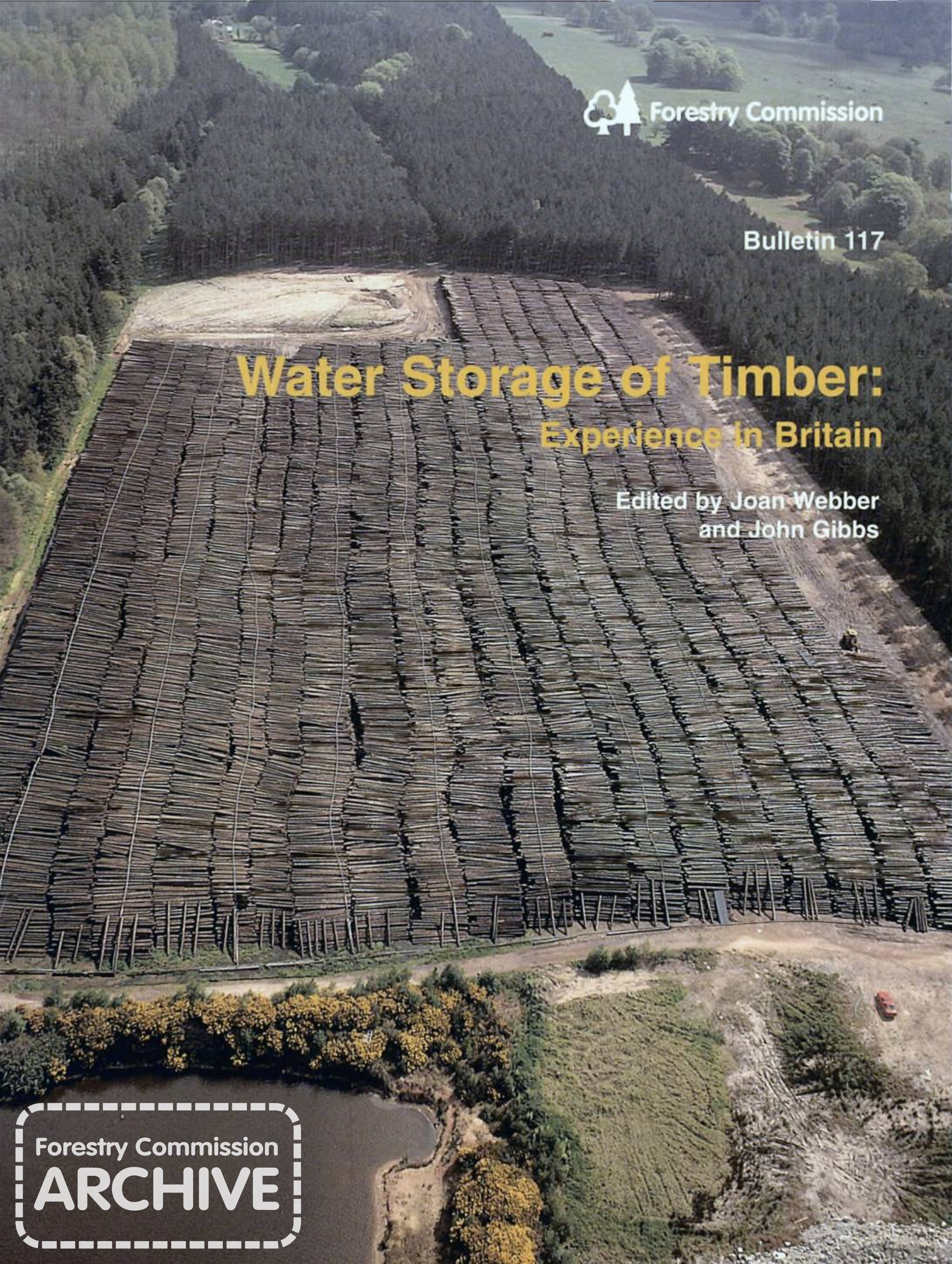

Forestry Commission

Bulletin 117

Water Storage of Timber:
Experience in Britain

Edited by Joan Webber
and John Gibbs

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Tim Cooper, Colin Palmer and Bob Brooker cut and collected many of the timber samples and arranged their safe delivery to the Building Research Establishment. Joan Rose did much of the fungal isolation work, while Andrew Jeeves prepared hundreds of moisture content samples.

Last, but not least, we are grateful to Jenny Claridge for her assistance in preparing the text, John Williams for producing the figures, and the ladies of the typing pool for preparing the typescript.

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Front cover: Aerial view of the Lynford wet store taken in May 1989. The security logs at the ramped end of the stacks and the sprinkler lines can clearly be seen. Bays of both 4.9 and 7.5 m length logs are visible in the northern part of the stack. (38790)

Back cover: Ice formation on wet store logs, taken during a period of freezing temperatures in winter 1990.

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Foreword

From time to time a calamity such as forest fire or violent storm requires that timber is salvaged quickly. Where such timber is plantation grown the investment loss that major destruction brings is catastrophic unless the most valuable timber can be saved and then marketed in an orderly way. This Bulletin reports on a successful British experience in which water storage employing overhead water sprinklers was used to prevent deterioration of high quality pine logs.

Not only was the operation successful with the majority of logs satisfactorily stored for up to four years before release onto the market, but all aspects of the storage operation itself were subject to detailed scientific investigation. Both the quality of the science and the comprehensive nature of the investigations will make this Bulletin of value to many organisations. The principles outlined should be of interest to many countries, particularly those relying on plantation forestry for timber supply.

I would add that the work reported here is a good example of collaboration between forest manager and scientist where a large investment in long-term storage was matched by an equally significant investment from a multi-disciplinary team. The benefit of this integrated approach is reflected in this account; there are few examples in forestry research, even when as well focused, where there has been such immediate value to industry.

Professor Julian Evans
Chief Research Officer (South)
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Water Storage of Timber: Experience in Britain

Summary

The gale of October 1987 blew down 4 million m^3 of timber in the south of England, about one-third of which was pine. On the basis of successful experience in Denmark and Germany, a decision was taken in early 1988 to store sawlogs from some of the windblown Scots and Corsican pine under water sprinklers to protect them from fungal degrade.

The construction and management of the store is described in some detail. Located on Forestry Commission land in Thetford Forest, the store was sited next to a flooded disused gravel pit which provided the water required for irrigation. At maximum it held 70 000 m^3 of pine logs, the majority of which were brought in from Rendlesham Forest some 85 km away. Irrigation operated continuously throughout the life of the store (March 1988 - July 1992) except when temperatures fell below freezing. The first logs were removed for sale after 18 months, with the bulk sold after three years of storage at an average price of £30 m^{-3}.

Throughout the wet store operation the quality of the effluent water was closely monitored and found to remain generally good. The colour was relatively stable at 40-70 hazen as the store was gradually filled and also for the first 6 months, thereafter declining to about 10 hazen by the time the store closed. Biological oxygen demand showed marked fluctuations between 1.2 and 7.3 mg l^{-1} while the store was being filled but fell to background levels after 18 months of storage. No threats were posed to water quality or aquatic life in the adjacent River Wissey.

Samples of experimental pine logs were removed regularly for moisture content determination and assessment of degrade. Overall, less than 2% of the wood was affected by bluestain and any present in logs prior to storage was prevented from developing further. In autumn 1989, fruit bodies of decay fungi *Heterobasidion annosum* and *Phlebia gigantea* were observed on *c.* 1% of log ends, most notably on the southern edge of the store where irrigation was incomplete. These fungi had apparently developed from basidiospore infections of the logs between cutting in the forest and insertion in the store. The extent of decay was limited to *c.* 0.1-0.2% of the total wood volume. After two years of storage *Armillaria* colonies were also visible in the bark of logs but did not cause any wood decay. Satisfactory storage was also achieved with Sitka spruce, Norway spruce, Douglas fir and Japanese larch among conifers, and beech and ash among hardwoods.

Boards sawn from pine logs wet stored for 6 months quickly suffered surface defacement from moulds and sapstainers. However, very little defacement occurred in boards cut from logs stored for two to three years, probably because

of the nutrient leaching associated with long-term water storage and the inhibitory action of bacteria which are abundant in wet stored wood. The porosity and strength of the timber of a range of species also altered during water storage; for both hardwoods and softwoods porosity increased significantly, and the strength of softwood timbers reduced slightly although this did not reduce the yields of construction grade timber.

The British experience of water storage related closely to experience elsewhere although transport comprised an unusually high proportion of the total costs. In future, water storage should be considered a major option whenever and wherever large quantities of pine are rendered vulnerable to stain and decay. However, although the technique worked well with softwoods and hardwoods, storage of windblown trees 'on their roots' is likely to be the most logical option in most circumstances for timber other than pine.

Stockage du bois sous arrosage: expérience menée en Grande-Bretagne

Résumé

Le grand vent d'octobre 1987 a déraciné 4 million de m^3 de bois dans le sud de l'Angleterre, dont un tiers consistait en pin. Par suite d'expériences réussies, menées au Danemark et en Allemagne, la décision a été prise au début de l'année 1988 de stocker les grumes de sciage d'un certain nombre de pins d'Ecosse et de pins de Corse déracinés par le vent sous arroseurs afin de les protéger de la dégradation fongique.

La construction et la gestion du dépôt est décrite en détail. Situé dans la Thetford Forest, sur des terres appartenant à la Forestry Commission, le dépôt se trouvait à côté d'une gravière abandonnée et inondée qui fournissait l'eau nécessaire à l'irrigation. Le dépôt a contenu un maximum de 70 000 m^3 de grumes de pins dont la majorité provenait de Rendlesham Forest distante de 85 km. L'irrigation a fonctionné de façon continue pendant toute la durée d'utilisation du dépôt (mars 1988 – juillet 1992), sauf lorsque les températures sont tombées en dessous de zéro. On a retiré les premiers blocs pour les vendre après 18 mois de stockage, tandis que le plus gros était vendu après trois années de stockage à un prix moyen de £30 m^{-3}.

