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Review

Waters and forests: from historical controversy to scientific debate

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Abstract

This article presents an historical perspective of the controversy concerning the hydrological impact of forests, and shows how a mostly romantic and emotional confrontation finally evolved into a scientific debate. We first analyze the historical evolution of ideas, starting with the views of Pliny the Elder in the first century AD and ending with the debate on the 'Eaux et Forêts' in France in the 19th century. Then, we give an up-to-date overview of the paired-watershed experiments conducted throughout 20th century, and identify some research issues that should help forest hydrology science to move forward in the 21st century.

Keywords: Forest hydrology; Paired-watershed design; Experimental watersheds; Deforestation impact; Reforestation impact; Hydrological trends

1. Introduction

The hydrological and meteorological role of forests has attracted considerable attention from the public over the last two centuries. The purpose of this article is to try to reconcile modern hydrological science with the debate and the arguments of the scientists of the past. Indeed, despite the huge amount of data and knowledge acquired over the last decades, the ghost of deforestation seems to reappear every time a new catastrophic flood or drought occurs somewhere in the world. Furthermore, we believe that many non-explicit assumptions by the public may have their source in arguments of the past.

This article first examines the historical aspects of the debate on water and forest, by trying to delve deeper into history than previous authors have done. Then, we present an updated summary of paired-watershed results, which will ultimately help to understand the contradictions of the past, as well as highlight yet unresolved issues in forest hydrology.

2. Origins of modern beliefs concerning water and forest interactions

2.1. Antiquity

Already during the Antiquity, Man tried to understand the impact of forests on the water

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cycle. Pliny the Elder was probably the first to allude to the hydrological role of forests. In his Natural History (written in the first century AD), he observes the following: "Often, after woods have been cut down, springs on which trees used to feed emerge: for example, on mount Himus, when Cassander besieged the Gauls, who cut down a forest to build themselves an entrenchment. Often, disastrous torrents are formed after the felling of mountain woods, which used to hold back clouds and feed on them" (XXXI, 30). Interestingly, Pliny's statement already covers the two main aspects of forest influence: the hydrological (impact of forest cutting on spring flow) and the meteorological one (impact on rainfall).

2.2. Middle Ages

In his book entitled 'Forest Influences', Kittredge (1948) considers France a pioneer in "the recognition of the close relation between water and forests". He refers to the royal ordinance "of the Waters and Forests" promulgated by king Philippe Auguste[1] in 1219. Since this date, the French administration has kept the habit of designating the officers in charge of forest management by associating the two words: 'Eaux et Forêts' (Waters and Forests), and the general public remains convinced (at least in France) that there is a natural dependence between water and forests.[2]

Concerning the meteorological impact of forests, Kittredge attributes its discovery to Christopher Columbus, who hypothesized that the observed difference of rainfall observed between the Azores and the Canary islands and the 'West Indies' was due to the destruction of forest cover. But we showed above that Pline the Elder already mentioned this hypothesis.

[1] Note that Kittredge confused French Kings and dates: he gave Louis VI as the king and 1215 as the date of ordinance. We took the exact information from Guérin and Meyer (2001).

[2] However, it seems to us that historically, this association of 'water' and 'forests' was initially only a practical way to name the persons in charge of managing the hunting grounds and the fisheries of the king of France.

2.3. The lasting debate on the hydrological and meteorological role of forests during the 19th century

Although observations concerning a possible impact of forests on the water cycle may be ancient, never in history was the debate on this topic livelier than during the 19th century: from the French revolution in 1789 to the end of the Second Empire in 1870, this subject attracted an exceptional amount of interest in France, involving both citizens, scientists and government officials.

2.3.1. At the root of the debate: the population pressure, the French revolution, and the sale of royal forest estates

Before the French revolution of 1789, some naturalists had already started to express more or less romantic views on the possible influence of forests on climate and water flow. The best known among them is probably Bernardin de Saint Pierre (1737–1814). Although best known for his romantic tale *Paul and Virginia*, his masterpiece is actually the *Studies of Nature* 'Etudes de la Nature' published between 1784 and 1788, a book rich in descriptive passages and largely based on a compilation of information collected by himself and other travelers. In the second volume of the *Studies*, he describes the impact of forests on rain and streamflow in Mauritius: "This attractive force of the forests on this island is such that a field in an uncovered situation close to them often suffers a lack of rain whereas it rains almost all year long in woods that are situated within gunshot. It is by destroying part of the trees crowning the heights of this island that one has caused most of the streams that watered it to dry up. I attribute to the same lack of foresight the notable diminishing of the streams and rivers in a large part of Europe." Bernardin de Saint Pierre therefore proposes to reforest the highlands of France, in order to restitute to the streams "their former volume of water" and bring about "the return of many of the brooks which have stopped flowing in our country."

The French revolution and the disappearance of state authority caused a wave of deforestation in France. Royal and church estates were sold; peasants misused forest resources, and these abuses were added to a growing demographic and industrial pressure on natural resources. Ten years after the revolution, Rougier de la Bergerie (1800) reports on his inspections of several regions in the country. In his book entitled "Note on the abuses of clear-cutting and the destruction of woods and forests", he provides a long list of ruined forests, denuded slopes and catastrophic floods, which he summarizes as follows: "The water disappears [...] and it is unnecessary to elaborate on this all too incontrovertible fact in view of the extreme drought witnessed by the year VIII during which, in all regions, one has, on several occasions, seen springs dry out in wells and fountains and in places where formerly one was, on the contrary, obliged to defend oneself against their too great abundance."

The changes that took place during the revolution had a considerable and long-lasting impact on people's minds. And as soon as the wars and political unrest stopped, a vigorous debate started in France between what we could call a 'foresters' party and an 'engineers' party, opposing those who believed that forests could regulate both climate and watershed behavior, stop floods and attract rain, and those who where dubious (or at least reticent) about the romantic ideas of their opponents, and who tried to approach the problem by collecting and analyzing hydrometric and meteorological data. Let us now review the arguments of the two groups.

2.3.2. The foresters between romanticism and mythology

One of the most prolific and enthusiastic leaders of the 'foresters party' is undoubtedly Rauch (1801, 1818, 1821–1825). In his first book, entitled *Hydro-vegetal Harmony* "Harmonie hydrovégétale", he proposes that the climate could be noticeably modified by forests (as much as to change climactic vegetation). One consequence of reforestation would be "to see the plants of southern France gradually move up into the temperate regions and the latter become associated with the plants of the northern regions." After the restoration of the monarchy in France in 1814, Rauch became extremely active in the debate on the hydrometeorological role of forests. Beginning in 1821, he published the *European Annals of Plant Physics and Public Economy* "Annales Européennes de Physique Végétale et d'Economie Publique[3]", where he writes for example: " We demonstrated that the successive deforestation (which already concerns half of the European surface area) caused a perceptible disorder in the course of meteors, in temperatures and seasons, and as a natural consequence, a diminution of the productions of the soil and the water." In the idealized earthly paradise dreamed of by Rauch, the role of trees is rather simple: "the trees may be considered as siphons—intermediaries between the clouds and the earth; by their attracting top boughs, they command from afar the wandering waters of the atmosphere to approach and pour into their protecting urns the water that is to feed the springs, make the streams flow [...]. Our hemisphere and its mountains, in particular, no longer have even half of the forests that crowned them, and as the sun still invariably pulls the same amount of water into the air [...], one must contemplate with horror what these suspended seas can and must become when the decimated vegetation can no longer pump out half of what they contain." Finally, Rauch firmly believes that the water that is not attracted down to the earth by trees is ultimately fixed at the poles, extending the realm of ice and causing global cooling.

It is important to note that several famous scientists adhered to the foresters' point of view:

- Lamarck (1820), in his book entitled *Analytical system of man's positive knowledge* (1820), writes: "by everywhere destroying the large plants that protected the soil, for reasons that satisfy his desire of the moment, man swiftly renders sterile the soil that he inhabits, causes the streams to dry up."
- Boussingault (1837), the famous agricultural chemist, brought back from his stay in South America a detailed description of the great lakes in Peru and Bolivia. He hypothesized that deforestation was the cause of the decrease in lake levels. From the latter and other observations, he concluded:

[3] This journal will later be renamed "European Annals of General Fructification" (*Annales Européennes et de Fructification Générale*). Rauch will use it between 1821 and 1825 to lead—in his own way—a crusade for reforestation and water conservation.

"1. That clear-cutting reduces the quantity of running water that flows across the surface of a country;
2. That it is impossible to say if this reduction is due to a smaller amount of annual rainfall, stronger evaporation of the rainwater or to a combination of the two effects; […]
3. That independently of conserving the running water, the forests safeguard and regulate its flow; […]
4. That by purely local deforestation, springs may disappear without it being possible to conclude that the annual rainfall amount has decreased;
5. That on the basis of meteorological observations collected in equinoctial regions, one must surmise that wide-spread clear-cutting diminishes the annual amount of rain that falls on an area."

Becquerel (1853, 1865),[4] was a well-established naturalist at the Museum National d'Histoire Naturelle in Paris, as well as a member of the Academy of Sciences. In his two successive books on the topic, he based most of his reasoning on Greek and Roman historians, as well as on stories brought back by travelers. He noted for example that "in the region of Troy, the Scamander river which was still navigable in Pliny's time is completely dried up today; but the cedars that covered mount Ida, where it rose,[…] no longer exist." On the basis of such demonstrations, he concluded that "the forests, while preserving the running water, safeguard and regulate its flow."

2.3.3. *The engineers in search of measurable evidence*

The members of what we refer to as the engineers party entered the debate on Water and Forests mostly as a reaction to the pronouncements made by the foresters party.

The most respected of these engineers was probably Surell (1841), who became famous for his theory on torrent control. His proposals involved a combined treatment by civil works (mainly check dams) and watershed rehabilitation (reforestation of slopes, improvement of pastures, etc.). However, in his book he did not emphasize the role of forests, although he considers that "their influence is incontrovertible, they are not the primary reason and gully erosion would have been nil in other climes and on other soils." Nevertheless, he recognized that "the destruction of a forest leaves the soil at the mercy of torrents" and that "forests are capable of causing the extinction of an already established torrent."

