However, even the best-managed paired catchment study of prescribed fire can produce surprises (Gottfried *et al.* 2012). Wildfire impacts on water quality evaluations reported in the literature have been a mixture of paired catchment methods and before-fire and after-fire approaches using the same catchment (DeBano *et al.* 1998, Neary *et al.* 2005, Smith *et al.* 2011).

Post-fire sediment yields can vary widely from  $<0.001$  to over  $204 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  depending on the type of fire (prescribed or wildfire), fire severity, topography, fuel type, and climate. The highest soil erosion values usually involve intense rainfall on steep terrain (Glendening *et al.* 1961, Moody and Martin 2001, Neary *et al.* 2012). Wright *et al.* (1976) demonstrated the effect of slope with his study in juniper stands in Texas. As slope increased from zero to the 43-54 % range, the annual prescribed fire sediment losses rose from about  $0.029$  to  $8.443 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  compared to a range of  $0.013$  to  $0.025 \text{ Mg ha}^{-1} \text{ yr}^{-1}$  in unburned paired catchments.

Usually post-fire maximum  $\text{NO}_3\text{-N}$  levels are in the  $0.1$  to  $0.6 \text{ mg L}^{-1}$  range since wildfires volatilize most of the N in the fuels they consume and prescribed fires are usually low-level disturbances (Neary *et al.* 2005). One of the few and the most striking response of water quality streamflow to fire was observed in southern California, where N loadings from atmospheric deposition are relatively high, and the frequent wildfires in the chaparral shrublands are characterized by high fire severity (Riggan *et al.* 1994). Severe burning of a catchment in the Mediterranean-type chaparral resulted in a maximum  $\text{NO}_3\text{-N}$  level of  $15.3 \text{ mg L}^{-1}$  in streamflow compared to  $2.5 \text{ mg L}^{-1}$  peak in streamflow from an unburned control watershed. The maximum concentration for a moderately burned catchment was  $9.5 \text{ mg L}^{-1}$ . These results represent an “unusual response” because the catchments studied were subject to a chronic atmospheric deposition of air pollutants from the Los Angeles basin that are among the highest recorded in the USA.

### 13.2.7 Pesticides

Another water quality parameter of considerable concern that has been amenable to study with the paired catchment approach is herbicide and insecticide residue environmental fate. Michael and Neary (1993) discussed this topic in considerable detail. A study by Neary *et al.* (1983) that utilized four  $1.0 \text{ ha}$  chemically-treated catchments plus an untreated control was adopted as a template for

required herbicide registration studies in the USA by the U.S. Environmental Protection Agency. Since that study, paired watersheds have been an integral part of forestry pesticide environmental fate studies the past three decades (Neary *et al.* 1993). Virtually all monitoring protocols now require use of untreated control watersheds. Any future research on newly developed forestry pesticides must incorporate paired-watershed methodology. Despite the frequent criticisms of pesticides like herbicides, they should be kept as tools that can achieve vegetation or other pest management goals and maintenance of water quality (Neary and Michael 1996).

Additional research conducted by Michael and Neary (1993) and Neary *et al.* (1993) expanded on the work of Norris (1970). However, it incorporated newer, rapidly degrading pesticides. They enhanced earlier findings regarding the importance of forest soils in protecting water quality. Neary *et al.* (1993) and Neary and Michael (1996) concluded that the risks to water quality posed by modern silvicultural chemicals is very low due to the low toxicity of the chemicals, infrequent use over the rotations of conventional forest stands, the lack of bioaccumulation by these pesticides, and the function of forest soil organic matter and microorganisms in adsorbing and decomposing pesticide residues. If forest pesticides are not applied directly to water, their tendency to migrate into streams is limited by forest soil biological and chemical processes. Although herbicides, especially water soluble ones like picloram and hexazinone, have been measured to move through forest soils, they do so in small non-toxic amounts because of the biological and chemical actions of organic matter in forest soils (Neary *et al.* 1985).

## 13.3 Politics

### 13.3.1 Key environmental regulations, laws, and policies related to forestry and water

The legal support for maintaining forest ecosystem sustainability and conservation is complicated since there is no national policy to guide lawmakers and land managers at all levels of governance. Most land-use regulations are not forestry specific but deal with general environmental concerns.

#### *National Environmental Policy Act of 1969*

This act requires all federal agencies proposing major land management activities that may substantially affect the environment to follow an analysis and reporting process. Agencies must produce an environmental analysis through either environmental assessments or environmental impact statements.