Pendant toute la durée du stockage sous arrosage, la qualité de l'eau de sortie qui a fait l'objet de contrôles serrés est demeurée généralement bonne. La couleur est restée relativement stable à 40-70 hazen pendant le remplissage graduel du dépôt et aussi au cours des premiers six mois, descendant ensuite jusqu'à environ 10 hazen à la fin de l'utilisation du dépôt. La demande biochimique en oxygène qui a montré des fluctuations marquées - entre 1.2 et 7.3 mg l^{-1} - au moment du remplissage du dépôt est descendue à des niveaux normaux après dix-huit mois de stockage. Ni la qualité d l'eau de la rivière Wissey qui est adjacente, ni sa vie aquatique n'ont été menacées en quoi que ce soit.

Des échantillons de grumes de pins conservées dans des conditions expérimentales ont été retirés régulièrement pour en déterminer le contenu en eau et pour en évaluer la dégradation. Dans l'ensemble, moins de 2% du bois était atteint de bleuissement et la progression de tout bleuissement présent dans les grumes avant le stockage se trouvait arrêtée. Au cours de l'automne 1989, des fructifications fongiques amenant la carie, de type *Heterobasidion annosum* et *Phlebia gigantea,* étaient observées sur environ 1% des extrémités des grumes, tout particulièrement dans le côté-sud du dépôt où l'irrigation était incomplète. Ces champignons parasites s'étaient apparemment développés à partir d'infections des grumes dues à des basidiospores, survenues entre la coupe en forêt et l'insertion au dépôt. L'étendue de la carie se limitait à environ 0, 1-0, 2% du volume total de bois. Après deux années de stockage, des colonies d'*Armillaria* étaient aussi visibles dans l'écorce des grumes mais elles n'avaient pas causé

de carie du bois. Ce stockage s'avérait aussi satisfaisant dans le cas de l'épicéa de Sitka, de l'épicéa commun, du sapin de Douglas et du mélèze du Japon, pour ce qui est des conifères, et dans le cas du hêtre et du frêne, pour ce qui est des feuillus.

Des planches sciées dans des grumes de pin mouillées stockées pendant six mois ont rapidement montrés des dégradations de surface dûes à des moisissures et à des décolorations fongiques de l'aubier. Néanmoins, les planches provenant de grumes stockées pendant une période de 2-3 ans n'ont montré que très peu de dégradation, probablement à cause du lessivage des éléments nutritifs associé au stockage à long terme sous arrosage et du fait de l'action inhibitive des bactéries qui abondent dans le bois stocké sous arrosage. La porosité et la solidité du bois d'un certain nombre d'espèces se sont aussi modifiées au cours du stockage sous arrosage: la porosité a augmenté de façon marquée à la fois chez les résineux et chez les feuillus, de plus la solidité des bois de résineux s'est trouvée légèrement réduite, bien que cela n'ait pas réduit le rendement du bois de construction.

L'expérience réalisée en Grande-Bretagne sur le stockage sous arrosage s'est avérée très semblable aux expériences réalisées ailleurs, bien que le transport ait constitué une proportion exceptionnellement élevée des coûts totaux. Dans le futur, le stockage sous arrosage devrait être considéré comme une option majeure dans toutes les circonstances où de larges quantités de pin sont rendues vulnérables aux tâches et à la carie. Néanmoins bien que cette technique ait bien marché dans le cas des bois de résineux et de feuillus, il est vraisemblable que le stockage des arbres déracinés par le vent, sur plac 'sur les quelques racines leur restant' soit dans la plupart des circonstances l'option la plus logique pour les types de bois autres que le pin.

Wasserlagerung von Holz: Erfahrungen in Britannien

Zusammenfassung

Der Sturm in Oktober 1987 warf in Südengland etwa 4 Millionen m^3 Holz um, etwa ein Drittel davon war Kiefer. Aufgrund erfolgreicher Erfahrungen in Dänemark und Deutschland, wurde Anfang 1988 beschlossen, Sägeholz von einigen der umgerworfenen Föhren und Schwarzkiefern unter Berieselungsanlagen zu lagern, um sie vor Abwertung durch Pilzbefall zu schützen.

Die Konstruktion und Bewirtschaftung des Lagers wird im Detail beschrieben. Es befindet sich auf Land der Forestry Commission in Thetford Forst und wurde neben einer alten, überfluteten Kiesgrube angelegt, die das zur Berieselung nötige Wasser liefert. Die Anlage enthielt maximal 70 000 m^3 Kiefernabschnitte die meist aus dem etwa 85 km entferntem Rendlesham Forst stammten. Die Berieselung lief während der Betriebszeit der Anlage (März 1988 – Juli 1992) ständig, es sei denn die Temperatur sank unter den Gefrierpunkt. Die ersten Abschnitte wurden nach 18 Monaten zum Verkauf entnommen, der Rest wurde nach drei Jahren Lagerung zu einem durchschnittlichen Preis von £30 m^{-3} verkauft.

Während der ganzen Wasserlagerungsoperation wurde die Qualität des Abwassers genau überwacht und es wurde festgestellt, daß sie allgemein gut blieb. Die Farbe war relativ stabil bei 40 - 70 Hazen während das Lager gefüllt wurde und in den ersten sechs Monaten, danach fiel sie langsam bis auf 10 Hazen bei der Schließung des Lagers ab. Der biologische Sauerstoffverbrauch zeigte starke Schwankungen von 1.2 bis 7.3 mg l^{-1} während das Lager gefüllt wurde, fiel aber nach 18 Monaten Lagerung auf Hintergrundwerte ab. Für die Wasserqualität und die Wasserlebewesen des benachbarten Flusses Wissey bestand keine Gefahr.

Regelmäßig wurden Kiefernabschnitte probeweise entommen um den Feuchtigkeitsgrad und Abwertung zu beurteilen. Im Ganzen waren weniger als 2% des Holzes mit Blaupilz befallen und dort wo er schon vor der Lagerung anwesend war, wurde eine Weiterentwicklung verhindert. Im Herbst 1989 wurden auf etwa 1% der Schnittenden Fruchtkörper der Fäulnispilze *Heterobasidion annosum* und *Phlebia gigantea* beobachtet, vor allem am Südende des Lagers wo die Berieselung mangelhaft war. Diese Pilze hatten sich anscheinenden aus Basidiosporinfektionen der Abschnitte swischen dem Schneiden im Wald und der Einlagerung entwickelt. Die Fäulnis war auf etwa, 0.1 - 0.2 % des gesamten Holzvolumens begrenzt. Nach zwei Jahren Lagerung waren auch *Armillaria* Kolonien in der Rinde der Abschnitte sichtbar sie verursachten jedoch keine Holzfäule. Von den Nadelhölzern konnten auch Sitkafichte, Rotfichte, Douglasie und japanische Lärche und von den Laubhölzern Buche und Esche erfolgreich gelagert werden.

Schnittware von Kiefernabschnitten, die 6 Monate lang naß gelagert waren, litt bald unter Oberflächenentwertung durch Schimmel und Splintholzverfärbung. Sehr wenig Entwertung enstand jedoch in Schnittware von Abschnitten die 2-3 Jahre lang gelagert warren, dies ist wahrscheinlich aufgrund der Nährstoffauswaschung die mit langfristiger Wasserlagerung verbunden ist und der Hemmwirkung von Bakterien die in wassergelagertem Holz reichlich vorhanden sind. Die Porosität und Festigkeit des Holzes einer Reihe von Arten änderte sich durch Wasserlagerung ebenfalls; sowohl bei Nadelhölzern als auch bei Laubhölzern stieg die Porosität bedeutsam an und die Festigkeit von Laubhölzern wurde leicht reduziert, dies verringerte jedoch nicht den Ertrag an Bauholz.

Die britische Erfahrung mit Wasserlagerung stimmt genau mit Erfahrungent andernorts überein obwohl Transport einen ungewöhnlich großen Anteil der Gesamtkosten ausmacht. In Zukunft solte Wasserlagerung immer dann und dort als Hauptoption angesehen werden, wo groß Mengen von Kiefernholz von Verfärbung und Fäulnis bedroht werden. Obwohl diese Methode sowohl mit Nadelhölzern als auch mit Laubhölzern funktioniert, ist in den meisten Fällen die Lagerung vom Wind geworfener Bäume 'auf ihren Wurzeln' die sinnvollste Option für andere Holzsorten auß Kiefer.

Almacenaje de Madra con Rociadura de Agua: Experiencia en Gran Bretaña

Resumen

La galerna de Octubre 1987 dessarraigó 4 millones m^3 de madera en el sur de Inglaterra, un tercio de la cual fué pino. A base de las experiencias logradas en Dinamarca y en Alemania, a comienzos del año 1988 se decidió a almacenar algunas trozas de sierra de árboles de pino silvestre y pino de Córcega desarraigados por el viento debajo de rociadores de agua, para dar protección contra la degradación fúngica.

Se describe los detalles de la construcción y la operación del almacén. El sitio del almacén estuvo en el Bosque de Thetford, en la propiedad de la Forestry Commission, junto a un yacimiento de grava inundado, que proveyó el agua requerida para la irrigación. El almacén tuvo una capacidad máxima de 70 000 m^3 de trozas de pino, la mayor parte viniendo del Bosque de Rendlesham, a algunos 85 kilómetros. Se operó la irrigación continuamente durante todo el tiempo de almacenaje (Marzo 1988 – Julio 1992), con excepción de los períodos debajo del punto de congelación. Se sacaron las primeras trozas de venta después de 18 meses, y se vendió la mayor parte de las trozas después de tres años de almacenaje a un precio promedio de £30 m^{-3}.

Durante el período de almacenaje con rociadura de agua, se controló cuidadosamente la calidad de las aguas efluentes. La calidad quedó generalmente bien. El color fue relativamente estable (40 - 70 hazen) durante el período de Ilenar el almacén, y también durante los primeros 6 meses; a partir de entonces, se observó una disminución gradual hasta aproximadamente 10 hazen al tiempo de la terminación del almacén. La demanda biológica de oxígeno ha mostrado fluctuaciones grandes entre 1.2 y 7.3 mg l^{-1} durante el período de Ilenar el almacén, perio después de 18 meses de almacenaje se disminuyó a los niveles del fondo. No hubo ningunas amenazas a la calidad del agua ni a la vida acuática en el río Wissey adyacente.