However, Surell remained prudent and avoided theorizing on the protective role of forests. He only discussed its positive impact where he could prove it. As to the different opinions concerning forest influence, he wrote: "as always happens in France, concerning fashionable topics, everybody added to what had been said before; and by endeavoring to find still more new arguments in favor of protecting the forests, one ended up advancing some very dubious ones[…]. But this exaggeration was in itself a great evil. Soon one wondered if these influences attributed to deforestation on temperature variations, on rainfall, on winds, on the composition of the air, etc. were not, all of them, at least a little doubtful. Imperceptibly, everybody cooled off and the topic, first elevated to such heights, slowly fell back into oblivion[…] If the matter had been pursued here with greater patience and restraint one could easily have discerned the truth in the midst of a few exaggerations."

Surell's book received the prize of the French Academy of Sciences in 1842, and several laws were subsequently proposed to promote the rehabilitation of badly eroded watersheds. A first attempt had been made in 1847, but it failed because of the 1848 revolution and the political unrest that followed. It was only in 1860 that the first law on the 'Reforestation of mountains' was voted by the French parliament. A second law on the 'Grassing over of mountains' followed in 1864, and some years later, in 1882, a law on 'Soil rehabilitation and conservation in mountain areas' provided a final framework for all conservation measures applied to this day. Surell's proposals provided the scientific and technical basis for these laws.

Belgrand (1853, 1854a,b), was a famous General Engineer of the corps of the Ponts et Chaussées who designed and directed the works on the Paris water supply. He was the first to organize comparative hydrometric measurements to evaluate the hydrological impact of forests (his experiment is described in Section 2.3.4). On the basis of his observations, he concluded that "woods do not greatly reduce the runoff

[4] Antoine César Becquerel should not be confused with Henri Becquerel, his grandson, Nobel Prize of Physics in 1903.

of rainfall” and that “forests, when in leaf, diminish rather than augment the flow of streams”.

Vallès (1857, 1862, 1865), himself a Chief Engineer in the corps of the Ponts et Chaussées, was a sworn enemy of the foresters. At first sight, however, his intentions seemed quite reasonable: “what we want, both for ourselves and for our adversaries, is that one should not limit oneself to be satisfied with assertions, with preconceived opinions, and that one should, at last, be willing to undertake a study of the facts and proofs able to justify beliefs that are, it is true, adhered to everywhere but justified nowhere.” But his beliefs were sometimes just as extreme as (albeit opposed to) those of the foresters. He wrote for example that “the existence of forests, far from diminishing floods, augments them; […] it is on bare soils rather than on the forests that the rains fall in greater abundance; […] the watering of the globe by the springs is much less secure the greater the extent of the forest growth.” And he enjoyed above all making fun of those foresters who cherished the ancient historians: “In the eyes of many people, when history tells us that a formerly flourishing city has disappeared under ruins, that a previously fertile soil no longer produces crops, the fault lies always and solely with deforestation.”

Champion (1858) is the author of a historical compilation on floods in France from the 6th century onward (in 6 volumes and 3000 pages). On the basis of studies of the past, he developed his own perception of the impact of deforestation on floods. Reacting to the opinion that “flooding is a new phenomenon in France, and deforestation is its cause”, he answered that “at all times, our country has suffered no less terrifying floods, relatively speaking, than those that we have witnessed; and the regions which, under our very eyes, have been devastated by the waters have never been spared this misfortune.”

Cézanne (1872) was also an engineer in the corps of the Ponts et Chaussées, who continued the work of Surell and added a second volume to his famous book. Having closely followed the debate on Water and Forests over many years, he concluded as follows: “One understands that a problem posed in this manner can only be solved by observations pursued during a long series of years in local circumstances that are very difficult to find. One must hasten to cover America and Russia with observatories and maybe, a few centuries hence, one shall have a clear idea of the influence of deforestation.[…] Regarding, in particular, water flow and floods, it is obvious that the role of forests has been exaggerated. The floods preceded deforestation; even if one replanted forests across the whole of France, one could not be certain to avert this scourge for the properties that are exposed to it.”

2.3.4. From the romantic to the scientific debate: the first research watersheds

As we have seen, the debate on Water and Forests remained for a long time confined to a romantic and historical argument. The only way out of this dead end was through measurements, and that is how Belgrand initiated what we consider to be the first-ever watershed hydrology comparison in the Yonne river basin, quickly followed by counter-comparisons initiated by foresters. Andréassian (2001) presented a detailed account of these historical experiments, and we will here review them only briefly:

- *Measurements by Belgrand (1850–1852).* Belgrand made measurements on three watersheds[5] to study the impact of forests on hydrological behavior. He chose a fully forested, a totally forestless and a partially forested watershed. By comparing their water stage times series, he concluded that all three watersheds reacted similarly to rainfall, and that the common opinion that “woods make the water supply to springs and stream more regular” was not based on any observable evidence.
- *Measurements by Jeandel, Cantégril and Bellaud (1858–1859).* Following Belgrand’s measurements, three foresters decided to counter-attack with measurements of streamflow and rainfall on two watersheds, one entirely wooded and the second one only half-wooded. They tried to introduce a type of raw hydrological model, where they compared the runoff yield and the ratio of rainfall and flood-event duration, to demonstrate that forest cover would slow down storm runoff. Although their reasoning does not

[5] The Grenetière river had a fully forested watershed, the Cousin river (at Avallon) had one where woods covered a third of the area, the Bouchart river watershed had no forest cover at all.

appear hydrologically sound today, their initiative was a major breakthrough in the thinking of the foresters party, who had for too long remained confined to that of the ancient historians.

- *Measurements of rainfall interception by Matthieu (1867–1877).* The three above foresters were followed, some years later, by Auguste Matthieu, the deputy director of the French Forestry School in Nancy. Matthieu (1878) investigated the impact of forests on rainfall and initiated the continuous monitoring of rainfall, temperature and evaporation at three locations (within the Nancy forest, at the forest edge, and 20 km away from the forest). To study rainfall interception, he was probably the first to build a large raingage, which would also intercept stem flow. Thermometric measurements showed that the mean annual temperature was lower under forest cover, and foresters were thus forced to give up the idea that a forest made the climate warmer. However, it so happened that a raingage located far from the forest received less rainfall than those within the forest and at its edge. This led Matthieu to consider that he had… a demonstration proving that forests attract precipitation.[6]

2.3.5. From the scientific to the political debate

From Sections 2.3.3 and 2.3.4, the reader might assume that the debate on Water and Forests was confined to a narrow circle of scholars. However, it quickly overflowed its banks to spill over into the political floodplain. As a demonstration, we can point to circular no 18, published on the 25th of April 1821 by Siméon, Minister of the Interior to king Louis the XVIIIth of France (Bainville and Ladoy, 1995), where the Minister requested all the préfets[7] of France to report changes, observed in their area of jurisdiction, in order to allow the Royal Academy of Sciences to give a ruling on the matter. His request was worded as follows: "for some years, we have witnessed a noticeable cooling of the atmosphere, sudden variations in the seasons and exceptional hurricanes or inundations to which France seems to be increasingly subjected. This is in part attributed to the deforestation of the mountains, to the cutting down of forests, to the lack of shelter suffered by our countryside and to the absence of natural obstacles which formerly impeded the winds and the clouds from the North and the West[…] In the present state of observations it is perhaps difficult to substantiate a judgment; and it is to form an opinion, in order to subsequently decide what measures to put in place that I hereby ask you to provide information on the following points:

1. What forests existed in your region 30 years ago? In what zone and at what altitude were they found? What was their extent and of what species did they consist?
2. Who were their owners?
3. Which ones do still exist and which ones have been cut down?
4. What influence has the difference been observed to exert on the meteorological system of the region? Has the water in the rivers been more or less abundant? Have floods, rains been more or less frequent? Has there been more rain or hail and, in mountainous areas, has one observed that the ice descends into lower-lying areas, driving and forcing the vegetation toward the plains or the valleys?
5. Have the winds been more violent, more pernicious, more variable and has it been observed that those from the South and the North have caused, suddenly and by abrupt changes, greater devastation than in the last century and when France had, in short, a better forest cover."

Immediately, the *European Annals* edited by François Rauch published the circular, even writing that this document was "perhaps the most important ever issued by the Ministry of the Interior". Then, from 1821 to 1825, Rauch published and commented on the reports of the préfets as they arrived. He did not hesitate to criticize openly those who dared to declare (as the préfet of the Lot département) that… plants do not have any influence on the climate. In its session of the 16th of February 1824, the Royal Academy of Sciences produced a summary of the collected information. It seems that the Academicians found little inspiration in the answers to the circular, and that the lack of quantitative data, the great diversity of

[6] An opinion still popular today among French foresters.
[7] The *préfet* is the chief administrator of a *département*.

opinions concerning the effects of forests on the climate led them to conclude that "there were no sufficiently positive or complete proofs of the controversial facts to allow an opinion to be expressed."

But the indecision of the academicians did not stop the debate. During the discussion of the forest code in the French parliament in 1836, the famous physicist Arago argued with the chemist Gay-Lussac about the climatic role of forests (Becquerel, 1853; Cézanne, 1872). While Arago considered that forest cover could easily be manipulated to improve the climate of France, Gay-Lussac remained very cautious: "In my opinion, we have not, at present, acquired any proof positive that the woods in themselves have a real influence on the climate of a large region or of any particular locality. By close scrutiny of the effects of deforestation, one might perhaps find that, far from being an evil, it is beneficial; but these questions are so complicated when examined from the point of view of the climate, that the solution is very difficult, not to say impossible."

The confrontation between foresters and engineers reached its height in the years 1865–1870, with the surprising intervention of a major political actor, Field Marshal Vaillant. This man was a very close collaborator of the emperor Napoleon III, and occupied the post of Minister of the Emperor's Household. In a letter to chief engineer Vallès in 1865 (and quickly published in the press by the foresters), Vaillant asked him to devise an experiment that would provide a definitive answer to the question of the hydrological impact of forests: "one has, perhaps, not sufficiently studied this action (by the forests) from the very special aspect of the drying-out of the soil that they cover and the depletion that might be inflicted on the springs[…]. There are here, I believe, a service to be rendered, maybe prejudices to destroy and truths to reveal." Of course, this request did not please the foresters' party (who hated Vallès), but nobody could contest the choice of his powerful protector… Unfortunately, nobody knows whether Vallès could set up his experiment and reach a firm conclusion on the hydrological impact of forests, since the Empire ended with the defeat of Napoleon III in 1870, which also caused the exile of Field Marshal Vaillant.