#### *Clean Air Act of 1970*

This comprehensive federal law regulates air emissions from area, stationary, and mobile sources. Its purpose is to protect and enhance the quality of the nation's air resources. It authorizes the Environmental Protection Agency to establish National Ambient Air Quality Standards to protect public health and the environment. The original Clean Air Act was passed in 1963, but the current air pollution control program is based on the 1970 version of the law. Substantial revisions of the 1970 law were made in the 1990 Clean Air Act Amendments.

#### *Clean Water Act of 1972*

The Clean Water Act established a regulatory system for navigable waters in the United States, whether on public or private land. It is intended to eliminate discharge of water pollutants into navigable waters, to regulate discharge of toxic pollutants, and to prohibit discharge of pollutants

from “point” sources (e.g., pipeline effluent) without permits. The legislation was amended in 1977, 1981, and 1987 and is currently being refined by Executive Order.

### *Endangered Species Act of 1973*

This law instructs federal land management agencies to conduct programs to sustain endangered and threatened species and to protect the ecosystems that are critical for supporting these species. Threatened or endangered species receive additional legal protection under the auspices of the Act. Specific management procedures are designed to restore populations to sustainable levels.

### *The National Forest Management Act of 1976*

This legislation requires the US Forest Service to develop land management plans for every National Forest. The agency must consider each unit under the principles of multiple use and sustained yield, factoring in both traditional and non-traditional uses and outputs. A key component of the planning process is public participation.

### *Forest Land Policy and Management Act of 1976*

This legislation is directed at the Bureau of Land Management for management of Federal forest and range lands under the agency’s purview. It was crafted in the same fashion as the National Forest Management Act of 1976.

### *Federal Insecticide, Fungicide, and Rodenticide Act of 1948 (amended 1996)*

This legislation was designed to allow provide federal regulation over the development, registration, sale, and application of pesticides. Since forestry is a minor use of pesticides, the law is primarily aimed at agriculture uses. However, forestry uses still fall under the regulation provided by the U.S. Environmental Protection Agency.

Increases in fire activity, area, and severity since 1995 have brought an increased focus on national fire management and budgeting requiring new sets of Federal and State legislation.

## **13.3.2 Additional State Regulation**

Regulations formulated by individual States provide additional governance over forest management and water use. Some States have adopted forest practices laws. The most commonly used are forestry Best Management Practices (BMP) codes and guidelines (Aust and Blinn 2004, American Forest and Paper Association 2006, Shepard 2006, Georgia Forestry Commission 2009, Neary *et al.* 2013, National Association of State Foresters 2016). Implementation for forest management is variable from State-to-State depending on the level of commercial forest industry. The National Association of State Foresters (2016) maintains up-to-date information as to the status of state BMP regulations as regulatory, quasi-regulatory, or voluntary. As of 2016, 10 states had regulatory BMPs, 19 operated under quasi-regulatory BMPs, and 20 used non-regulatory BMPs. Seventy five percent of the states west of the Mississippi River are non-regulatory BMP states. State and Federal agencies involved in BMP policy and regulation monitoring vary from state to state. The most recent guidelines are posted on the web site *Forestry Best Management Practices by State* (National Association of State Foresters 2016).

### 13.3.3 Role of Forest Certification Systems in Managing Water Quantity and Quality.

The key environmental laws relating to forestry and water at the National level in the USA include the National Environmental Policy Act of 1969, the Clean Water Act of 1972, the National Forest Management Act of 1976, and the Forest Land Policy and Management Act of 1976 (See Section 3.1 above). Individual states are also free to implement additional regulations and policies as deemed necessary by local conditions. Enforcement has traditionally been the responsibility of a mix of State and Federal agencies. Implementation of new regulations and practices to protect water resources relies on landowner cooperation in both the public and private forestry sectors. Forest certification systems have been very successful in disseminating knowledge and encouraging incorporation of BMPs that protect water and other forest resources through sustainable forest management (Rametsteiner *et al.* 2003).

In contrast to national Criteria and Indicators developed by the 1998 Montreal Process (Castañeda 2000), forest certification is designed for use by individual forest landowners for marketing purposes as well as ensuring good forest land stewardship by establishing proof of sustainable forest management. There are over 50 forest certification systems world-wide. The main certification systems in North America are the American Tree Farm System (ATFS), the Sustainable Forest Management System Standard of the Canadian Standards Association (CSA), the Sustainable Forestry Initiative (SFI), the Program for Endorsement of Forest Certification (PEFC), and the Forest Stewardship Council Standards (FSC). The two largest certification systems are FSC and PEFC. Presently, PEFC is mostly based in Europe and is certifying the largest area. The FSC program is the fastest growing. Certification systems are currently being utilized mainly by industrial and non-industrial private forest land owners. As the area of forests under certification management increases, the benefits to water resources will likewise increase. The main benefits will certainly be in improved water quality.