Periodicamente se sacó muestras de trozas experimentales de pino para determinar el contenido de humedad y la degradación. En total, menos que 2% de la madera fué afectada por azulado, y se impidió el desarrollo de toda decoloración presente en las trozas atenes del almacenaje. En el otoño 1989, se observó fructificaciones de los hongos *Heterobasidion annosum* y *Phlebia gigantea* sobre aproximadamente 1% de las testas de las trozas, especialmente en el margen meridional del almacén, donde la irrigación fué incompleta. Al parecer, estos hongos habían desarrollado de infecciones basidiospóricas en las trozas entre la corta en el bosque y la instalación en el almacén. El grado de la pudrición fué solamente 0.1 – 0.2% del volumen total de la medera. Después de dos años de almacenaje, colonias de *Armillaria* fueron visibles en la corteza de las trozas, pero no provocaron ninguna pudrición de la madera. Se alcanzó tam-

bién un almacenaje satisfactorio con picea de Sitka, picea de Noruega, pino de Oregón y alerce del Japón ente las coníferas, y con la haya y el fresno entre las frondosas.

Tablas aserradas de trozas de pino, almacenadas durate 6 meses con rociadura de agua, sufrieron dentro de poco una desfiguración superficial por mohos y por hongos que causan coloración de albura. Sin embargo, se ocurrió desfiguración muy pequeña en tablas aserradas de trozas almacenadas por 2-3 años, probablemente a causa de la lixiviación de los nutrientes asociada con el almacenaje prolongado con rociadura de agua, y también la acción inhibitoria de bacterios que son abundantes en esta madera humeda. Se observó también modificaciones en la porosidad y en la resistencia de la madera de varias especies durante el almacenaje con rociadura de agua; se aumentó significativamente la porosidad de las frondosas y las coníferas, y se disminuyó un poco la resistencia de la madera de las coníferas, pero sin reducir el rendimiento de madera para estructuras.

La experiencia en Grad Bretaña de almacenaje con rociadura de agua es muy semejante a las experiencias en otros países, aunque el transporte representó una proporción excepcionalmente alta de los costes totales. En el futuro, el almacenaje con rociadura de agua debería ser una opción importante cuandoquiera y dondequiera cantidades grandes de pino sean vulnerables a la decoloración y la pudrición. Sin embargo, aunque este que, en la mayoría de circunstancias, el almacenaje de árboles desarraigados 'sobre sus raices' sea la opción más lógica para todas las especies con excepción del pino.

Chapter 1

Background

Joan Webber, Barry Griggs and John Gibbs

During the night of 15-16 October 1987, the worst storm since 1703 struck south-east England, causing more damage to trees, woodlands and forests than any other recorded gale in Britain (Figure 1.1). Wind speeds of 100-150 km h^{-1} were widespread and some 4 000 000 m^3 of timber were blown, equivalent to about five years of accumulated harvest in the seven worst affected counties (Table 1.1). The impact of the storm and the responses to it are described in some detail in Forestry Commission Bulletin 87 (Grayson, 1989).

Among Forestry Commission forests, Thetford Forest which lies across the border between Norfolk and Suffolk had 173 000 m^3 blown, equivalent to just under 90% of all the previous year's cut, while Rendlesham Forest in Suffolk suffered 484 000 m^3 of windblown timber, equating to the accumulated cut of 14 years. Virtually all of the timber consisted of pine, a timber which degrades very rapidly once felled because it is susceptible to attack by bark beetles and sapstaining fungi.

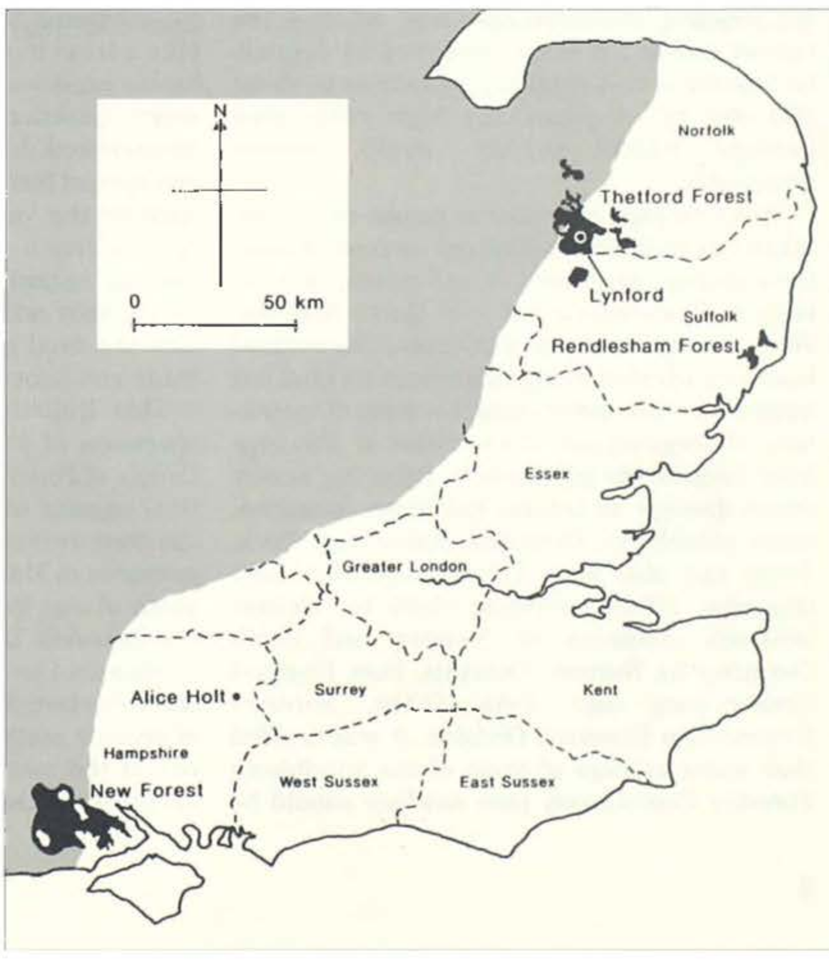

Figure 1.1 Counties worst affected by the October 1987 gale in southern England. The approximate areas of Thetford Forest, Rendlesham Forest and the New Forest are shown in black.

Table 1.1 Estimated volume blown by key species, size class and ownership.

Species	*Size*	*Volumes ('000 m³)*		
		Forestry Commission	*Private woodlands*	*Total*
Pine	Small roundwood (<14 cm diameter)	200	200	400
	Sawlogs (>14 cm diameter)	500	350	850
Other conifers	Small roundwood	100	200	300
	Sawlogs	100	250	350
Beech	Under 40 cm diameter	60	240	300
	Over 40 cm diameter	20	360	400
Other broadleaves	Under 40 cm diameter	15	520	535
	Over 40 cm diameter	15	780	795

The estimated clearance time using the combined harvesting resources of both Forest Districts, taking into account potential contract and standing sales, was calculated at two to three years but sawmill capacity and end product markets were insufficient to take up the extra volume that would be available over this relatively short period. The overriding concern, therefore, was how to store the timber and at the same time prevent degrade by bluestain; this applied particularly to about 300 000 m^3 of potentially high value pine sawlogs which quickly would become unsaleable.

Water storage of timber in ponds, rivers and lakes has been the traditional method of long-term storage to prevent deterioration, particularly in Scandinavia but also North America. However, during the past 20 years this method has been adapted so logs are stored on land but saturated with water using a system of sprinklers. Emergency use of wet stores of this type have been made successfully following severe storm damage in several European countries, most notably in Germany (Liese and Peek, 1984) and also after fire damage elsewhere (Bussche, 1993). Following visits to relevant research institutes in Sweden and north Germany by Norman Dannatt, East England Conservancy, and John Gibbs, Forestry Commission Research Division, it was decided that water storage of some of the windblown Forestry Commission pine sawlogs should be undertaken before the summer of 1988 when the development of stain and decay was likely to increase. This decision was aided by the availability of a suitable site for a wet store at Lynford, Thetford Forest, and the store eventually extended to cover 4 ha, containing some 70 000 m^3 of sawlogs. This was the first time water storage using sprinklers had been used to safeguard the quality of logs from windblown trees in Britain, and despite the considerable experience of its successful use abroad, many questions about its value remained unanswered. In part these related to the possible special features to be found in this country, such as the vagaries of our climate, the tree species grown here and the range of degrade causing organisms; but perhaps most importantly, they related to doubts over how acceptable the final product would be to the timber trade and hence its marketability.

This Bulletin examines all aspects of the operation of the store in some detail. Barry Griggs of Forest Enterprise describes the practical aspects of establishing and maintaining the store from the time when the site was first prepared in March 1988 through to the last dispatch of logs in December 1992. Tom Nisbet of the Research Division reviews the monitoring studies on the quality of water draining from the wet store, the potentially polluting effects of organic matter leaching from the logs being one of the most sensitive issues raised by an operation of this type. In addition to commercially saleable Scots and Corsican pine sawlogs, a number of experimental batches of timber were introduced into the store to evaluate the effectiveness of water storage in preventing degrade over prolonged periods of storage and the subsequent performance of the timber during and after sawmilling. Nine species, six conifer and three broadleaves, were examined in this way. John Gibbs and co-workers present data on wood moisture content and bluestain levels in the different species; this chapter also describes studies on logs that already had some bluestain prior to being placed in the store, and work on the development of decay fungi. An extension of this work by Michael Powell and Rod Eaton, University of Portsmouth, focuses on the resistance of pine timber sawn from water stored logs to wood degrading fungi compared with the susceptibility of freshly felled and sawn timber. A further study, commissioned by the Forestry Commission and carried out by Keith Maun of the Building Research Establishment, evaluates the changes in timber strength and porosity that occur during water storage. The final chapter then briefly reviews the success of the wet store from both operational and economic perspectives.