2.3.6. An American view of a French debate

It is highly instructive to see how the French debate was seen from abroad, and we can rely for this on a first-class testimony by Gifford Pinchot (1905), the first director of the US Forest Service. Pinchot, who knew France well since he had studied at the Forestry school of Nancy, described the debate as follows: "The discussion of forest influence on climate began in this way. When the French revolution broke out in 1789, the old restrictions on the management of private forests were done away. A wholesale cutting of these timberlands promptly followed, and as early as 1792 the consequences began to be observed. The question of forests and climate was then raised for the first time; but questions of this kind can not be answered without long and careful observations."

About the influence of forests on rainfall, Pinchot wrote further: "It is unfortunate that so much of the writing and talking upon this branch of forestry has had little definite fact or trustworthy observation behind it. The friends and the enemies of the forest have both said more than they could prove. Both have tried to establish the truth of their opinions by referring to observations of temperature and rainfall which cover too short a time to prove anything, or by hearsay and general impressions, which are not to be trusted in such matters. Such discussions make nothing clear except that the pith of the matter has not been reached by either party. […] A great number of observations has been made in different parts of the world to discover how much the rainfall really is affected by the forest, but for several reasons no generally accepted result has yet been reached. In the first place, accurate observations on rainfall are not easy to make. The height above the ground at which a rain gauge is placed affects it very seriously. A variation of 10 feet in height will often make more difference in the amount of rain caught than most observers claim for the whole action of the forest." And he concluded: "The best evidence at hand fails to show a decrease in rainfall over the United States in the last 100 years, in spite of the immense areas of forest that have been burned and cut. […] The truth probably is that more rain falls over the forest than over open country similarly placed, but how much more it is impossible to say."

2.4. *The invention of the paired-watershed design*

We consider that the first satisfying answers to the question of forest influence on the water cycle came from direct experimentation at the watershed scale. Who was the first to set up such an experiment? McCulloch and Robinson (1993) considered that the ‘first true catchment study’ was the Swiss study of the Sperbelgraben and Rappengraben basins (Engler, 1919), which started in 1900. Our view is that, as far as a catchment study is concerned, Belgrand (1853) and Jeandel et al. (1862) were the first (although Engler’s work would still qualify as the first *long-term* watershed study). However, all these studies were based on comparisons of watersheds with different forest covers, and none of them was able to bring a definite answer to the problem of the hydrological impact of a forest. Clearly, only the paired-watershed design was able to identify the respective roles of the forest cover, ‘internal’ watershed behavior and climate variability. This design was first used in the Colorado mountains, at Wagon Wheel Gap, from 1910 to 1926 (Bates and Henry, 1928). It rapidly gained recognition among foresters and hydrologists and was generalized all over the world for the rest of the 20th century. In Section 3, we present an overview of the results obtained on paired-watersheds over the past century.

3. From historical controversy to scientific debate: contribution by paired-watershed experiments

3.1. *The input of paired-watershed experiments to watershed hydrology: a discussion of principles*

The principle of the paired-watershed design is simple (Hewlett, 1971, 1982; Cosandey, 1995) and remains the reference for all studies of the impact of land-use changes on hydrology. It is based on selecting two watersheds (Fig. 1) as similar as possible (in particular, in terms of size, morphology, geology, climatic forcing and land use). A high degree of similarity leads us to believe that both watersheds will react similarly to climatic inputs. However, inevitably, each basin has its peculiarities. Therefore, we need to monitor both watersheds jointly during a given time period, to understand their differences. Ideally, this preliminary calibration period would be varied enough to characterize, as completely as possible, the hydrology of both basins (indeed, they may behave very similarly in average years, and differ more during dry years).

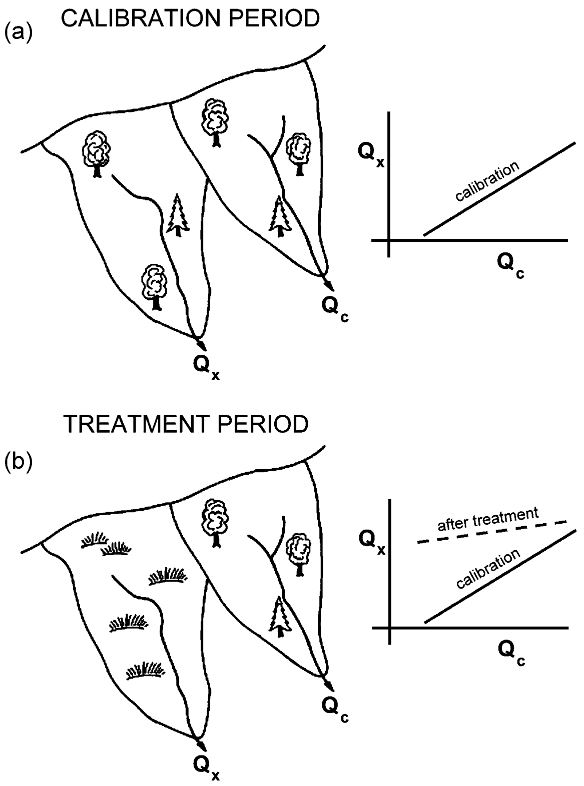

Fig. 1. Sketch of a paired-watershed experiment (from Hewlett, 1982).

At the end of the calibration period, land use can be modified on one of the basins (the ‘treated’ watershed), while the other one remains untouched (the ‘reference’ or ‘control’ watershed). The relationship between the basins established prior to treatment can be used to reconstitute the streamflow of the treated watershed, and thus, to assess the impact of the treatment in mm runoff or $m^3\,s^{-1}$ of flow.

What hypotheses underlie this experimental design?

- first, we need two very similar basins with highly correlated behavior (a poor correlation would render the reconstitution of flow on the treated watershed very uncertain, and the interpretation of the differences between measured and reconstituted flows more difficult);

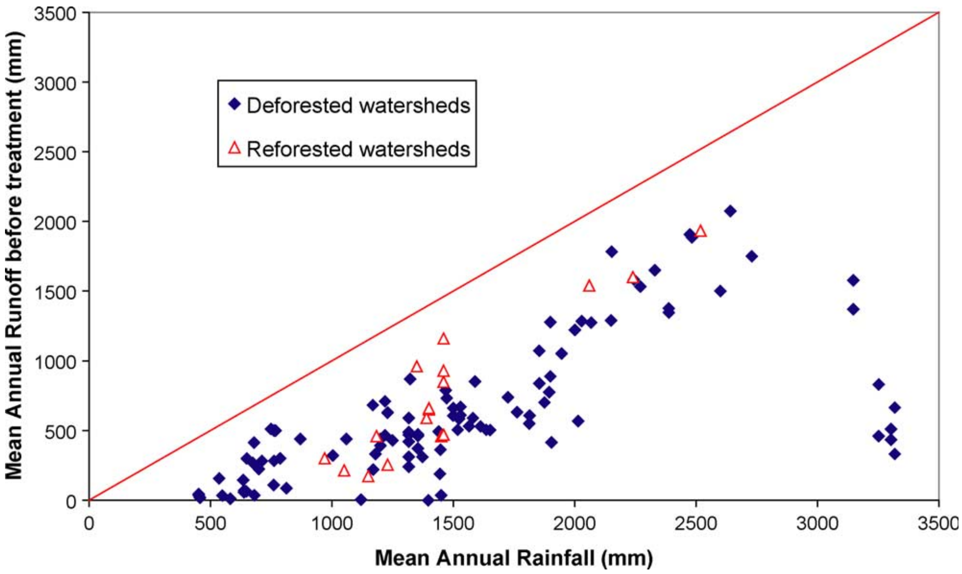

Fig. 2. Mean annual precipitation vs discharge for the 137 experimental watersheds taken from the hydrological literature.

- then, both watersheds must be geographically close, to insure that they are subjected to the same climate variations. This condition allows us to reduce climate interference within the design, and also improves the interpretability of the results;
- last, the reference basin must be stationary—as far as its hydrological behavior is concerned—throughout the study period.

The paired-watershed design presents two important advantages: it avoids the two major problems encountered in uncontrolled experiments, namely *climate variability* and *inter-basin variability*. Indeed, a design that relies on a single basin would be problematic to interpret, because of natural climate variability, and a design comparing two basins with different land-use would also be impossible to interpret, since without prior calibration, no distinction could be made between land-cover impact and natural watershed behavior variability.

Given the crucial scientific value of the paired-watershed experiments for the understanding of the hydrological impact of forests, we present a synthesis of published results. The presentation partly follows that of the classical article by Bosch and Hewlett (1982), to which we have added the results published over the last 20 years. The sites used in this synthesis are listed in appendix. We considered a total of 137 paired experiments (115 of deforestation and 22 of reforestation). Figs. 2 and 3 show the main characteristics of the sample. Most of the published studies deal with deforestation experiments (which is quite understandable considering the time needed to obtain interpretable results of reforestation experiments!). For similar reasons, most experiments dealt with very small watersheds (80% are smaller than 2 km^2). Note that the largest ones are not truly 'experimental': they are in fact watersheds belonging to the classical hydrometrical network where the evolution of land-cover had been documented and where it was possible to identify a stable reference watershed.

Regarding the type of results analyzed in the literature, we can see that they focus mostly on the impact of land-use change on annual flow and flood peaks, sometimes only on the impact on low flows and baseflows. Some authors also examine changes in the flow regime (i.e. on the flow distribution curve). The next sections successively detail these impacts.