## 13.4 Climate change and the future of forestry and forest research

### 13.4.1 Effects of climate change in the USA

Climate change is certain to exert a large impact on USA forests and water yields produced by those forests. The most profound impacts will be exhibited through alteration of the frequency, intensity, duration, and timing of natural disturbances beyond anything observed in the past several centuries (Dale *et al.* 2001). Unprecedented drought, flooding, wildfire, insect outbreaks, and exotic species infestations are already announcing the presence of climate change. Since water integrates the impacts of natural and human disturbances, significant changes in water resources can be expected. The IPCC Scenario A1 for 2050 forecasts a 20% decrease in water availability for the Southwest, the Great Plains, the Upper Midwest, and the Northeast. If these projections occur, the impact on water resources will be the greatest where water is already in short supply and the demands from a growing population are high. Impacts on aquatic and riparian ecosystems are likely to be high and the interactions with wildfire certain to aggravate an already out-of-bounds fire regime.

### 13.4.2 Area occupied by forest plantations

About 303.5 million ha of the USA total land area, or 33.3% of the land base, is classified as forest (Zhang and Stanturf 2008). Two thirds of this forest land is classified as timberland, forests capable of producing  $>1.5 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Smith *et al.* 2002). Plantation forests account for only 11% of the USA timberland and most are found in the southern part of the country. Common plantation species are *Pinus* spp., *Pseudotsuga menziesii*, *Populus* spp., *Quercus* spp., *Larix* spp., *Salix* spp., and *Eucalyptus* spp. The intensity of plantation management varies by ownership, region, and tree species. High intensity silviculture is most likely to be practiced on forest industry and corporate investment sites. Government-owned plantation forests and small ownership stands typically have the least intensive management prescriptions. Plantations are likely to become more important for



future wood supplies in the USA due to reduced availability of wood products from Federal forests (Haynes 2002). However, international market forces and competition from Canadian and South American sources may have an impact on reducing American plantation demands. Rising demand for bioenergy feedstocks from wood pellets may offset reductions due to off-shore competition.

### **13.4.3 Future research and management practices to improve water quality and water yield.**

Through achievements in the 20<sup>th</sup> Century, the USA has been able to supply its residents with reliable supplies of safe drinking water. Much of this supply originates in forest lands which constitute 33% of the national land base. As the nation enters into the 21<sup>st</sup> Century there are numerous challenges to maintaining the high quality of water supply that will require future research investments and development or refinement of management practices (Levin *et al.* 2002). Some of these challenges are:

- Insufficient resources to deal with infrastructure deterioration
- Modernization of water economics and ownership
- Groundwater and surface water changes due to climate change
- Spread of water borne infectious diseases
- Sharing of water resources on regional and national basis
- Remediation strategies for depleted and contaminated groundwater
- Sub-standard quality of surface waters due to sediment
- Nutrient contamination of surface waters in agricultural areas
- Deterioration of water quantity and quality due to increased wildfires
- High technology water monitoring tools
- Updating regulatory requirements and procedures
- Development of and implementation of BMPs
- Training of adequate numbers of hydrologists and water managers needed to cope with water resource issues in forest lands, agricultural lands, municipalities, and other parts of the national landscape.

## **13.5 Acknowledgments**

Support from the USDA Forest Service, Rocky Mountain Research Station, Air-Water-Aquatic Environments Program is gratefully acknowledged. Program Manager, Dr. Frank McCormick, is acknowledged here for being instrumental in providing the creative atmosphere for this and many other publications.

## **13.6 References**

American Forest and Paper Association. 2006. State Forest Best Management Practices.

[http://www.afandpa.org/Content/NavigationMenu/Forestry/State\\_Forestry\\_Best\\_Management\\_Practices/State\\_Forestry\\_Best\\_Management\\_Practices.htm](http://www.afandpa.org/Content/NavigationMenu/Forestry/State_Forestry_Best_Management_Practices/State_Forestry_Best_Management_Practices.htm). Accessed August 2015.