The Commission's expenditure on the water store represented a substantial investment, both commercially and in the knowledge and expertise accumulated over the five-year life of the store. This Bulletin provides the opportunity to bring together this information which covers many aspects of water storage of timber. We hope it will also inform and guide future decisions on the water storage of timber when the need for large scale storage arises again.

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Chapter 2

Creating and managing the wet store

Barry Griggs

Introduction

Soon after the severe gale in October 1987 which caused substantial damage in southern Britain, the idea of constructing one or more wet stores for the long-term storage of windblown timber came under serious discussion. Storing timber under a water sprinkler system which prevented attack by fungi and insects could reduce the quantity of logs flooding onto the market so maintaining some stability in timber prices. By good fortune an excellent account was available in English of the procedures adopted in north-west Germany in the early 1970s when 139 000 m^3 of conifer logs were placed under water storage after a major gale (Liese and Peek, 1984). This provided invaluable guidance on suitable site characteristics and storage practices.

A number of possible sites for a wet store were considered; ideally it needed to be situated close to a large area of windblown pine. However, water supply problems precluded the establishment of a store at a possible site in the vicinity of the largest volume of blown sawlog-quality pine in Rendlesham Forest, south-east Suffolk (Chapter 1). Lynford, the site in Thetford Forest that was eventually selected, had many advantages but was 85 km from Rendlesham with serious implications for carriage costs.

This chapter describes the practical and financial aspects of establishing and maintaining the Lynford wet store from the initial choice of site, through nearly 5 years of operation, and up to the removal of the last batch of logs.

Site selection

The prime requirements for a suitable site were:

- An adequate water supply.
- Sufficient storage space on a reasonably level free-draining site with good bearing capacity in all weathers.
- Good access to the site from public roads.

Requirements which became self-evident were:

- The facility to monitor and control haulage input and dispatch, i.e. the existence of a weighbridge.
- The proximity of suitable staff to supervise and maintain the store.

Initially a possible site was identified in Rendlesham Forest but Anglian Water was not prepared to guarantee that water extraction would be permitted during a period of drought. However, the site later found at Lynford in Thetford Forest did meet all the essential requirements. It was next to a flooded gravel pit from which Anglian Water was prepared to allow continuous water extraction given certain acceptable conditions. The site itself was reasonably level with a slope allowing natural drainage to the pit. The soil was gravel with varying depth of top soil and sand as an overburden. It was carrying a crop of 30-year-old Scots pine but was considered to require minimum site preparation once the trees and their stumps had been removed.

There was an 'A' class road in the vicinity, leaving only 1.6 km of minor public road to the entrance to the gravel pits. A well-used gravel surface entrance road that required no improvement led to an active pit being used for gravel extraction and this lay next to the water-filled pit. A weighbridge belonging to the gravel company was located on this road (see Figure 2.1).

Water supply

The flooded gravel pit was estimated to contain 180 000 m³ of water, and water was being pumped from the active gravel pit into the flooded pit as a regular feature of the quarry water management. As a consequence, the level was very stable. Overflow was fed into the adjacent River Wissey. Since it was proposed that run-off water from the wet store should drain back into the pit, it seemed likely that the available supply would be adequate.

There were two sensitive issues that needed to be resolved. Firstly, ground water reserves were low, due to a series of very dry years. Secondly, the River Wissey is a trout stream with a fishery downstream from the proposed site. In consequence, Anglian Water and the National Rivers Authority scrutinised the plans for the store very carefully, and permission for abstraction was finally given with the provision that water quality was monitored periodically (see Chapter 3).

Site preparation and road construction

On the basis of an initial plan, which was to store 20 000 m³ of timber, 2.5 ha of the existing crop of Scots pine were clear felled in January 1988. Once produce had been extracted, the brash was chipped and the stumps removed. The site was graded to slope south to north and east to west according to the natural lie of the land. A ditch was dug along the northern edge of the site to channel the return flow of water back to the gravel pit (see Figure 2.1). A metalled road of a standard above the Forestry Commission Category 1A was built to gain access to the site and to the pump positioned in its north-west corner. Within the site itself, it was considered that no surfacing was necessary

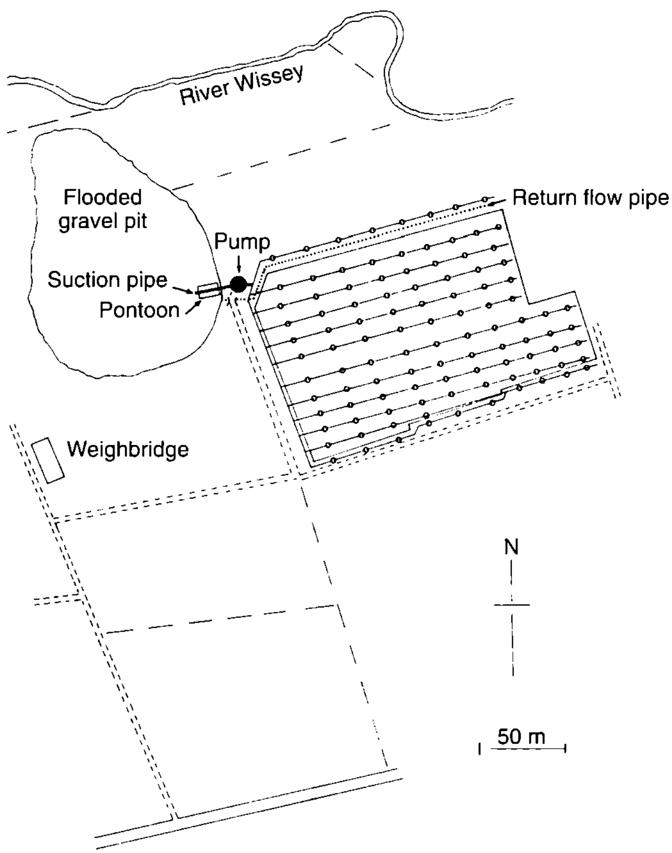

Figure 2.1
Map of the Lynford wet store.

— — — compartment boundaries
========= access road
═══════ public road
—o—o— supply pipe and sprinklers

due to the free-draining nature of the soil and its good bearing capacity. In August 1988, almost a year after the gale, when it was realised that logs in good condition could still be obtained, the site was extended by a further 2 ha on its southern edge by clearing a stand of 30-year-old Corsican pine.

Once the full extent of the store had been determined, it was decided that for dispatch from a perpetually saturated site, a Category 1 lorry road would be required along the southern edge with a turn-round at the eastern end. This road was built during the summer of 1989. As sales proceeded and the store shrank in size, it was found necessary to build another dispatch road through the centre of the site. This was completed in 1991.

Log input and stack building

Logs were brought to the site at the end of January 1988 although the irrigation system did not come into full operation until early March. Up to the end of June all the logs came from Thetford Forest. Delivery from Rendlesham started in July 1988 and continued until May 1989. Input was monitored by weight using the Forestry Commission weighbridge at Brandon Central Depot, about 8 km from the store. By the end of March 1988 9000 m^3 were in store, and this figure had risen to 65 900 m^3 by early 1989. The intention from the outset was to store only high quality logs (Anon., 1990). From time to time, however, logs with some stain were inadvertently placed in the store (see Chapter 4).

The original intention was to limit log lengths to 4.9 m and 7.5 m, these being the most popular lengths in the trade. Logs were sorted into the two lengths and transported separately to allow stacking in separate bays (see front cover). Minimum top diameter under bark was specified as 14 cm, although in practise very few logs under 16 cm were supplied. Later in the operation the decision was taken to cut random lengths in order to maximise sawlog volume. However, this created some problems in using the available space in the store and also when it came to marketing. In each bay logs were stacked as tight as possible, with butts and tips being alternated to keep the stack level. At the start of each bay the logs were ramped to a natural angle, and security logs were laid up the ramped ends to prevent rolling and to increase stack stability (see front cover and Plate 1). Stack height ranged from 3.2 to 3.6 m, with an average of 3.5 m. Front end loaders were able to load at the end of the stack and to heights up to 2 m (Plate 2). Lorries equipped with cranes were able to park along the southern edge of the stack and load to 4 m. On completion each bay was ramped and security logs were positioned as at the start.

Establishment and maintenance of the sprinkler system

The objective was to distribute an adequate supply of water, via plastic irrigation pipes fitted with sprinklers to ensure that logs were saturated. It was assumed that the system would remain in place for 2 years, and that some 20 000 m^3 of wood would be wet stored. In the event it was nearly 5 years before the last logs were removed and the store held, at its maximum, 70 000 m^3 of wood. Not surprisingly this created practical difficulties, mainly with the pump but also with other parts of the system.

Pumps

The finding of a suitable pump became a prime requirement for the successful water storage operation. Initially a Wright Rain pump was used, mounted on a tractor and powered from the tractor PTO shaft (Plate 3). It was capable of delivering 1.75 m^3 of water per minute and performed well at first. However, by the end of 1988 it had become obvious that its effectiveness was diminishing as the store size increased. Moreover, the continuous operation had proved too much for a total of eight tractors on which either the engine or the transmission had 'blown-up'. In early 1989 a Sykes pump capable of delivering 4.2 m^3 per minute was obtained. It was attached to a Deutz air-cooled 3-cylinder engine. The Wright Rain pump was refurbished to provide back-up together with yet another tractor. In addition a Fordson irrigation pump unit became available and this was brought in to provide further back-up.