3.2. Forests and water yield

The 'classical' way to present and interpret the results of paired-watershed studies is to follow Bosch

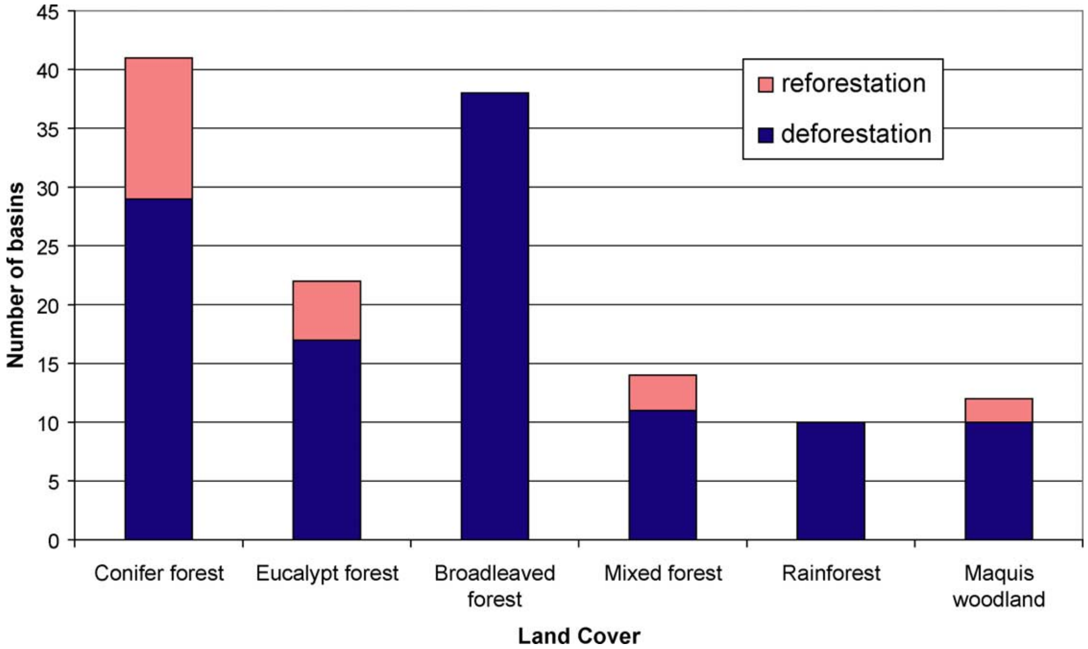

Fig. 3. Distribution of experimental watersheds according to the type of forest cover.

and Hewlett (1982) and draw a graph such as the one presented in Figs. 4 and 5. There, the evolution of flow computed from the paired design is compared to the percentage of watershed that has been 'treated' (i.e. either reforested or deforested). It is obvious from these graphs that deforestation increases annual flow, while reforestation decreases it (we discuss later the increases that occur without land-use change). But it

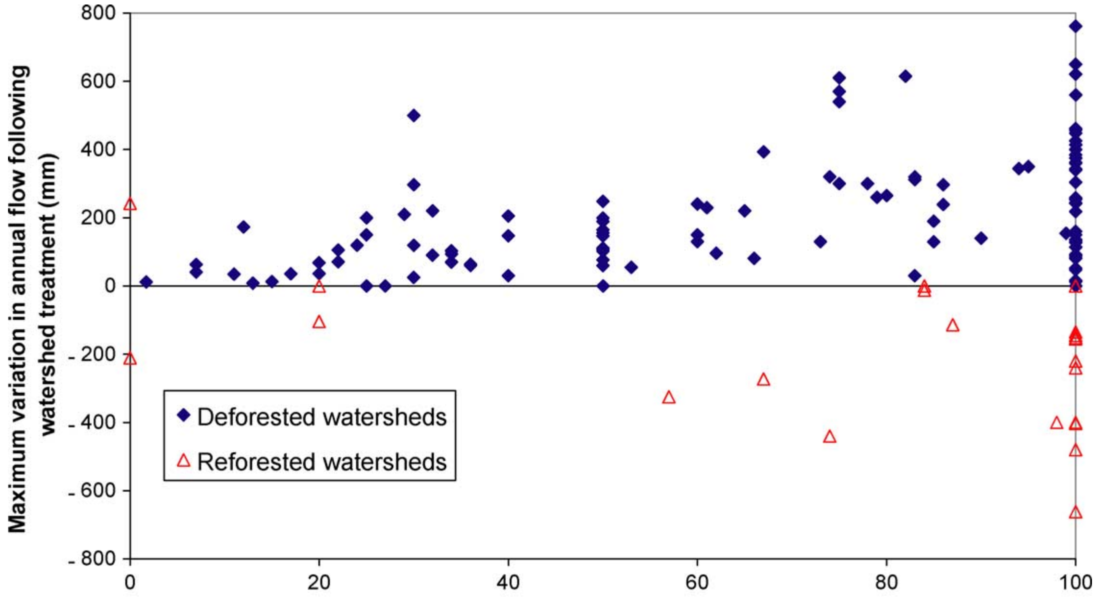

Fig. 4. Maximum variation in annual flow following watershed treatment as a function of percentage of basin subjected to treatment (see Appendix for a list of the sites).

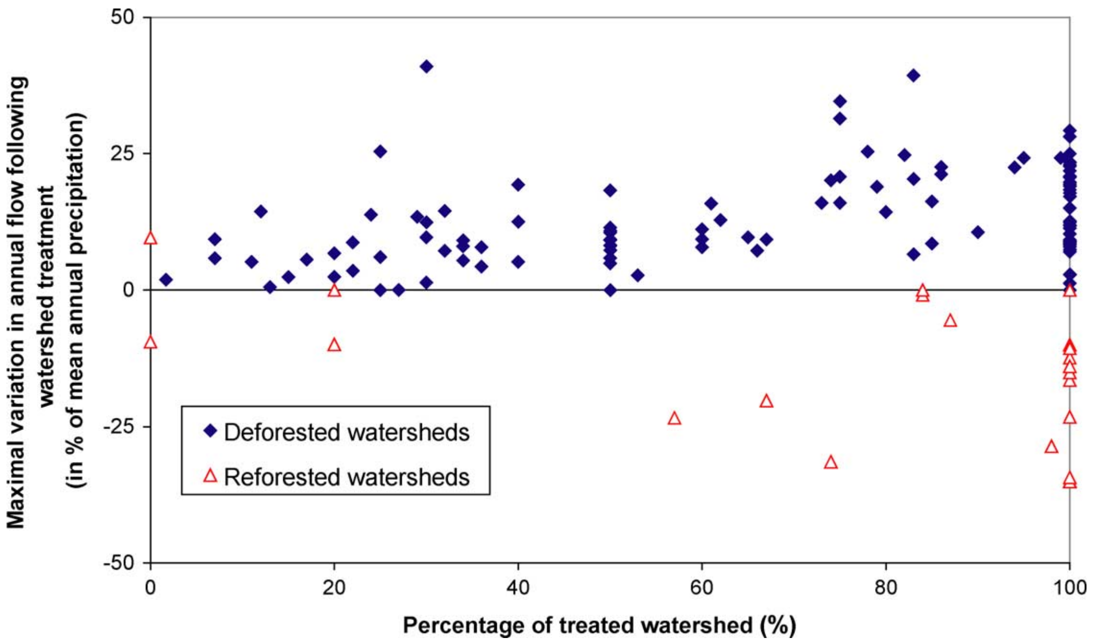

Fig. 5. Maximum variation in annual flow (in percentage of mean annual rainfall) following watershed treatment as a function of percentage of basin subjected to treatment (see Appendix for a list of the sites).

is also obvious that the results are extremely scattered, as already observed by Hibbert (1967) who found the hydrological response to forest treatments "highly variable and, for the most part, unpredictable".

However, the 'classical' mode of presentation in Figs. 4 and 5 prompts some reservation:

- first, a 'maximum variation in annual flow' is not easy to interpret, the reason being that it is dependent on the annual rainfall amount during the years immediately following the treatment. We used this characteristic because Bosch and Hewlett (1982) proposed it and because, very often, this datum was the only one that we could extract from the publications. A better way to assess the impact of change would be to compare the rainfall-runoff relationship before and after treatment, as suggested by Hibbert et al. (1975). Indeed, if in a first approximation we consider that the relationship between annual rainfall and annual streamflow is linear, we show in Fig. 6 that the 'maximum variation in annual flow' value depends on the total rainfall amount of the year in question. The ideal would thus be to characterize watershed evolution by, for example, the ratio of the slopes of the rainfall-runoff relationship before and after treatment. As this is seldom possible, we have to content ourselves with maximum variations expressed in mm.
- second, it must be stressed that for most of the watershed experiments, the impact of treatment is not stable in time; it is therefore impossible to define a stationary rainfall-runoff relationship. This aspect is discussed in Section 3.6.

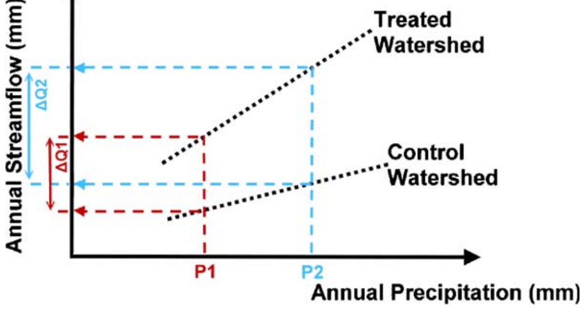

Fig. 6. Watershed response after treatment depends on annual rainfall (modified from Hibbert et al., 1975).

Table 1
Selection of observations concerning the impact of deforestation on floods

Watershed	Surface area (km^2)	Reference	Treated area (%)	Variation in flood peak	Variation in flood volume
Wagon Wheel Gap	0.81	Bates and Henry (1928)	100	+50%	+30%
Coweeta	0.44–1.44	Swank et al. (1988)	100	+7 to +30%	
Hubbard Brook	0.16–0.35	Hornbeck et al. (1997)	100	−40 to +63%	
Fool Creek	2.89	Troendle and King (1985)	40	−18 to +108% (mean +23%)	−5 to +18% (mean +8%)
Réal Collobrier	1.5	Lavabre et al. (1993)	85	0 to +200%	+30% to +40%
ECEREX (basins A, C, D, E, G, H, I, J)	0.01–0.016	Fritsch (1990)	100	+17% to +166%	+21% to +104% (mean +57%)
Brownie creek	21.34	Burton (1997)	25	+45%	

3.3. Forest impact on floods

Already in 1910, at Wagon Wheel Gap, the assessment of the impact of deforestation on floods was one of the major objectives of the experiment. Table 1, showing a selection of paired-watershed results relevant to the impact of forest cover on floods, speaks for itself: deforestation generally increases flood peaks and flood volumes.