Aubertin, G.M.; Patric, J.H. 1974. Water quality water after clearcutting a small watershed in West Virginia. *Journal of Environmental Quality* 3: 243-249.

- Aust, W.M.; Blinn, C.R. 2004. Forestry Best Management Practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years (1982–2002). *Water, Air, and Soil Pollution: Focus* 4: 5–36.
- Aber, J.D., Nadelhoffer, K.J., Steudler, P. and Melillo, J.M. 1989. Nitrogen saturation in northern forest ecosystems. *Bioscience* 39:378-386.
- Archer, S.R.; Predick, K. I. 2008. Climate change and ecosystems of the southwestern United States. *Rangelands* 30: 23-28.
- Bateridge, T.E. 1974. Effects of clearcutting on water discharge and nutrient loss. Bitterroot National Forest, Montana. M.S. Thesis. Office of Water Resources Research, University of Montana, Missoula, MT. 68 p.
- Beasley, R.S. 1979. Intensive site preparation and sediment losses on steep watersheds in the gulf Coastal Plain. *Soil Science Society of America Journal* 43:412-417.
- Beasley, R.S.; Granillo, A.B. 1988. Sediment and water yields from managed forests on flat coastal plain sites. *Water Resources Bulletin* 24:361-366.
- Beschta, R.L. 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. *Water Resources Research* 14: 1011-1016.
- Binkley, D.; Brown, T.C. 1993. Forest practices as nonpoint sources of pollution in North America. *Water Resources Bulletin* 29: 729-740.
- Binkley, D.; Burnham, H.; Allen, H.L. 1999. Water quality impacts of forest fertilization. *Forest Ecology and Management* 121: 191-213.
- Bormann, F.H.; Likens, G.E. 1967. Nutrient cycling. *Science* 155: 424-429.
- Bosch, J.M.; Hewlett, J.D. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55:3-23.
- Bouraouii, F.; Grizzetti, B.; Granlund, K.; Rekolainen, S.; Bidoglio, G. 2004. Impact of climate change on the water cycle and nutrient losses in a Finnish catchment. *Climate Change* 66: 109-126.
- Brooks, K.N.; Ffolliott, P.F.; Gregerson, H.M.; DeBano, L.F. 2003. *Hydrology and the Management of Watersheds*. Iowa State University Press, Ames, IA, 574 p.
- Brown, H.E., Baker, M.B. Jr., Rogers, J.J., Clary, W.C., Kovner, J.L., Larson, F.R., Avery, C.C. and Campbell, R.E. 1974. Opportunities for increasing water yields and other multiple use values on ponderosa pine forest lands. USDA Forest Service Research Paper RM-129, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- Castañeda, F. 2000. Criteria and Indicators for sustainable forest management: International processes, current status and the way ahead, FAO, Rome, Unasylva No. 203.
- Cawley, R.M.; Freemuth J. 1997. *Western Public Lands and Environmental Politics*. Westview Press, pp. 32-44.
- Clary, W.P., Baker, M.B. Jr., O'Connell, P.F., Johnsen, T.N. Jr. and Campbell, R.E. 1974. Effects of pinyon-juniper removal on natural resource products and uses in Arizona. USDA Forest Service Research Paper RM-128, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. 28 p.
- Corbett, E.S.; Lynch, J.A.; Sopper, W.E. 1975. Forest-management practices as related to nutrient leaching and water quality. Pp. 157-173. In: Conference on Non-point Sources of Water Pollution Proceedings. Virginia Water Resources Research Center; Virginia Polytechnical Institute and State University, Blacksburg, Virginia, May 1-2, 1975.
- Dale, V.H.; Joyce, L.A.; McNulty, S.; Neilson, R.P.; Ayres, M.P.; Flannigan, M.D.; Hanson, P.J.; Irland, L.C., Lugo, A.E.; Peterson, C.J.; Simberloff, D.; Swanson, F.J.; Stocks, B.J.; Wotton, B.M. 2001. Climate change and forest disturbances. *Bioscience* 51(9): 723-734
- DeBano, L.F., Neary, D.G. and Ffolliott, P.F. 1998. *Fire's Effects on Ecosystems*. John Wiley & Sons, New York, NY. 333 p.
- Diaz-Chavez, R.; Neto, A.E.; Berndes, G.; Neary, D.G. 2011a. Chapter 4: Bioenergy-related water quality issues. Pp. 41-61. In: *The Bioenergy and Water Nexus*. United Nations Environment Program, the Oko-Institut eV. Institute for Applied Ecology, and International Energy Agency Bioenergy Task 43. 173 pp.
- Diaz-Chavez, R.; Berndes, G.; Neary, D.; Nieto, A.; Fall, M. 2011b. Water quality assessment of bioenergy production. *Biofuel. Bioprod. Bior.* 5: 445–463.
- Dissmeyer, G.E. (ed.) 2000. *Drinking water from forests and grasslands: a synthesis of the scientific literature*. USDA Forest Service, General Technical Report SRS-39, Southern Research Station, Asheville, North Carolina. 246 p.