By the end of July 1989 following numerous problems, including two broken shafts on the Deutz engine, the Sykes engineers came to the conclusion that their original calculations had underestimated both the friction due to the movement of water in the pipes and the effect of the height difference between the pump and the highest point in the store: the south-east corner was some 8 m higher than the north-west corner where the pump was sited. In consequence it was decided to split the system and use two pumps, and for the next 18 months various combinations of the Wright Rain, the Fordson and the Deutz/Sykes were used. However, even with this system, there were occasions during the summer of 1990 when water distribution was considered to be less than optimum and supply pressure was suspect. In December 1990, the breakage of the third Deutz shaft prompted the ordering of a second-hand Gardner 6LB 6-cylinder, 180 brake horse-power, long-stroke engine fitted with a Weir Isoglide 200/150/400 pump which was designed to deliver 5.7 m^3 per minute. Its installation in late February 1991 marked the end of a catalogue of problems resulting from a failure to identify and quantify all relevant factors at the outset and, most of all, the decision to expand the size of the stack part-way through the proceedings. A concrete standing was prepared for the Gardner with suitable levels to ensure that no spills of fuel or oil found their way into the water. The whole area, including the bulk fuel tank was contained within a high security fence with double gates to provide easy access for fuel delivery and pump maintenance.

Suction pipes

Various types of material were tried for the piping that carried water from the gravel pit to the pump. The most successful proved to be a combination of lengths of rigid pipe with flexible lengths of reinforced nylon pipe at either end for entry into the water and attachment to the pump. Effective filtering of the water was found to be vital: weed and various fish, including eels, were discovered in the pumps, and fragments of these sometimes got through into the pipework and became lodged in the sprinkler jets. The final solution to the problem was the construction, from perforated metal sheets, of a triangular box with a base and with sides approximately 90 cm in length. The suction pipes, complete with perforated end filters, were then lowered into it, thus achieving a two-stage filtering of the water. This complete suction assembly was floated on a pontoon with the top edge of the filter box just above water level.

Distribution pipes and sprinklers

The basic system, as specified in early 1988 by John Macleod, Civil Engineer, East England Conservancy, Forest Enterprise, comprised a 110 mm manifold with 75 mm sprinkler lines laid over and alongside the log stack. Sprinklers fitted with 4 mm nozzles were attached at 16 m spacing to each sprinkler line (Plate 4). The area covered by each sprinkler was to be approximately 256 m^2 and the output per sprinkler 0.80 m^3 per hour, giving a precipitation of around 3 mm per hour.

The first sprinkler line was laid on the ground beyond the return flow ditch on the northern edge of the site in order to ensure saturation of the butts exposed on this first face. The second line was connected to the manifold using a T-piece and ran up on to the top of the stack via the ramped end. A stopcock was built into the line near the T-piece allowing it to be turned off for maintenance purposes. The pipes for the sprinkler line were supplied in 5 m lengths and were readily cut and jointed with the use of collars and a suitable bonding agent. This made them sufficiently flexible to follow the irregular contour of the top of the stack. The stack sprinkler lines, of which there were eventually nine (see front cover and Figure 2.1) were placed approximately 12 m apart. A ground line was installed along the south face of the stack to ensure saturation of the exposed butts on this final face, but not until the autumn of 1989. Initially only one manifold pipe was used but in July 1989, when a second pump was brought into service, the original pipe was used to supply the first five sprinkler lines and the second manifold pipe the remainder.

Maintenance

The fuel, oil and water levels in the pumps were monitored daily by Forestry Commission staff who also checked for obvious failures in the sprinkler system. At weekly intervals all lines were carefully inspected over their whole length. This was a hazardous process once the bark on the logs had become loose and slippery, and staff were issued with rubber chainsaw boots, fitted with additional spikes. Checks were conducted for broken joints and failed sprinklers. Also at the weekly maintenance the end-cap on each line was removed in order to flush out the system. Apart from repair and maintenance periods, and times of very severe cold, the system was operated for 24 hours per day. In November 1988 a sudden drop in temperature resulted in the stack becoming covered with ice producing spectacular icicles of varying length (see back cover). The sprinkler system was kept running until it was almost completely frozen up, when the pump was stopped and drained. No serious damage occurred: a small number of joints parted when the system was switched on again and ice cones shot to the end of the sprinkler pipes, forcing the caps off like bullets. On the basis of this experience the system was only switched off when fully iced-up.

In the weekly inspections, the general state of the logs was also checked and any signs of deterioration noted. This point is covered in greater detail in Chapter 4.

Dispatch of the logs

There was some debate as to whether the logs should be removed in the order in which they had been laid down, or whether the last logs in should be the first logs out. The final decision, something of a compromise, was to work evenly back from the eastern end of all the bays in the southern half of the stack (see Figure 2.1). This had the advantage that loading started on the highest and driest ground and that the pump and manifold pipes could be left untouched until last. It also meant that a steady improvement in quality could be expected from random log lengths to regular log lengths, and from logs which had been taken from the forest over a year after the gale to those that had been selected within the first few months. Front-end loaders were used to remove logs from the stack, transport them to the roadside and load them onto the customer lorries. Butts and tops were alternated to give a level load. All loose bark was removed before departure and all loads were strapped.

Sales were conducted on the basis of volume. All loads were weighed on the gravel pit weighbridge, and, for each separate customer, every tenth load was measured to provide a volume to weight ratio to be applied to the next nine loads.

Sprinkler management during removal

The objective was to keep all logs that remained in the store saturated up to the time of loading. Each Saturday the probable dispatch level for the following week was assessed and a judgement made on the modifications required in the sprinkler system. As log removal proceeded, so the southern edge of the remaining half of the stack became exposed. In order to keep this face saturated a ground sprinkler line was taken from an appropriate point off the adjacent stack line.

As the area of stack decreased, so the demands on the pump were reduced to the point where end caps had to be removed from the sprinkler lines to exhaust excess pressure. Eventually even the end cap on the manifold pipe had to be removed. Effective positioning of the sprinklers became progressively more difficult. Three millimetre holes were made in the remaining sprinkler lines, giving excellent distribution and resolving any excess pressure problems. The final arrangement provided a high quality fountain display and, more to the point, kept the remaining logs saturated to the last.

Costs of the water storage operation

The costs of the operation by 'forest year' (1 April - 31 March) are shown in Table 2.1. Some explanation of the various items is required.

1. *Site preparation and roading* shows all the initial costs of work on the site plus the cost in 1991/92 of constructing the central dispatch road.
2. *Purchase of equipment* covers purchase of the pipes and sprinklers and of the first pump. The engines and, later, the pumps were included in 'running costs', following normal Forestry Commission procedures of levying a 'predetermined charge' which takes account of costs and depreciation.
3. *Carriage of logs* includes cost of haulage from Thetford and Rendlesham (the latter being 85 km from the store) and off-loading of logs to the stack.
4. *Running costs* covers not only most of the pumping machinery, as described above, but also includes all maintenance and all system extension and dismantling costs. No overhead charges are included but all wages include an on-cost element, amounting to 63.4%. No charge was made for the water.
5. *Measurement of sample loads* covers the costs of weighing every tenth load and the calculation of the volume:weight ratios.
6. *Loading for dispatch* covers cost of removal from store and loading onto the customers' lorries. (Charges for loading were covered by the seller not the buyer.)

Marketing the water stored logs

After a few months of water-sprinkling, the outside of the logs had become black and slimy (Plates 1 and 5). As described by Liese and Peek (1984), brightly coloured masses of slime moulds also appeared on the log ends (Plate 5), but with time these faded to grey-browns and some patches of green algal growth appeared. The external appearance of the logs was thus very unattractive. As already indicated, the bark on the logs became loose and considerable amounts were then lost during handling. Moreover, although the wet inner bark retained a near normal appearance and colour, once this was removed the outermost 1–2 mm of the wood quickly turned bright orange. None of these characteristics could be expected to create a favourable impression on a saw-milling trade with no previous experience of water stored wood. However, demonstration of the appearance of some sawn boards quickly brought reassurance, and interest in the material was raised further when it was discovered how easily the wood, with its very high moisture content, could be sawn. Saw-life was increased in consequence. Also, there was a general view that seasoning occurred more rapidly than in freshly felled wood, consistent

Table 2.1 Costs[a] in £ sterling at current prices of the water storage operation by forest year (1 April – 31 March).

	Item	*1987-89*	*1989-90*	*1990-91*	*1991-92*	*1992-93*	*Total*	*Unit cost £m⁻³*
1	Site preparation and roading	5 200	9 000	–	9 200	–	**23 400**	**0.33**
2	Purchase of sprinkling equipment, pumps, etc.	16 100	800	400	500	400	**18 200**	**0.26**
3	Carriage of logs	356 200	16 500	–	–	–	**372 700**	**5.32**
4	Running costs	4 000	71 300	48 200	26 200	15 500	**165 200**	**2.36**
5	Measurement of sample loads	–	–	2 000	3 200	1 100	**6 300**	**0.09**
6	Loading for dispatch	–	–	23 400	29 900	21 600	**74 900**	**1.07**
	Total	381 500	97 600	74 000	69 000	38 600	**660 700**	**9.43**

[a] Unit costs calculated on total overbark volume of 70 000 m^3.

with observations from South Africa on wet stored timber (Bussche, 1993).

In July 1989 1000 m^3 of logs from the bed of the research bay (see Chapter 4) were offered at auction, and were bought at £37.00 m^{-3}. In the following February 12 000 m^3 were sold at an average price of £38.14 m^{-3}. Parcels were offered at sales every six months thereafter but with the country moving towards recession, prices fell back. Thus in July 1990 prospects of clearing the store within two years of its establishment had to be reassessed.

By 1992, however, sawmillers were beginning to sense impending timber shortages, and by this time, had had some experience of handling the water stored material. This boosted prices with a result that when the final 12 000 m^3 were offered for auction in July of that year, the mean price was £38.53 m^{-3}. Table 2.2 contains data on volume sold and income received by forest year which runs from 1 April to 31 March.