Note that in the detection of forest impact on floods, the paired-watershed design reveals some of its limitations. This is made particularly clear by the results presented by Troendle and King (1985), who compiled some 30 years of hydrological observations at Fool Creek, in Colorado. Fig. 7, which collates their results, shows that a 40% cut of the forest cover resulted in an increase of annual flow, flood peaks and flood volume. It also shows, however, that the results concerning floods are much more variable than those for annual flow: while the hydrological impact of treatment remains constantly positive for the annual flow over the 30 years, it becomes negative in some years for the flood flow and especially for the flood peak (i.e. in these years, the effect of cutting the forest was to decrease the flood intensity!). This reminds the comments by Fritsch (1990) on the variability of flow: "the variability of hydrological behavior is of the same order of magnitude as the effect of treatment".

Among many other studies, we can cite the one by McGuinness and Harrold (1971), who studied the impact of reforestation on the floods in a small watershed, and compared the frequency distribution of the floods before and after reforestation, to conclude that for the rarest events, the impact of reforestation was either slight or nil. A similar conclusion was reached by Robinson et al. (1991) in Germany, by Cosandey (1993) in southern France, and by Beschta et al. (2000), who considered that for return periods longer than 5 years, the impact of forest exploitation was of the same order of magnitude as the discharge measurement uncertainty.

On watershed 5 of the Hubbard Brook Experimental Forest, Hornbeck et al. (1997) showed that the impact of forest exploitation on large floods (flood peak >10 mm per day) was different according to the season: cutting had increased flood peaks by 15–60% during the growing season, and it had decreased them by 2–40% during the dormant season. The explanation given by the authors refers to the origin of the floods: during the dormant season, flood peaks were always linked to snowmelt. As snowmelt would start earlier on the treated watershed, it was more gradual and thus the flood peaks were lower.

To summarize, we can say that the paired-watershed studies have shown that deforestation could definitely increase both flood volumes and flood peaks. However, this effect is much more variable than the effect on total flow and may even be inverted in some years or in some seasons. Concerning the (rare) existing studies on reforestation, they show a very limited effect on floods in general, and no effect at all on the large ones. Therefore, we are inclined to believe, as Cosandey (1993) proposes, that the increased floods observed in deforestation studies reveal rather the impact of exploitation than that of the forest cover itself. This is also what Fritsch (1990)

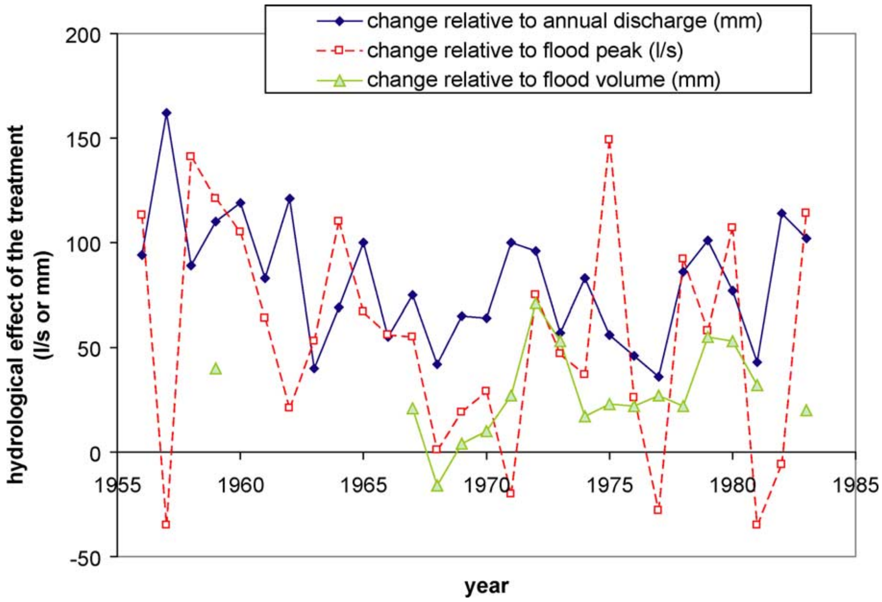

Fig. 7. Annual variation of three parameters of flood flow after deforestation of 40% of the Fool Creek watershed (data from Troendle and King, 1985).

concludes for the ECEREX experiment in French Guiana: "at the scale that we studied, the essential cause of flow increase was not directly linked to the suppression of the forest cover, but rather to the conditions in which this suppression occurred".

3.4. Forest impact on low flows

The impact of forest cover on low flows seems much more straightforward than the impact on floods. A review of this topic was published by Johnson (1998), who underlined the clear effects of felling, which increases low flows, and of reforestation, which decreases low flows. Effects started to become detectable when 25% of the watershed had been treated. Several examples illustrate this general statement:

- In the Three Bar deforestation experiment, Hibbert (1971) showed that the eradication of chaparral cover had turned ephemeral watersheds into perennial ones, which shows that deforestation increases low flows.
- In the Coshocton reforestation experiment, McGuinness and Harrold (1971) reported that the low flow difference between the reference and the treated watersheds increased with time, i.e. that reforestation led to a reduction of low flows. This observation is confirmed by all similar reforestation studies, the most striking ones being those where there is a complete cessation of flow.
- The study by Scott and Lesch (1997) probably provides the most complete demonstration, as it includes both a reforestation and a deforestation period. In their study, two watersheds were monitored for 16 years after afforestation with eucalypts or pines. Then, the trees were felled and the watershed allowed to return to its initial grassland state. At first, the afforestation had a very definite impact as it dried up the water courses, which stopped flowing completely after 9 and 12 years, respectively. The felling of the eucalypts allowed the low-flow levels to recover, but complete recovery required 5 years.

Note the existence of one case study, which did not follow the general trend, and where deforestation was apparently followed by a decrease of low flows (Ingwersen, 1985). This case, which occurred in the Oregon coastal range (Bull Run watershed), was interpreted as being the consequence of reduced fog interception after the felling. Indeed, 'fog drip' seems to play a significant role in the water balance of this very wet basin, where mean precipitation is close to 3000 mm/year.

3.5. Forest impact on the time-distribution of flows

The published results relative to the deforestation or reforestation impact on the time-distribution of flows concern either the snowmelt period, the date of resumption of flow after the summer, or flow-duration curves:

- *Snowmelt period*: at Wagon Wheel Gap (Bates and Henry, 1928) as in Fool Creek (Troendle and King, 1985), deforestation resulted in an earlier start of snowmelt (by an average of 12 and 7.5 days, respectively). The interpretation was that felling advanced the snowmelt because of earlier melt outside the forest cover, while the lower water consumption allowed a more rapid recharge of the soil. Hornbeck et al. (1997) showed that this earlier melt could result in decreased flood peaks.
- *Resumption of flow*: in Coshocton, McGuinness and Harrold (1971) showed that the reforestation of watershed 172 had, after 30 years, resulted in a 1-month delay of the date by which a given percentage of the flow had passed through the outlet. Their interpretation was that the soil needed a longer recharge period when depleted by forest trees.
- *Flow-duration curves*: Hornbeck et al. (1997) used flow-duration curves to characterize the impact of forest cutting. They noted an effect when the whole year was included, or when only the growing season was concerned. For flows during the dormant season alone, the difference between flow-duration curves became imperceptible.

3.6. Non-stationarity of forest cover impact

In their classical article, Bosch and Hewlett (1982) focused essentially on the *long-term effect* of reforestation, and on the *short-term effect* of deforestation. They paid no specific attention to the transitions between forested and non-forested states, which were more difficult to characterize with the paired-watershed design. However, in his 1967 review, Hibbert showed greater interest in the longer-term effects, taking as an example the persistence of deforestation impact in Coweeta. The fact that changes in hydrological behavior were sometimes observed without change in watershed land-use (Fig. 4), simply because of the aging of the stands, shows that a discussion of forest cover impact on hydrology should also try to take into account transitional features. The Australian experience described below showed that the 'transition' phase could cause the greatest problems encountered by watershed managers.

If it is not artificially maintained bare, a deforested watershed returns to its initial state through a succession of vegetation types (Hibbert, 1967; Swank et al., 2001). Fig. 8 illustrates the transition of three watersheds in the northeastern USA, where data are available over two decades following treatment. The effects of treatment appear rather short-lived: watersheds return to a state where the estimated impact of the treatment is close to zero after a period of 7–25 years. On watershed 2 of the Hubbard Brook experimental forest, there is even a decrease of water yield on the treated watershed after 13 years. The interpretation given by Hornbeck et al. (1997) is that the tree species have changed during regrowth, the new species mix is richer in trees with a lower stomatal resistance.

Swift and Swank (1981) and Swank et al. (2001) discussed the long-term effect of regrowth following clearcutting experiments at Coweeta. They describe a situation where, after large increases in water yield, the watersheds returned to their previous rainfall-runoff relationship, and water yield gains decreased progressively. Unfortunately, the hydrometric measurements where terminated when water yield gains had returned to zero for watersheds 28 and 37. On watershed 7, data presented by the authors might indicate a decrease of water yield 17 years after treatment, but this is to be confirmed by more recent data.