- Fox, T.R.; Allen, H.L.; Albaugh, T.J.; Rubilar, R.; Carlson, C.A. 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. *Southern Journal of Applied Forestry* 31: 5-11.
- Fredriksen, R.L.; Moore, D.G.; Norris, L.A. 1975. Impact of timber harvest, fertilization, and herbicide treatment on stream water quality in the Douglas-fir regions. p. 283-313. In: Bernier, B.; Winget, C.H. (eds.) *Forest Soils and Forest Land Management: Proceedings of the Fourth North American Forest Soils Conference*, Laval University, Quebec City, Canada.
- Georgia Forestry Commission 2009. *Georgia's Best Management Practices for forestry*. Georgia Forestry Commission, Macon, Georgia, 75 p.
- Glendening, G.E.; Pase, C.P.; Ingebo, P. 1961. Preliminary hydrologic effects of wildfire in chaparral. Pp. 12–15. In: *Proc. 5th Ann. Arizona Watershed Symposium*, September 21, 1961, Phoenix, Arizona, Tucson, University of Arizona.
- Goodell, B.C. 1958. A preliminary report on the first year's effects of timber harvesting on water yield from a Colorado watershed. USDA Forest Service Station Paper No. 36, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. 12 p.
- Gottfried, G.; Neary, D.; Ffolliott, P.; Koestner, K. 2012. Cascabel prescribed fire long-term watershed study: An opportunity to monitor climate change. Revisiting Experimental Catchment Studies in Forest Hydrology, Proceedings of a Workshop held during the XXV IUGG General Assembly in Melbourne, June–July 2011.
- Harr, R.D. 1976. Forest practices and streamflow in western Oregon. USDA Forest Service General Technical Report PNW-49, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 18 p.
- Harr, R.D.; McCorison, F.M. 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon. *Water Resources Research* 15:90-94.
- Haynes, R.W. 2002. Forest management in the 21st century: Changing numbers, changing context. *Journal of Forestry* 100: 38-43.
- Heede, B.H. 1987. Overland flow and sediment delivery five years after timber harvest in mixed conifer forest. *Journal of Hydrology* 91:205-216.
- Helvey, J.D.; Kochenderfer, J.M.; Edwards, P.J. 1989. Effects of forest fertilization on selected ion concentrations in Central Appalachian streams. Pp. 278-282. In: *Proceedings of the 7th Central Hardwood Conference*. USDA Forest Service General Technical Report NC-132, North Central Forest and Range Experiment Station, St. Paul, Minnesota.
- Hewlett, J.D.; Doss, R. 1984. Forests, floods, and erosion: A watershed experiment in the Southeastern Piedmont. *Forest Science* 30:424-434.
- Hewlett, J.D.; Helvey, J.D. 1970. The effects of clear-felling on the storm hydrograph. *Water Resources Research* 6:768-782.
- Hobbs, F.; Stoops, N. 2002. Demographic trends in the 20th Century. U.S. Department of Commerce Economics and Statistics Administration, U.S. Census Bureau Report CENSUR-4, 222 p.
- Hornbeck, J.W.; Martin, C.W.; Pierce, R.S.; Bormann, F.H.; Likens, G.E.; Eaton, J.S. 1987. The northern hardwood forest ecosystem: 10 years of recovery from clearcutting. USDA Forest Service Research Paper NE-596. Northeastern Forest Experiment Station, Broomall, PA. 30 p.
- Ice, G.G.; Stednick, J.D. 2004. *A Century of Forest and Wildland Watershed Lessons*. Society of American Foresters, Bethesda, MD, 292 pp.
- Keppler, E.T.; Ziemer, R.R. 1990. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in northwestern California. *Water Resources Research* 26:1669-1679.
- Kochenderfer, J.N.; Edwards, P.J.; Wood, F. 1997. Hydrologic impacts of logging an Appalachian watershed using West Virginia's Best Management Practices. *Northern Journal of Applied Forestry* 14:207-218.
- Leaf, C.F. 1975. Watershed management in the central and southern Rocky Mountains: A summary of the status of our knowledge by vegetation type. USDA Forest Service Research Paper RM-142, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. 28 p.
- Levin, R.B.; Epstein, P.R.; Ford, T.E.; Harrington, W.; Olson, E.; Reichard, E.G. 2002. U.S. Drinking water challenges in the Twenty-first century. *Environmental Health Perspectives* 110: 43-52.
- Lewis, D.C. 1968. Annual hydrologic response to watershed conversion from oak woodland to annual grassland. *Water Resources Research* 4:59-72
- Likens, G.E.; Driscoll, C.T.; Buso, D.C. 1996. Long-term effects of acid rain: Response and recovery of a forest ecosystem. *Science* 272: 244-246.