The advantages of wet stored logs have been outlined above. The disadvantages of the material, real or imagined, should not be overlooked. Perhaps the most important of these is that due to the high moisture content, the logs were significantly heavier than freshly felled logs: the mean volume to weight ratio being 0.8 m^3 per tonne as compared to 0.95 m^3 per tonne. As a result haulage costs to the mill were high, almost prohibitively so for mills located at a distance. The slipperiness of the logs and the looseness of the bark gave some handling difficulties in a few smaller mills and the strong 'kippery' smell caused some offence. Loss of bark from the logs before arrival at the mill (up to 30%) constituted some loss in revenue through reduced bark sales. In addition, in some cases, the wet bark needed to be mixed with dry bark to make it acceptable for sale. Finally, one major customer who sold wood residues to the paper industry received complaints about the orange colour of the outermost wood. Although there was no reason to believe this had a detrimental effect on paper quality, the sawmill arranged matters so that logs from the store were only milled one day per week ensuring that only a small proportion of the residues sold for pulping originated from the water stored logs.

Table 2.2 Volumes of wood dispatched from the Lynford wet store and income in £ sterling at current prices.

Forest year	*Volume dispatched m^3 underbark*	*Income (£)*	*Income m^{-3} underbark (£)*
1989 – 90	872	30 770	35.29
1990 – 91	12 927	466 001	36.04
1991 – 92	27 922	784 339	28.09
1992 – 93	21 620	616 127	28.49
Totals	**63 341**	**1 897 237**	**29.95**

Conclusions

The original concept was to store the logs for no more than two years. In the event, a significant proportion of the logs were stored for more than four years and still found ready acceptance in the market at the end of that time.

With the hard work and goodwill of those involved, the difficulties encountered in running the store did not prove too onerous. However, the importance of deciding on the final store size at the outset cannot be too strongly emphasised. It is essential that the demands that are to be placed on the pump and water distribution system can be correctly assessed in advance.

Finally, although it was recognised at the outset that many of the logs would have to be hauled to the store over distances of 85 km, it was not realised that haulage costs would eventually count for nearly half the total cost of the operation.

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Chapter 3

Impact of the Lynford wet store on water quality

Tom Nisbet

Introduction

The practice of storing large quantities of logs under water sprinklers naturally raises concern about the possible impact of such an operation on local water quality. Although the practice of wet storage has been carried out successfully in other countries, apparently with minimal effect on receiving watercourses (Peek and Liese, 1977; Bussche, 1993), the storage of 70 000 m^3 of pine at Lynford in Thetford Forest was the first significant trial of the process in the UK. The selected site drained directly into an adjacent flooded gravel pit, and thence into the River Wissey (see Figure 2.1). It was also situated on a major chalk aquifer which formed the main drinking water supply for the region. In view of the proximity of these important water resources it was essential that the effect of the store on drainage water quality was monitored.

The main threat posed by the store was believed to be associated with the soluble organic compounds (such as sugars and tannins) leaching from the sapwood and bark of the stored timber. It is known that such leachates represent a readily available source of carbon for microbial growth and could impart a high degree of water colour. The former can enhance the biological oxygen demand of a receiving water body leading to possible oxygen starvation and fish death, while the latter may interfere with water treatment processes and be aesthetically displeasing. Mandatory standards are prescribed for water colour in regulations under the Water Act 1989 which protects drinking water supplies. In addition, guide values for biological oxygen demand are listed in the European Commission (EC) directives relating to the quality required of surface water intended for the abstraction of drinking water (75/440/EEC) and for supporting freshwater fish life (78/659/EEC).

It was thought unlikely that the organic leachates would exert any direct toxic action to fish or other freshwater fauna at the concentrations expected under open water conditions. Laboratory studies have demonstrated a slight acute toxicity to salmonids (more sensitive to pollution than coarse fish) only at the higher concentrations associated with ponded logs within enclosed tanks (Schaumburg, 1973; Sedell and Duval, 1985). The leaching of nutrients such as nitrogen and phosphorus was also unlikely to be a matter of concern in view of the low nutrient content of wood and bark (Freedman *et al.*, 1986). Schaumburg (1973) reported trace amounts of nitrate and phosphate in the leachate from the storage of Douglas fir logs.

Water pollution problems from wet storage have mainly arisen from the complete immersion of a large quantity of logs in fresh or sea water, often for the purpose of transportation. This practice has resulted in localised deoxygenation beneath the submerged logs (Levy *et al.*, 1990), benthic habitat changes through bark deposition (McDaniel, 1973) and sediment compaction (Levy *et al.*, 1982). The wet storage of logs on land using a sprinkler irrigation system is likely to be much less disruptive to the freshwater environment, particularly where soil drainage allows absorption of the organic leachates. The use of a gravel filter bed or natural vegetated buffer strip is now recommended where surface drainage is directly into a watercourse, in order to retain small pieces of bark and other particulate material (Bussche, 1993).

Site details and methodology

The wet store was located on a very gently sloping site on the alluvial floodplain of the River Wissey. The site was at 10 m elevation and approximately 100 m from the river. Soils are typical humic sandy gleys developed from a variable depth of glaciofluvial sand (Hodge *et al.,* 1984). These deep permeable sandy soils are affected by ground water and waterlogged at depth for a large part of the year. The underlying geology is chalk, comprising a soft, fine grained and well-fissured limestone of the Cretaceous age.

The combination of a naturally high water-table in the soil and the constant application of water to the store at approximately 45 mm per day, resulted in the bulk of drainage water leaving the site as surface run-off. Consequently, there was little opportunity for the organic leachates from the stored timber to be absorbed by the soil. The run-off was collected by a cut-off ditch and directed back to the gravel pit where it could be recycled (Plates 6 and 7).

Water samples were collected fortnightly (May 1988–September 1990) to monthly (October 1990–December 1992) from the storage effluent and monthly from the flooded gravel pit. The sampling point for the latter was located 100 m along the shore from the point where the effluent entered the pit and the water was extracted for irrigating the store. Unfortunately, no baseline samples were available from the gravel pit prior to the clearing of the site for setting up the store in February 1988. Water samples were sent to Anglian Water Authority Laboratories in Colchester on the day of collection for routine analysis of water colour and biological oxygen demand (BOD), according to the approved NAMAS procedures manual (National Measurement Accreditation Service, 1991). BOD is the amount of oxygen required for the biological oxidation of the available organic material in a water sample.

Results and discussion

Colour

The level of water colour in the storage effluent remained relatively stable during the first 21-month period of the store (Figure 3.1(a)). Values generally fluctuated between 40 and 70 hazen (mean = 58 hazen) as the store was filled to capacity in April 1989 and for the first 6 months thereafter. This response suggests that the leaching of tannins and other colour-producing organics from the stored logs was constant in the short and medium term. Leaching losses following each new addition of timber remained in line with the increase in water volume commensurate with the extension of the irrigation network. This result is in agreement with laboratory leaching studies carried out by Graham (1970) who showed the leaching rate to remain constant for at least 80 days. A peak of 102 hazen occurred on 26 July 1989, around 3 months after completion of the store. This coincided with the end of a 4-week period of hot, dry weather, during which time the breakdown of organic matter and release of soluble organic compounds could be expected to reach a maximum. After this peak there was a sharp decline to a new equilibrium level of around 30 hazen, followed by a gradual decline to 10 hazen as the store was run-down to closure in December 1992.

As expected, the response in colour levels in the receiving gravel pit was dampened compared to that of the storage effluent and lagged behind the latter by about 1 month (Figure 3.1(b)). The overall pattern, however, was very similar, with values in the gravel pit averaging 20 to 30% lower than those in the effluent. The colour reached an equilibrium of 40 hazen within 6 months of the initiation of the store, from which level it declined after 21 months to a value of around 10 hazen by its close. Two marked peaks occurred in the record, one of 87 hazen on 24 August 1989 and another of 67 hazen on 22 August 1991. The first was a delayed response to the peak in effluent colour at that time, while the second was unrelated to the effluent record. However, this may have

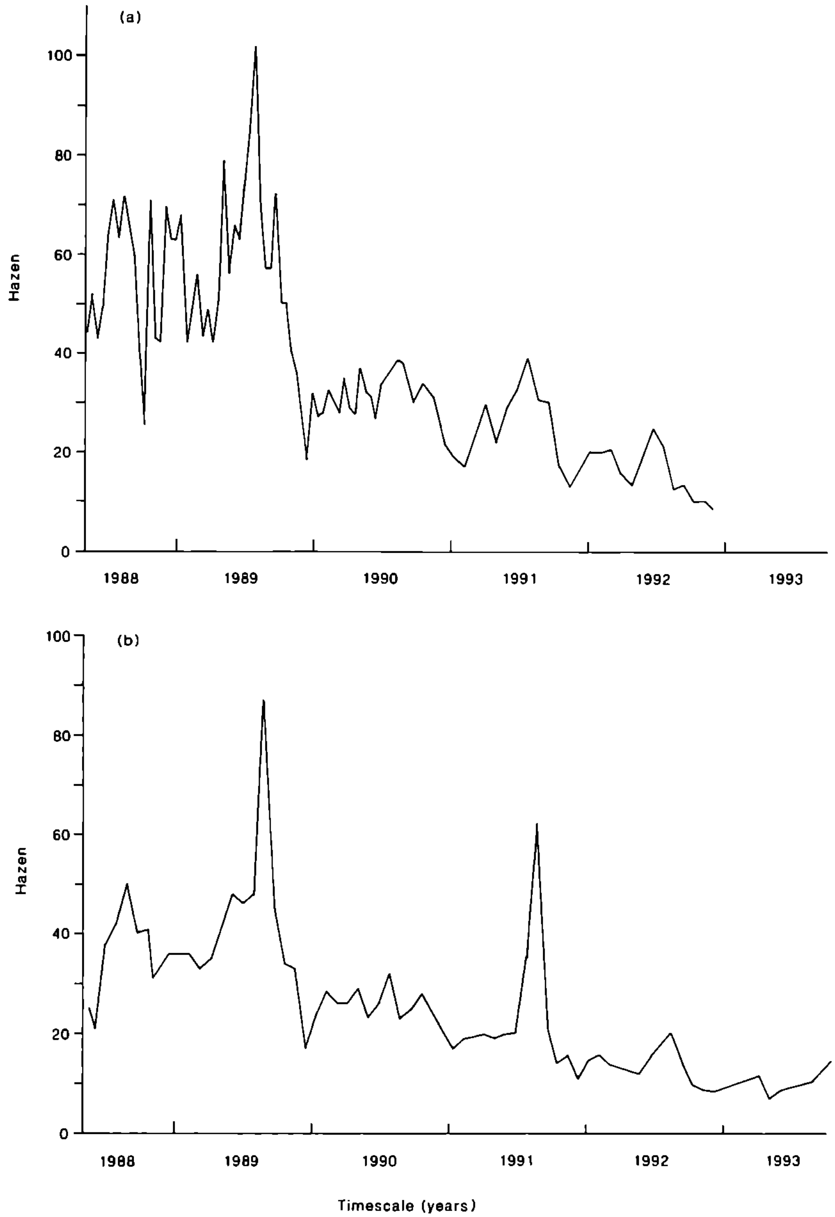

Figure 3.1 Water colour levels: (a) of the effluent draining from the wet store, (b) in the receiving gravel pit.

been due to an unrecorded event such as site disturbance during timber removal occurring between sampling occasions.