If water yield decreases during forest regrowth seem the exception rather than the rule in the northern hemisphere, they appear quite common in Australia. Kuczera (1987) studied *Eucalyptus regans* (Mountain Ash) forests, which cover the watersheds supplying water to the city of Melbourne. He described

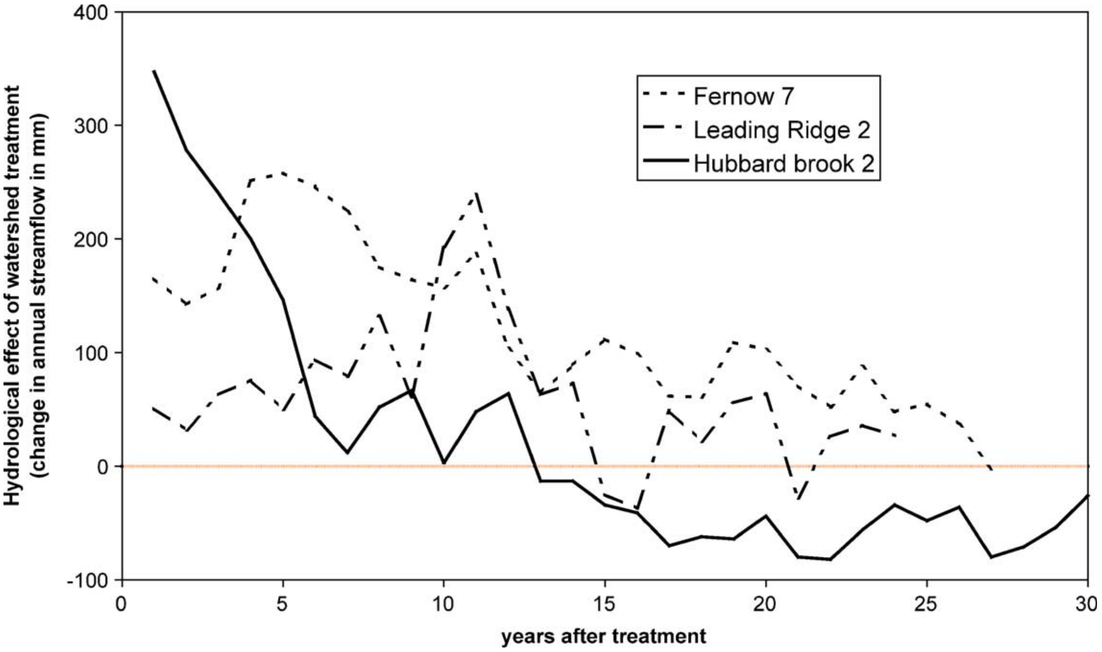

Fig. 8. Attenuation of deforestation impact after treatment on three watersheds in northeastern USA (data from Hornbeck et al., 1993).

a situation where wildfires can be followed by a short (2–3 years) period of water yield increase, and then by a long and pronounced period of water yield decrease, which reaches its maximum 15–20 years after the fire. This decrease, which can reach 300–400 mm, is not linked to the disappearance of the mature forest, but to its replacement by a young and rapidly growing one. Kuczera (1987) proposed to model this process according to a curve shown in Fig. 9, and Watson et al. (2001) illustrate this behavior with several examples from Mountain Ash covered experimental watersheds.

This behavior seems common to all eucalypts: Cornish and Vertessy (2001) studied a paired-watershed design where various proportions of six forested watersheds covered by sclerophyll eucalypts (*E. saligna*, *E. laevopinea*, *E. campanulata*, *E. quadrangulata*) were cut (from 25 to 80%). Five of the six treated watersheds showed a significant increase in streamflow for 2 years following treatment. But during the 16 years following treatment, all six watersheds experienced a decrease of water yield, which started between the 5th and the 12th year after treatment.

In Coshocton, McGuinness and Harrold (1971) and Langford and McGuinness (1976) documented the progressive impact of reforestation on the hydrological balance of a reforested agricultural watershed. They showed that in the first years following treatment, the decrease in mean water yield was very rapid, but stabilized at its low level after 10–15 years. However, Andréassian (2002) used a longer record of the same watershed, and showed that the reforested watershed, in fact, followed a pattern very similar to that described by Kuczera (1987) in his above-mentioned curve (Fig. 9). Fig. 10 shows that in the Coshocton long-term experiment, the depressive effect of reforestation on water yield does not seem as steady as had been expected, and that the yield can be at least partially recovered when the forest ages and/or is thinned.

The key to the interpretation of the surprising and sometimes conflicting observations presented above might be supplied by the research by Australian hydrologists, who examined the physiological determinants of tree transpiration (Vertessy et al., 1995, 1997, 2001; Roberts et al., 2001). These authors attempted to explain a behavior that seems specific to

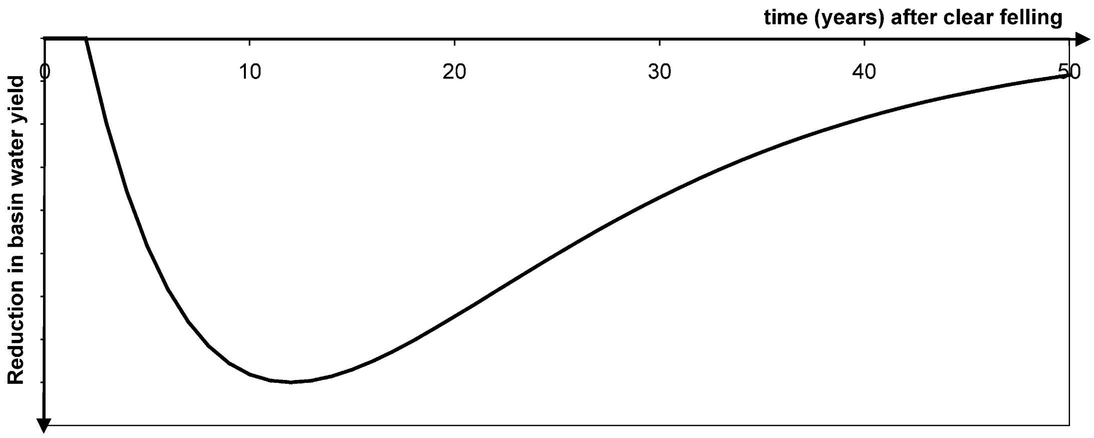

Fig. 9. Curve proposed by Kuczera (1987) to describe water yield reductions due to eucalypt regrowth (the water yield increase immediately after clear-cutting is not represented).

eucalypt stands: they reach a transpiration peak towards 15 years of age, which can be explained by a simultaneous peak of the stand-scale sapwood area.

Is the above behavior a characteristic specific to eucalypts? This is not completely certain, as a few other studies have revealed a similar pattern:

- Hudson et al. (1997b) reported on water yield decrease in the Plynlimon experimental watershed (Wales), for the Severn control basin. They interpreted it as being due to the 'approaching senescence' of spruce stands across the basin, and concluded that "there is strong evidence to suggest that the physiologies of plantation forest trees are not as consistent throughout the life cycle as was once assumed".
- Andréassian et al. (2003) analyzed the stationarity of watershed behavior in the Réal Collobrier

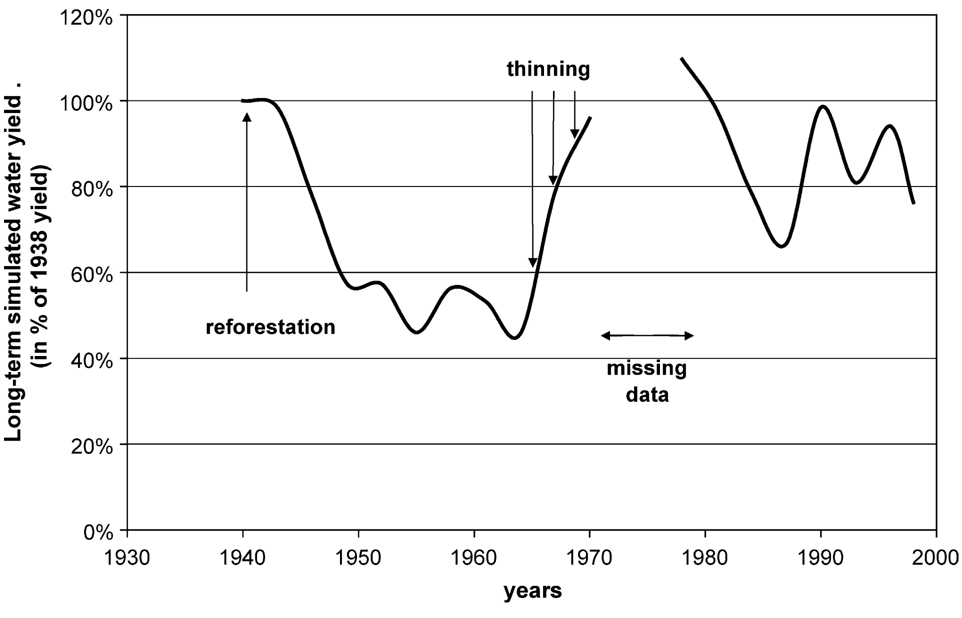

Fig. 10. Evolution of long-term water yield for the reforested watershed 172 in Coshocton.

experimental watershed. They found that the Valescure control basin (preserved from felling and fire since the late 1940s) showed a significant trend of decreasing water yield over the 1967–2000 period. They related it to the aging of the maquis woodland covering most of the watershed.

To summarize the topic of non-stationarity of forest impacts, we must recognize that describing a watershed solely in terms of forest surface area is far from sufficient to enable us to understand the huge variability observed in Figs. 4 and 5. Which are the best explanatory variables? The basal area, for a long time a descriptor very much in favor among foresters (see for example Eschner and Satterlund, 1966) might be useful. Calder (1993) found a linear relationship between the basal area of forest stands and their evapotranspiration. Leaf Area Index (LAI), a descriptor favored by agronomists could also prove useful: see for example its explanatory value in the study of Cornish and Vertessy (2001). These authors also identified Basal Area Increment as the most powerful indicator of yield decline. But the Australian studies suggest that the best descriptor of evaporative ability may be the sapwood area, and authors such as Vertessy et al. (1995, 1997) and Roberts et al. (2001) demonstrated the existence of (albeit species-specific) strong relationships between sapwood and basal area.

3.7. Summary of paired-watershed results

The compilation of paired-watershed results presented in this article, based on a total of 137 basins, can be summarized as follows:

Forests undoubtedly have an impact on the water balance at the basin scale: forest water consumption is generally higher than that of other vegetation types. Deforestation therefore results in an increase of water yield and reforestation in a decrease. However, we do not quite know the consequences of the aging of forest stands, or of the densification of forest cover at the watershed-scale. Although deforestation is always immediately followed by a period of water yield increase, the subsequent period of recovery (forest regrowth) may or may not be characterized by a decrease in water yield (relatively to pre-treatment conditions).

The impact of forests on floods seems, at first sight, simple as almost all the deforestation experiments were followed by increased flood peaks. However, the question is probably more complicated, because reforestation of agricultural land causes only very limited reductions of flood peaks. Last, it now seems well established that the floods with long return periods are not significantly affected by reforestation or deforestation.

The impact of forests on low flows seems well substantiated: reforestation decreases low flows and deforestation increases them, i.e. flow periods (in general) are shortened by reforestation, which can even cause the flow to cease. However, note that the impact of reforestation may change in the long term. Observations from the Draix experimental watersheds in France (Mathys et al., 1996), where a watershed reforested in the 1880s is compared to another one which has remained bare, indicate that on very shallow soils, where reforestation results in a thickening of the soil layer, it can actually cause an increase of low flows (i.e. increase the duration of flow in an ephemeral watershed). Unfortunately, both watersheds were gaged a 100 years after the reforestation, which means that no precisely quantified conclusions can be drawn from this case, as opposed to that of a paired-watershed design.