- Miller, E.L.; Beasley, R.S.; Lawson, E.R. 1988. Forest harvest and site preparation effects on stormflow and peakflow of ephemeral streams in the Ouachita Mountains. *Journal of Environmental Quality* 17:212-218
- Michael, J.L.; Neary, D.G. 1993. Herbicide dissipation studies in forest ecosystems. *Environmental Toxicology and Chemistry* 12: 405-410.
- Moody, J.A.; Martin, D.A. 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes* 26: 1049-1070.
- National Association of State Foresters. 2016. <http://www.stateforesters.org/state-forestry-BMPs-map>. Accessed 05 September 2015.
- Neary, D.G. 2000. Changing perspectives of watershed management from a retrospective viewpoint. p. 167-176. In: Ffolliott, P.F.; Baker, M.B. Jr.; Edminster, C.B.; Dillion, M.C.; Mora, K.L. (editors) *Land Stewardship in the 21st Century: The Contributions of Watershed Management*. USDA Forest Service Proceedings, RMRS-P-13.
- Neary, D.G. 2013. Best Management Practices in forest bioenergy for protecting water quality. *WIREs Energy and Environment* 2013. 2: 614-632. Doi:10.1002/wene77 *Wiley Interdisciplinary Reviews in Energy and Environment*.
- Neary, D.G.; Koestner, K.A. 2012. Forest bioenergy feedstock harvesting effects on water supply. *Wiley Interdisciplinary Reviews in Energy and Environment*. *WIREs Energy Environment* 1: 270-284. 2012. doi: 10.1002/wene.26.
- Neary, D.G.; Bush, P.B.; Douglass, J.E. 1983. Offsite movement of hexazinone in stormflow and baseflow from forest watersheds. *Weed Science* 31: 543-551.
- Neary, D.G.; Hornbeck, J.W. 1994. Chapter 4: Impacts of harvesting and associated practices on off-site environmental quality. p. 81-118. In: Dyck, W.J.; Cole, D.W.; Comerford, N.B. (editors) *Impacts of Forest Harvesting on Long-term Site Productivity*, Chapman & Hall, London
- Neary, D.G.; Michael, J.L. 1996. Herbicides - protecting long-term sustainability and water quality in forest ecosystems. *New Zealand Journal of Forestry Science* 26:241-264.
- Neary, D.G.; Lassiter, C.J.; Swindel, B.F. 1982. Hydrologic responses to silvicultural operations in southern coastal plain flatwoods. p. 35-52. In: Coleman, S.S.; Mace, A.C. Jr.; Swindel, B.F. *Impacts of intensive Forest Management Practices*. School of Forest Resources and Conservation, University of Florida, Gainesville, FL. 110 p.
- Neary, D.G.; Bush, P.B.; Michael, J.L. 1993. Fate of pesticides in southern forests: a review of a decade of progress. *Environmental Toxicology and Chemistry* 12: 411-428.
- Neary, D.G.; Ryan, K.C.; DeBano, L.F. (eds.) 2005. *Fire Effects on Soil and Water*. USDA Forest Service, Gen. Tech. Rep. RMRS-GTR-42, Volume 4, Rocky Mountain Research Station, Fort Collins, Colorado. 250 p.
- Neary, D.G.; Bush, P.B.; Douglass, J.E.; Todd, R.L. 1985. Picloran movement in an Appalachian hardwood forest watershed. *Journal of Environmental Quality* 14: 585-592.
- Neary, D.G.; Smethurst, P.J.; Baillie, B.; Petrone, K.C. 2011. *Water quality and biodiversity effects of harvesting Streamside Management Zone tree plantations*. CSIRO Special Report, Canberra, Australia, 101 p.
- Neary, D.G.; Hayes, D.; Rustad, L.; Vose, J.; Gottfried, G.; Sebesteyn, S.; Johnson, S.; Swanson, F.; Adams, M. 2012. *U.S. Forest Service Experimental Forests and Ranges Network: A Continental Research Platform for Catchment-Scale Research*. Revisiting Experimental Catchment Studies in Forest Hydrology, Proceedings of a Workshop held during the XXV IUGG General Assembly in Melbourne, June-July 2011.
- Norris, L.A. 1970. Degradation of herbicides in the forest floor. pp. 397-412. In: Youngberg, C.T.; Davey, C.B. (eds.), *Tree Growth and Forest Soils*. Oregon State University Press, Corvallis, Oregon,
- Northern Research Station 2008. *Who owns America's forests? Forest ownership patterns and family forest highlights from the National Woodland Owner Survey*. NRS-INF-06-08. U.S. Department of Agriculture, Forest Service, Northern Research Station. 8 p.
- Patric, J.H.; Reinhart, K.G. 1971. Hydrologic effects of deforesting two mountain watersheds. *Water Resources Research* 7:1182-1188.
- Pierce, R.S.; Hornbeck, J.W.; Likens, G.E.; Bormann, F. H. 1970. Effect of elimination of vegetation on stream water quality and quantity. *International Association of Hydrological Science* 96:311-328.
- Rametsteiner, E.; Simula, M. 2003. Forest certification – an instrument to promote sustainable forest management? *Journal of Environmental Management* 67: 87-98.
- Rango, A. 1995. A look to the future in watershed management. Pp. 15- 22. In: Ward, T.J. (ed.) *Watershed Management: Planning for the 21st Century*. Proceedings of the Symposium, Watershed Management Committee,