Increased water colour is only considered a pollutant in the context of drinking water supplies. Regulations under the Water Act 1989, which incorporate standards set out in the EC Surface Waters Directive (75/440/EEC), assign colour standards that are based on the type of water treatment available. Where normal treatment facilities are present, as in many parts of the country, a mandatory value of 100 hazen is set as the maximum limit required for the abstraction of drinking water. Despite the higher levels of water colour generated by the wet log store, particularly during the first 18 months of its operation, the colour in the storage effluent and receiving gravel pit generally remained well within this value and therefore acceptable for public supply. The effluent quality, however, failed to meet the mandatory standard of 20 hazen set for the abstraction of drinking water where only simple water treatment facilities are available, such as in the more remote parts of upland Britain. The discharge of this effluent into such waters would require a 5 to 6 fold dilution to be acceptable for public supply.

Biological oxygen demand

The BOD of the storage effluent followed a slightly different pattern of response to that of colour (Figure 3.2(a)). BOD concentrations were generally less stable with marked fluctuations between 1.2 and 7.3 mg l^{-1} during the period when the store was being filled. This variation did not appear to be directly linked to precipitation or temperature patterns and was probably a function of both of these factors together with the condition of the timber being added to the store. Overall, concentrations declined from a mean of 5.2 mg l^{-1} during the first 10 months to 2.3 mg l^{-1} for the period after 18 months. The latter is equivalent to the mean annual BOD concentration (1988-1992) for the adjacent River Wissey (NRA, 1993), indicating a return to background levels. This response represents a more rapid improvement compared to that for colour, suggesting that the organics contributing to BOD (principally wood sugars) were more rapidly leached and exhausted from the stored timber. The trend in BOD concentrations in the gravel pit showed a very different response to that in the effluent (Figure 3.2(b)). The pattern was one of a series of marked peaks in concentration superimposed on a relatively stable baseline level of 1.0 to 3.0 mg l^{-1}. These peaks occurred during the summer or autumn of the years 1988 to 1991, and then again in 1993, and corresponded with periods when there was a marked growth of algae around the shores of the gravel pit. It was the consumption of oxygen by the respiration or death and decay of the algae present in the water samples during the BOD determination (a measure of the oxygen consumed after 5 days storage in the dark at 20°C), rather than the degradation of an input of organic leachate from the store, that was believed to be responsible for these peaks. This is supported by the fact that the BOD peaks did not correlate with the BOD or colour records for the storage effluent. Algal growths are known to cause night-time reductions in dissolved oxygen as a result of respiration, a feature which is normally compensated for during the daytime by the production of oxygen by photosynthesis. Death and decay of algae are also known to consume large quantities of oxygen, occasionally leading to anaerobic conditions.

While the BOD peaks in the water samples from the gravel pit can be ascribed to an algal effect rather than an input of organic leachate from the wet log store, the latter is likely to have indirectly contributed to the former through the provision of a readily available source of carbon for algal growth. The absence of a marked BOD peak in 1992 after the closure of the store and the smaller peak in 1993 provides some support for this view, although data accumulated over several years would be required to prove a definite link. Unfortunately, no information is available on the presence of algal growths in the gravel pit prior to the setting up of the store. Water quality data for the River Wissey and local ground water supplies, however, show the waters in the area to be eutrophic in nature and therefore susceptible to algal growths.

No mandatory standards are set for BOD under existing water quality legislation. Two EC directives set guide values as standards which should be respected in the context of surface water supplies and fishery protection. The BOD concentrations in the storage effluent generally met the guide value of 5 mg l^{-1} under the EC Surface Waters Directive (75/440/EEC) where normal treatment is available, but exceeded that of 3 mg l^{-1} where only simple treatment is present. Similarly, concentrations met the guide value of 6 mg l^{-1} under the EC Fisheries Directive (78/659/EEC) for the protection of designated

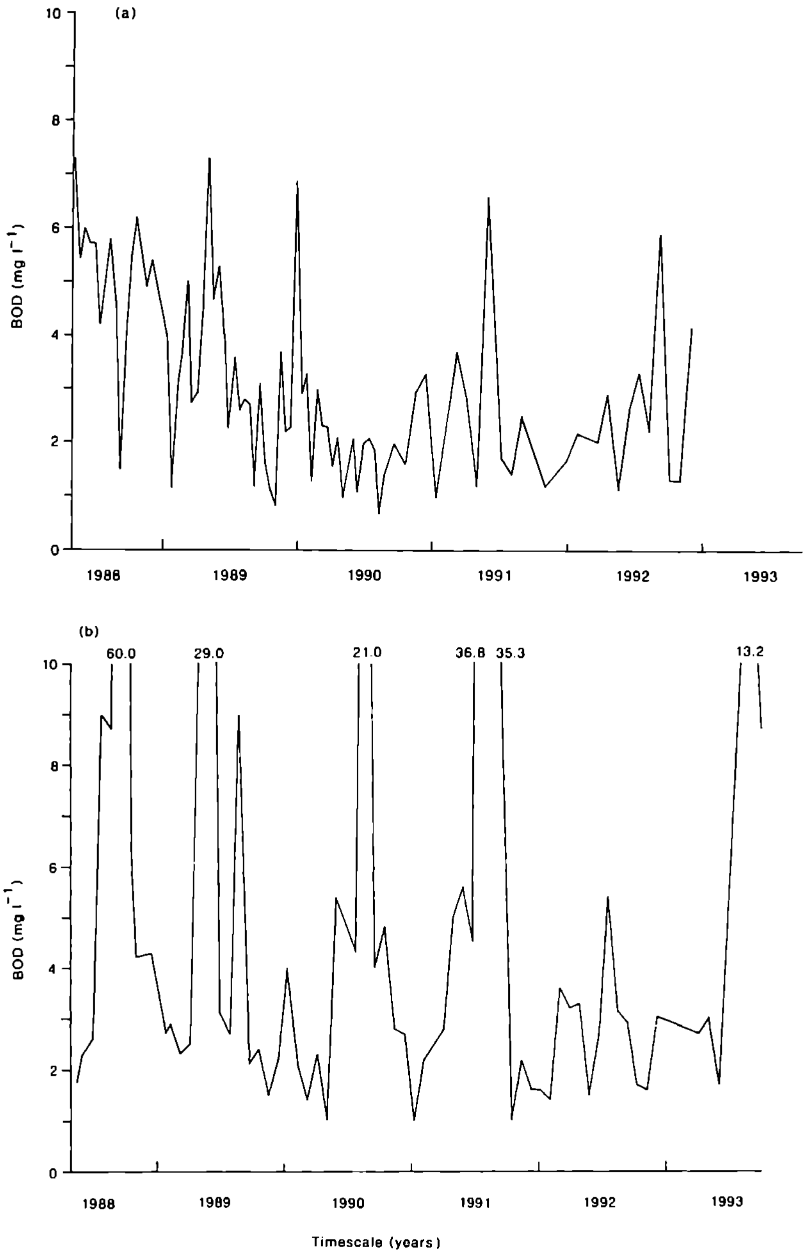

Figure 3.2 Biological oxygen demand: (a) of the effluent draining from the wet store, (b) in the receiving gravel pit.

coarse fisheries, but failed that of 3 mg l^{-1} for salmonids. The exceedances under the more sensitive conditions of simple water treatment or salmonid fisheries, however, are of a relatively small magnitude, and only a limited amount of dilution would be required to make the discharge acceptable. BOD concentrations in the gravel pit receiving the storage effluent generally met the stricter 3 mg l^{-1} guide standard, with the exception of the peaks due to an algal effect. These results agree with German work which found the organic leachates from wet log storage to exert a short-term oxygen demand which was unlikely to have a detrimental effect on a receiving stream (Peek and Liese, 1977).

Conclusions

The effluent quality from the large wet store at Lynford, containing 70 000 m^3 of logs at its peak, remained generally good throughout the period of its operation. Short-term increases in colour and BOD were found but were expected to have a negligible effect on the water quality of the River Wissey. Providing a limited amount of dilution is available in the form of a receiving watercourse, a water sprinkler system for log storage is unlikely to pose a pollution threat to high quality water supplies. However, the growth of algae in the receiving gravel pit at Lynford suggests that such wet stores should be sited away from eutrophic standing waters.