4. Conclusion

4.1. What are the prerequisites for a significant forest impact on basin water balance?

Although we can consider the hydrological impact of forests as proven, the fact remains that, in different basins, with specific climatological and pedological contexts, forests do not have the same impact. What are then the prerequisites for actually observing forest influence at the watershed scale?

- First, there is a *pedological condition* (Trimble et al., 1963; Cosandey, 1995): watershed soils must be deep enough to allow deep-rooted trees to gain a definite advantage over shallow-rooted grass species. Otherwise, the difference between forest and grass will be reduced to the impact of their different interception capacities;

- There are also *climate conditions*, which complement the preceding one: even where the soil is deep enough, a difference in water consumption will only become apparent if the climate has periods of hydrological surplus, allowing soil water reserves to be replenished. The climate must also include periods of water deficit. Otherwise, if the precipitation regime is such that the potential evapotranspiration demand is always satisfied, the energetic and aerodynamic balance will be the only controls on the actual evapotranspiration. However, this statement must be qualified according to the observations by Calder (1990), who showed that the very notion of potential evapotranspiration depends on the vegetation type, and cannot be seen as a climatic constant: the greater roughness and albedo of the tree canopy increases the forest ability to use advective energy for interception. The formula proposed Zhang et al. (2001) for forested and grassland watersheds provides empirical evidence on this matter.
- There are also *physiological conditions*, which are progressively being taken into account by foresters: depending on the tree species, stands may show large age-dependent differences in transpiring ability. This is particularly true for eucalypts (Vertessy et al., 2001).

4.2. Lessons of the past and further research needs

The long historical debate on Water and Forests has shown how popular myths and misconceptions may prevent the emergence of sound scientific reasoning. It also demonstrates that Man's natural tendency to generalize local observations may be the source of many misunderstandings, and that the truth can only be found by appropriate experimental designs and repetition of experiments.

After nearly a century of sound forest hydrology research, several myths concerning forests are still alive (Bruijnzeel, 1990; Calder, 1998), and we are still too often faced with conclusions recalling the words by Hibbert (1967), who 35 years ago stated that the response of a watershed to forest-cover changes was "extremely variable, and, for the most part, unpredictable". Judging from the number of publications, forest hydrology research is now focusing on the study of elementary processes, at the scale of a stand, a tree, or a leaf (see on this topic the review by Bonell, 1993). These studies are, of course, fundamental to the interpretation of results from experimental watersheds, but we consider that there is still a long way to go, before we are able to integrate the results of physiological and physical soil research at the watershed scale, and produce models which are actually helpful to water resources managers. An example is provided by Hudson et al. (1997a), who compared the results of process and watershed-scale studies on the Plynlimon watershed, and observed large differences between the two approaches. They concluded that, for the time being, the results of the two approaches agreed only on the direction of the changes, not on their magnitude. We therefore believe that at the beginning of the 21st century, watershed-scale research is still needed to advance our understanding of forest impact on hydrology. And if basin-scale research is to progress, we think that the following seven issues should receive special attention:

1. *Watershed size*: Paired-watershed research has traditionally focused on very small basins (given the constraints of active experimentation), and studied sudden changes. We believe that the time has come to study larger watersheds, of several tens of km^2, experiencing more diffuse and gradual changes, because their results will be directly usable by water resource managers.
2. *Using models to mimic control watersheds*: as we move towards the study of larger watersheds, one possibly insurmountable obstacle will be to find steady control watersheds to serve as a reference. Therefore, models will have to be used to mimic the paired-watershed design, and we believe that comparisons are needed to assess the difference between actual control watersheds and modeled ones, especially regarding the uncertainties.
3. *Forest descriptors*: it is clearly not enough to base the analysis and modeling of watershed-scale studies on a percentage of forest cover. New studies should include descriptors such as basal area, live biomass, leaf area and perhaps even sapwood area. For the larger watersheds, the data acquired routinely by national forest services could be very valuable.

4. *Gradual changes*: paired-watershed research has tended to focus on the study of short-term changes. However, the changes occurring on many watersheds are gradual and may take several decades to express themselves fully (Vertessy et al., 2001). Many developed countries now experience a slow but steady increase in both forest area and density, as marginal farmland is abandoned and natural and/or artificial reforestation takes place. Research on the impact of this kind of evolution would be very useful to land- and water-use planning.
5. *Long-term impacts*: there are now quite long series of hydrometeorological observations, which make it possible to address the question of long-term, possibly non-stationary, impact of forest cover on the hydrology of watersheds. In the United States, several former experimental forests have been converted into Long Term Ecological Research (LTER) observatories, and we think that it is very important to protect the remaining sites as well. Moreover, these hydrological observatories can also be used to identify possible hydrological impacts of global warming on forested watersheds. Of course, preserving the homogeneity and quality of measurements over long periods is a difficult challenge, and quality control procedures are needed to maximize the benefits to science from these long time series.
6. Distinguishing forest stands from forest soil impacts: a key issue in the study of the long-term effects of reforestation or deforestation is the soil-forest relationship. The soil may keep the memory of its previous cover for centuries, and several researchers have pointed out that the alleged effect of deforestation might be more precisely characterized as the effects of an alteration of the forest soil. The results of the century-long Draix experiment (Mathys et al., 1996) show that, on highly erosive soils, the forest may, over the long term, contribute to create soil where none existed before and to modify hydrological behavior to a considerable extent. More research is needed to identify the respective roles of trees and soils in forest influence.
7. Number of watersheds: last, we believe that hydrologists have now a sufficient understanding of the tremendous variability among basins to realize that no significant knowledge can be acquired without its being based on a large number of observed watersheds. Indeed, the history of the 19th century has shown that too many misunderstandings originated in a too hasty generalization of a single point observation.

Acknowledgements

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Appendix A. List of published paired-watershed studies

Tables 2 and 3 present the main characteristics of the 137 basins used for this study. The content of each column is as follows:

P_a	mean annual precipitation on the watershed (mm)
Q_a	mean annual runoff on the watershed (mm), before treatment
ΔS	percentage of watershed area submitted to treatment
ΔQ^{max}	maximum variation in runoff (in mm or in %), due to treatment
DQ^{max}	maximum variation in runoff (in percentage of the mean annual precipitation), due to treatment

Table 2
List of published deforestation experiments (see text for details)

Source	Basin	Country	Forest type	Surface area (ha)	P_a (mm)	Q_a (mm)	ΔS (%)	ΔQ^{max} (mm)	ΔQ^{max} (%)	DQ^{max} (% P)
Bosch and Hewlett (1982)	Fox Creek 1	USA	Conifer	59	2730	1750	25	0	0	0
	Fox Creek 2	USA	Conifer	71	2730	1750	25	0	0	0
	Kamabuchi 2	Japan	Mixed	3	2641	2075	100	218	11	8
	Takaragawa-Shozawa	Japan	Mixed	118	2153	1783	50	199	11	9
	Alsea (Needle Branch)	USA	Conifer	71	2483	1885	82	615	33	25
	Alsea (Deer Creek)	USA	Conifer	303	2474	1906	25	150	8	6
	H.J. Andrews 1	USA	Conifer	96	2388	1376	100	462	34	19
	H.J. Andrews 3	USA	Conifer	101	2388	1346	30	297	22	12
	H.J. Andrews 6	USA	Conifer	13	2150	1290	100	425	33	20
	H.J. Andrews 7	USA	Conifer	21	2150	1290	60	240	19	11
	H.J. Andrews 10	USA	Conifer	9	2330	1650	100	400	24	17
	Coweeta 13	USA	Broadleaved	16	1900	889	100	362	41	19
	Coweeta 13	USA	Broadleaved	16	1900	889	100	375	42	20
	Coweeta 28	USA	Broadleaved	144	2270	1532	65	220	14	10
	Coweeta 37	USA	Broadleaved	44	2244	1583	100	255	16	11
	Coweeta 17	USA	Broadleaved	14	1895	775	100	414	53	22
	Coweeta 22	USA	Broadleaved	34	2068	1275	50	189	15	9
	Coweeta 19	USA	Broadleaved	28	2001	1222	22	71	6	4
	Coweeta 1	USA	Broadleaved	16	1725	739	100	150	20	9
	Coweeta 3	USA	Broadleaved	9	1814	607	100	127	21	7
	Coweeta 10	USA	Broadleaved	86	1854	1072	30	25	2	1
	Coweeta 41	USA	Broadleaved	29	2029	1285	53	55	4	3
	Coweeta 40	USA	Broadleaved	20	1946	1052	27	0	0	0
	Coweeta 6	USA	Broadleaved	9	1854	838	80	265	32	14
	Kericho Sambret	Kenya	Broadleaved	688	1905	416	34	103	25	5
	Kimakia A	Kenya	Broadleaved	35	2014	568	100	457	80	23
	Fernow 1	USA	Broadleaved	30	1524	584	85	130	22	9
	Fernow 2	USA	Broadleaved	15	1500	660	36	64	10	4
	Fernow 5	USA	Broadleaved	36	1473	732	20	36	5	2
	Fernow 3	USA	Broadleaved	34	1500	607	13	8	1	1
	Fernow 7	USA	Broadleaved	24	1469	788	50	155	20	11
	Fernow 6	USA	Broadleaved	22	1440	493	50	165	33	11
	Upper Bear Cr. XF1	USA	Mixed	53	1397	0	50	102	–	7
	Upper Bear Cr. XF2	USA	Mixed	53	1397	0	86	297	–	21
	Hubbard Brook WS2	USA	Mixed	16	1219	710	100	343	48	28
	Hubbard Brook WS5	USA	Mixed	35	1219	710	30	500	70	41
	Grant Forest WS18	USA	Mixed	33	1219	467	100	254	54	21
	Coyote Creek 1	USA	Conifer	69	1230	627	50	60	10	5
	Coyote Creek 2	USA	Conifer	68	1230	630	30	119	19	10
	Coyote Creek 3	USA	Conifer	50	1230	630	100	360	57	29