Water Resources Engineering Division, American Society of Civil Engineers, August 14-16, 1995, San Antonio, Texas. 442 p.

Reimold, R.J. 1998. *Watershed Management: Practice, Policies, and Coordination*. McGraw-Hill Company, New York, 391 p.

Reinhart, K.G.; Eschner, A.R.; Trimble, G.R. Jr. 1974. Effect on streamflow of four forest practices in the mountains of West Virginia. USDA Forest Service Research Paper NE-1, Northeastern Forest Experiment Station, Broomall, PA. 59 p.

Riekerk, H.; Swindel, B.F.; Replogle, J.A. 1980. Effect of forestry practices in Florida watersheds. Pp. 706-720. In: *Proceedings of the Symposium on Watershed Management 1980*, ASCE, Boise, ID, July 21-23, 1980.

Riggan, P.J.; Lockwood, R.N.; Jacks, P.M. 1994. Effects of fire severity on nitrate mobilization in watersheds subject to chronic atmospheric deposition. *Environ. Sci. Tech.* 28: 369–375.

Rothacher, J. 1970. Increases in water yield following clear-cut logging in the Pacific Northwest. *Water Resources Research* 6:653-658.

Rutstein, S.O. 2000. Factors associated with trends in infant and child mortality in developing countries during the 1990s. *Bulletin of the World Health Organization* 78, 1256–1270.

Ryan, D.F.; Glasser, S. 2000. Chapter 1: Goals of this report. Pp. 3-6. In: Dissmeyer, G.E. (ed.). *Drinking water from forests and grasslands: a synthesis of the scientific literature*. USDA Forest Service Gen. Tech. Rep. SRS-39. Southern Research Station, Asheville, North Carolina.

Shakesby, R.A.; Doerr, S.H. 2006. Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews* 74: 269-307.

Shepard, J.P. 2006. Water quality protection in bioenergy production: the U.S. system of forestry Best Management practices. *Biomass & Bioenergy* 30: 378-384.

Smith, H.G.; Sheridan, G.J.; Lane, P.N.J.; Nyman, P.; Haydon, S. 2011. Wildfire effects on water quality in forest catchments: A review with implications for water quality. *Journal of Hydrology* 396: 170-192.

Smith, W.B.; Vissage, J.S.; Darr, D.R.; Sheffield; R.M. 2002. *Forest resources of the United States, 1997*. USDA Forest Service, General Technical Report NC-222. North Central Research Station, St. Paul, MN. URL: [http://www.ncrs.fs.fed.us/pubs/gtr/gtr\\_nc222.pdf](http://www.ncrs.fs.fed.us/pubs/gtr/gtr_nc222.pdf)

Snyder, G.G.; Haupt, H.F.; Belt, G.H. Jr. 1975. Clearcutting and burning slash alter quality of stream water in Northern Idaho. USDA Forest Service Research Paper INT-1698, Intermountain Forest and Range Experiment Station, Ogden, Utah. 34 p.