	Leading Ridge WS2	USA	Broadleaved	43	1004	321	20	68	21	7
	Sierra Ancha, Workman Creek, North Fork	USA	Conifer	100	813	86	73	130	151	16
	Sierra Ancha, Workman Creek, South Fork	USA	Conifer	129	813	87	83	320	368	39
	Fraser Exp. For., Fool Creek	USA	Conifer	289	762	283	40	147	52	19
	San Dimas Exp. For, Monroe Canyon	USA	Maquis	354	648	64	1.7	12	19	2
	Castle Creek	USA	Conifer	364	639	71	17	36	51	6
	Placer County Ws C	USA	Maquis	5	635	145	99	154	106	24
	Three Bar C	USA	Maquis	39	638	58	100	132	228	21
	Three Bar B	USA	Maquis	19	582	11	40	30	273	5
	Three Bar B	USA	Maquis	19	582	11	100	52	473	9
	Three Bar F	USA	Maquis	28	681	36	100	81	225	12
	White Spar B	USA	Maquis	100	549	34	15	13	38	2
	Natural Drainages B	USA	Maquis	5	452	34	100	0	0	0
	Natural Drainages A	USA	Maquis	5	452	43	100	13	30	3
	Beaver Creek 1	USA	Conifer	124	457	20	100	0	0	0
	Beaver Creek 3	USA	Conifer	146	457	18	83	30	167	7
	Wagonwheel Gap	USA	Conifer	81	536	157	100	47	30	9
	Maimai M7	New Zealand	Broadleaved	4	2600	1500	100	650	43	25
	Maimai M9	New Zealand	Broadleaved	8	2600	1500	75	540	36	21
Stednick (1996)	Blue Mts no 1	USA	Conifer	n.a.	1355	472	50	248	53	18
	Blue Mts n°2	USA	Conifer	n.a.	1355	460	50	147	32	11
	Blue Mts n°3	USA	Conifer	n.a.	1355	372	50	111	30	8
	Deadhorse creek	USA	Conifer	270	762	500	36	60	12	8
	St Louis creek	USA	Conifer	289	712	283	100	88	31	12
	Thomas creek, AZ	USA	Conifer	227	768	500	34	70	14	9
	Willow creek, AZ	USA	Conifer	n.a.	749	512	62	96	19	13
	Ouachita no 10	USA	Broadleaved	5.7	1317	490	50	107	22	8
	Ouachita no 12	USA	Broadleaved	5.9	1317	590	100	242	41	18
	Ouachita no 14	USA	Broadleaved	4.3	1317	470	50	77	16	6
	Ouachita no 15	USA	Broadleaved	5.1	1317	421	100	136	32	10
	Ouachita no 17	USA	Broadleaved	4.2	1317	312	50	0	0	0
	Ouachita no 18	USA	Broadleaved	4.1	1317	241	100	16	7	1
Cornish (1993)	Karuah/Kokata	Australia	Eucalypt	97.4	1565	531	29	210	40	13
	Karuah/Coachwood	Australia	Eucalypt	37.5	1447	362	61	230	64	16
	Karuah/Corkwood	Australia	Eucalypt	41.1	1636	505	40	205	41	13
	Karuah/Jackwood	Australia	Eucalypt	12.5	1373	311	79	260	84	19
	Karuah/Barratta	Australia	Eucalypt	36.4	1581	590	25	0	0	0
	Karuah/Bollygum	Australia	Eucalypt	15.1	1518	505	32	220	44	14

(*continued on next page*)

Table 2 (*continued*)

Source	Basin	Country	Forest type	Surface area (ha)	P_a (mm)	Q_a (mm)	ΔS (%)	ΔQ^{max} (mm)	ΔQ^{max} (%)	DQ^{max} (% P)
O'Shaughnessy et al. (1979) and Watson et al. (2001)	Monda 1 (North Maroondah)	Australia	Eucalypt	6.3	1876	702	75	300	43	16
	Monda 2 (North Maroondah)	Australia	Eucalypt	4	1813	550	75	570	104	31
	Monda 3 (North Maroondah)	Australia	Eucalypt	7.3	1763	632	75	610	97	35
	Myrtle 2 (North Maroondah)	Australia	Eucalypt	30.5	1590	852	74	320	38	20
	Picaninny (Corranderk)	Australia	Eucalypt	53	1180	332	78	300	90	25
O'Shaughnessy et al. (1979), Jayasuriya et al. (1993) and Watson et al. (2001)	Black Spur 1 (North Maroondah)	Australia	Eucalypt	17	1652	504	60	130	26	8
	Black Spur 3 (North Maroondah)	Australia	Eucalypt	7.7	1612	530	60	150	28	9
Hornbeck et al. (1993)	Marcell 4	USA	Mixed	34	760	110	100	114	104	15
O'Shaughnessy et al. (1979), Jayasuriya et al. (1993) and Watson et al. (2001)	Leading Ridge 2	USA	Broadleaved	43	1060	440	86	239	54	23
Bren and Papworth (1991)	Clem creek	Australia	Eucalypt	46.4	1445	190	95	350	184	24
Stoneman (1993)	Yarragil 4L	Australia	Eucalypt	126	1120	4.3	66	80.9	1881	7
Burton (1997)	Brownie Creek	USA	Conifer	2134	787	300	25	200	67	25
Oyebande (1988)	Lien-Hua-Chi 4	Taiwan	Mixed	5.86	n.a.	1100	100	448	41	
	IITA	Nigeria	Rainforest	44	1450	35	100	340	971	23
	North Creek Babinda	Australia	Rainforest	18.3	4239	2873	67	393	14	9
Bent (2001)	Cadwell creek	USA	Mixed	155	1170	220	34	94	43	8
	Dickey brook	USA	Broadleaved	308	1250	430	32	90	21	7
Jewett et al. (1995)	Nashwaak	Canada	Mixed	391	1322	870	90	140	16	11
Lane and Mackay (2001)	Wicksend	Australia	Eucalypt	68	1200	440	22	105	24	9
	Wilbob	Australia	Eucalypt	86	1200	392	12	173	44	14

Brechtel and Führer (1991)	Krofdorf A1	Germany	Broadleaved	9.3	650	300	100	82	27	13
Troendle et al. (2001)	Coon creek	USA	Conifer	1673	870	440	24	120	27	14
Fahey and Jackson (1997)	Big bush DC1	New Zealand	Broadleaved	8.6	1530	610	83	312	51	20
	Big bush DC4	New Zealand	Broadleaved	20.2	1530	670	94	344	51	22
Cosandey (1990)	Latte (Mont Lozère)	France	Conifer	19.5	1900	1278	100	160	13	8
Lavabre et al. (1993)	Rimbaud (Réal Collobrier)	France	Maquis	153	1169	683	85	190	28	16
Fritsch (1990)	Ecerex A	French Guiana	Rainforest	1.3	3318	665	100	762	115	23
Fritsch (1990)	Ecerex C	French Guiana	Rainforest	1.6	3318	332	100	304	92	9
Fritsch (1990)	Ecerex D	French Guiana	Rainforest	1.4	3303	511	100	244	48	7
	Ecerex E	French Guiana	Rainforest	1.6	3303	434	100	92	21	3
	Ecerex G	French Guiana	Rainforest	1.5	3147	1370	100	621	45	20
	Ecerex H	French Guiana	Rainforest	1	3147	1577	100	560	36	18
	Ecerex I	French Guiana	Rainforest	1.1	3252	460	100	258	56	8
	Ecerex J	French Guiana	Rainforest	1.4	3252	831	100	384	46	12
Sarkissian (2001)	Dantzoud	Armenia	Broadleaved	14,100	680	413	11	35	8	5
	Girants	Armenia	Broadleaved	12,200	700	224	7	41	18	6
	Hakhoum	Armenia	Broadleaved	16,900	675	268	7	63	24	9

Table 3
List of published reforestation experiments (see text for details)

Source	Basin	Country	Succession	Surface area (ha)	P_a (mm)	Q_a (mm)	ΔS (%)	ΔQ^{max} (mm)	ΔQ^{max} (%)	DQ^{max} (% P)
Bosch and Hewlett (1982)	Coweeta 17	USA	Clear cut → conifer	14	1895	n.a.	100	−662	n.a.	−35
	Coweeta 1	USA	Clear cut → conifer	16	1725		100	−400		−23
	Cath. Peak II	South Africa	Grassland → conifer	190	1400	650	74	−440	−68	−31
	Cath. Peak III	South Africa	Grassland → conifer	142	1400	650	84	−13	−2	−1
	Cath. Peak IX	South Africa	Grassland → maquis	62	1400	650	20	0	0	0
	Jonkershoek (Bosboukloof)	South Africa	Maquis → conifer	200	1390	590	57	−325	−55	−23
	Jonkershoek (Biesievlei)	South Africa	Maquis → conifer	27	1400	660	98	−400	−61	−29
	Jonkershoek (Langrivier)	South Africa	Maquis (protected against fire)	246	2240	1600	0	−211	−13	−9
	Jonkershoek (Lambrechtsbos B)	South Africa	Maquis → conifer	65	1451	460	84	0	0	0
	Mokobulaan CA	South Africa	Grassland → eucalypt	26	1150	173	100	−403	−233	−35
	Pine Tree Branch	USA	23% mixed → 100% mixed	36	1230	255	100	−152	−60	−12
	White Hollow	USA	65% brodleaved → 100% mixed	694	1184	460	100	0	0	0
	Graceburn	Australia	Wildfire → eucalypt	2500	1460	850	100	−240	−28	−16
	Watts	Australia	Wildfire → eucalypt	10300	1460	930	100	−220	−24	−15
	Donnelys	Australia	Wildfire → eucalypt	1430	1460	470	100	−145	−31	−10
	Coranderrk	Australia	Wildfire → eucalypt	1860	1460	1160	100	−155	−13	−11
	Coshocton 162	USA	30% broadleaved → 100% mixed	18	970	300	100	−135	−45	−14
Smith (1992)	Nelson C4	New Zealand	Grassland → conifer in the riparian zone	2.7	1051	214	20	−104	−49	−10
Robinson et al. (1991)	Chiemsee North	Germany	Moor → conifer	3	1400	n.a.	100	−480		−34
Hudson et al. (1997b)	Cwm (Llanbrynmair)	United Kingdom	Heather → 87% conifer	289	2060	1539	87	−114	−7	−6
	Severn (Plynlimon)	United Kingdom	Aging of forest (68% conifer)	870	2518	1934	0	242	13	10

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