Steen, H.K. 1976. *The U.S. Forest Service, A History*. University of Washington Press, Seattle, 356 p.

Stottlemyer, R. 1992. Nutrient concentration patterns in streams draining alpine and subalpine catchments, Fraser Experimental Forest, Colorado. *Journal of Hydrology* 140: 179-208.

Swank, W. T.; Douglass, J. E. 1975. Nutrient flux in undisturbed and manipulated forest ecosystems in the Southern Appalachian Mountains. *International Association of Scientific Hydrology. Symposium Proceedings, Tokyo, Japan. December 1970. Publication 117. Pp. 445-456.*

Swanson, F.J.; Scatena, F.N.; Dissmeyer, G.E.; Fenn, M.E.; Verry, E.S.; Lynch, J.A. 2000. Chapter 3: Watershed processes –fluxes of water, dissolved constituents, and sediment. Pp. 26-41. In Dissmeyer, G.E. (ed.). *Drinking water from forests and grasslands: a synthesis of the scientific literature*. USDA Forest Service General Technical Report SRS-39. Southern Research Station, Asheville, North Carolina.

Swift, L.W. Jr. 1988. Chapter 23: Forest access roads: Design, maintenance, and soil loss. Pp. 313-324. In: Swank, W.T.; Crossley, D.A. (eds.) *Forest Hydrology and Ecology at Coweeta*. Springer-Verlag, New York, NY. 469 p.

Swift, L.W. Jr.; Swank, W.T. 1980. Long-term responses of streamflow following clearcutting and regrowth. p. 245-256. In: *Proceedings on the Influence of Man on the Hydrological Regime with Special Reference to Representative and Experimental Basins, Helsinki, Finland, June 1980. I.A.H.S. – A.I.S.H. Publication No. 130.*

Swindel, B.F.; Lassiter, C.J.; Riekerk, H. 1982. Effects of clearcutting and site preparation on water yields from slash pine forests. *Forest Ecology and Management* 4:101-113.

Swindel, B.F.; Lassiter, C.J.; Riekerk, H. 1983. Effects of different harvesting and site preparation operations on the peak flows of streams in *Pinus elliotii* flatwoods forests. *Forest Ecology and Management* 5:77-86.

Terrene Institute. 1993. *Proceedings of a technical workshop on sediments*. Terrene Institute, Washington, D.C. 143 p.

Trimble, S.W.; Crosson, P. 2000. U.S. soil erosion rates – myth and reality. *Science* 289: 248-250.

U.S. Geological Survey. 2015. The National Map. From: <http://nhd.usgs.gov/wbd.html> Accessed 06-30 2015.

Van Lear, D.H.; Douglass, J.E.; Fox, S.K.; Augsberger, M.K. 1985. Sediments and nutrient export in runoff from burned and harvested pine watersheds in the South Carolina Piedmont. *Journal of Environmental Quality* 14: 169-174.

Verry, E.S. 1972. Effect of aspen clearcutting on water yield and quality in northern Minnesota. p. 276-284. In: Csallany, S.C.; McLaughlin, T.G.; Striffler, W.D. (eds.) *Watersheds in Transition. Proceedings of a Symposium*, Fort Collins, CO, June 19-22, 1972, American Water Resources Association and Colorado State University. 405 p.

Vose, J.M.; Sun, G.; Ford, C.R.; Bredemeier, M.; Otsuki, K.; Wei, X.; Zhang, L. 2011. Forest ecohydrological research in the 21st century: what are the critical needs. *Ecohydrology* 4: 146-158.

White, A.; Martin, A. 2002. Who owns the world's forests? Forest tenure and public forests in transition. *Forest Trends*, Washington, D.C. 30 pp.

World Health Organization 2006. Guidelines for drinking water quality. Volume:1 Recommendations. World Health Organization, Geneva, Switzerland, 595 p.

Wright, H.A.; Churchill, F.M.; Stevens, W.C. 1976. Effect of prescribed burning on sediment, : 294–298.

Zhang, D.; Stanturf, J. 2008. Forest plantations. Pp. 1673-1680. In: Jorgensen, S.E.; Fath, B.D. *Encyclopedia of Ecology*, Elsevier, Oxford.



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