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Plate 1 *Western end of wet store showing the security logs in place.* (38804)

Plate 2 *Grapple loader moving logs into wet store.*

Plate 3 *Early pumping system, located between wet store (foreground) and gravel pit (background).*

Plate 4 *Sprinkler system in action on the log stack.* (38789)

Plate 5 *Coloured masses of slime visible on log ends after several months of irrigation.*

Plate 6 *Point of water abstraction (background) from the gravel pit for irrigating the wet store and point of return (foreground) for the coloured effluent draining from the site.*

Plate 7 *Cut-off ditch beside the log stack receiving drainage water from the wet store.* (TOM NISBET)

Plate 8 *Disc of wood cut from pine log after 2 years of water storage showing the imprints of circular* Armillaria *colonies on the surface. No invasion of the wood has occurred.*

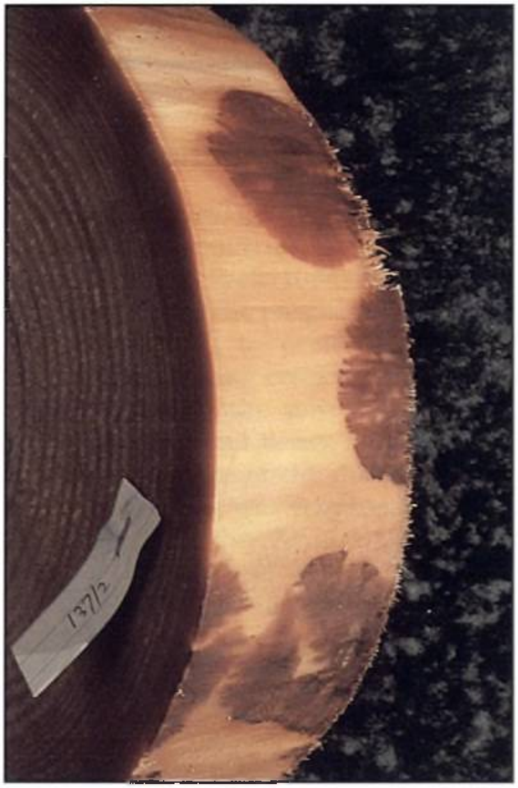


Plate 10 *Cessation of development of pre-existing bluestain in water stored pine. (a) Section cut 5 cm from the end of a Corsican pine log showing the same amount of bluestain after 21 months as was recorded when the log went into store.* (39331) *(b) Section cut 25 cm from the end of the same log showing a little discoloration but no bluestain.* (39332)

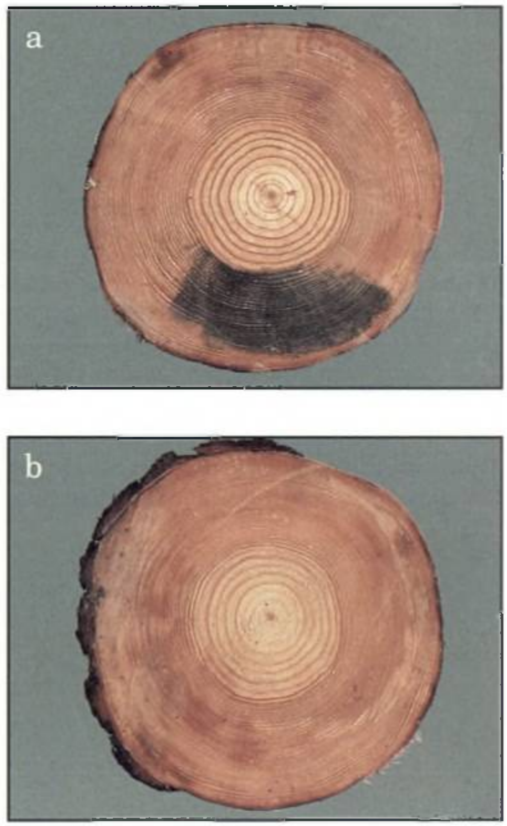


Plate 9 *Portion of sycamore log after 18 months of water storage showing the development of* Armillaria gallica *decay in the outer sapwood. Rhizomorphs of the fungus can be seen in the bark.*

Plate 11 *Small fruit bodies of* Heterobasidion annosum *on the surface of a disc cut from a log after 20 months in the wet store.* (39328)

Plate 12 *Susceptibility of five replicate boards cut from freshly felled logs (left), 6-month water stored (centre) and c. 4-year water stored logs (right) exposed in stacks for 8 weeks.* (MICHAEL POWELL)

Chapter 4

Fungal stain and decay in wet stored logs

John Gibbs, Joan Webber, Brian Greig and Donald Thompson

Introduction

Wet storage of sawlogs has been used successfully in several countries, usually for pine and spruce (Liese and Peek, 1984) but also for beech (Moltesen, 1971). The purpose of using a water storage system is to protect against insect attack and seasoning cracks, but most importantly it inhibits the development of fungi that cause stain and decay. However, with no previous experience of the process in Britain, regular monitoring was required to assess the effectiveness of the Lynford wet store in achieving this purpose.

Various investigations were carried out, comprising one major experiment using batches of logs incorporated into the wet store especially for research purposes and some *ad hoc* studies exploring the condition of wet store pine logs destined for sale. Of the latter, one study was aimed at determining the progress of stain already present in a small proportion of logs when they were placed in the store. Another *ad hoc* study derived principally from concerns aroused by the appearance of fruit bodies of the decay fungi *Heterobasidion annosum, Phlebia (Peniophora) gigantea* and *Stereum sanguinolentum,* which developed on some logs during storage.

Experimental evaluation of water stored logs

For the major experiment, it was decided that the study should not be restricted to Corsican and Scots pine, the two species that made up the bulk of the 70 000 m^3 of logs in the wet store. Rather, it was recognised that opportunity should be taken to examine the performance of a range of common British grown conifers and broadleaves retained in the wet store for 18 months (Table 4.1). However special attention was directed to Corsican pine, Sitka spruce and beech because of the commercial importance of spruce and pine and the large quantity of beech affected by the windblow. For these three species the effect of various storage periods ranging from 6 to 36 months was investigated. Finally, for Corsican pine and Sitka spruce, logs from freshly felled trees were compared with logs from windblown trees that were held for periods of 2 weeks, 6 weeks and 10 weeks before being placed in the store (Table 4.1).

Logs for all these treatments were contained in a research bay established in the middle of the wet store (see Figure 2.1) during the period June to August 1988. Each sample had a volume of about 10 m^3 (corresponding to between 20 and 30 logs according to size) and was placed on a 2 m high bed created from non-experimental 4.8 m length pine logs. Spaces between the sample lots were in-filled with similar non-experimental logs to the standard height of *c.* 3.5 m. For logistical reasons it was necessary for the logs with the shortest storage period to be at the eastern end of the bay to facilitate easy removal. The Corsican pine, Scots pine and beech logs all came from windblown trees in the south-east of England that had at least part of the root system in the ground right up to the time of harvesting. The Sitka spruce logs also came from windblown trees but in this case from an area of local damage at Grizedale Forest, Cumbria. Trees of the other species were felled specifically for research on water storage and came from various locations.

Table 4.1 Experimental treatments in the wet store research bay.

Treatment	*Details*	*Tree species*	*Number of logs sampled*
Species comparison	Logs put into store within 0-2 weeks of felling and removed after 18 months	*Major species*	
		Beech	20
		Corsican pine	20
		Sitka spruce	20
		Other species	
		Ash	20
		Douglas fir	20
		Japanese larch	20
		Norway spruce	20
		Scots pine	20
		Sycamore	20
Length of storage	Windblown logs put into store within 0-2 weeks of felling and then removed at 6, 12, 24 (pine only) and 36 months	Beech	60
		Corsican pine	80
		Sitka spruce	60
'Ageing' before storage	Freshly felled logs placed in store immediately and windblown logs held on site for 0-2, 4-6 or 8-10 weeks before being placed in store. All logs removed after 18 months	Corsican pine	80
		Sitka spruce	80

Destructive analysis of the experimental logs consisted of cutting a board 2.5 cm thick through the middle of each log; this was carried out at a commercial sawmill. A visual estimate of the extent of any stain or decay was made and then a block 4-5 cm long was removed from the middle and from each end of the board (Figure 4.1). Where stain or decay was present larger sections of board were also removed. All this material was immediately placed in polythene bags to prevent moisture loss and stored at 5°C until it could be examined in detail.

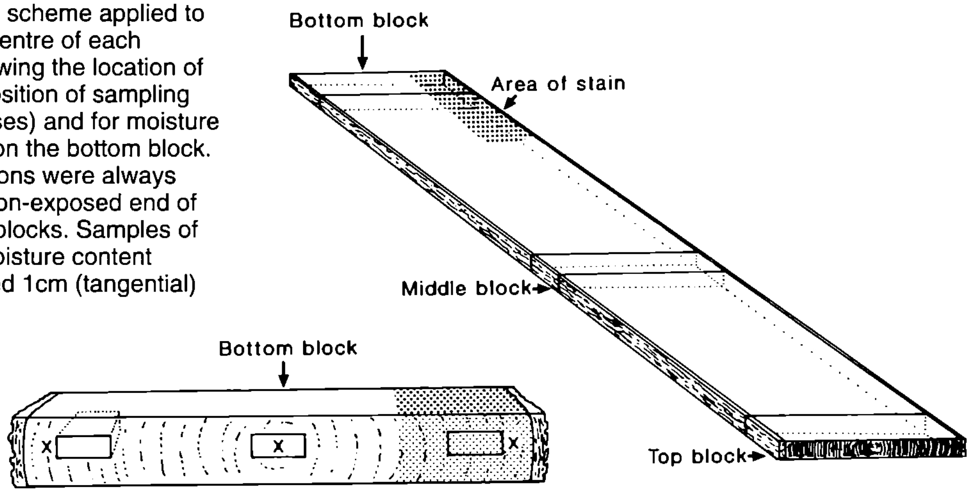
In the laboratory, samples were taken for fungal culturing and wood moisture content determination from each block (see Figure 4.1). Samples were also taken at 15-20 cm intervals along sections of board showing stain or decay. Fungal culturing was conducted by removing small fragments of wood ($1 mm^3$) under aseptic conditions and plating them onto (a) 2% malt agar, (b) 2% malt agar containing streptomycin and cyclohexamide, and (c) Hendrix and Kuhlman medium. The cyclohexamide medium is selective for certain bluestain fungi such as *Ophiostoma* and the related imperfect genera *Leptographium* and *Graphium* (Harrington, 1981), while the Hendrix and Kuhlman medium is selective for wood-rotting basidiomycetes (Hendrix and Kuhlman, 1962).

Wood moisture content was determined by removing samples of wood with a chisel, weighing them immediately and then drying them in an oven at 100°C to a constant weight. The moisture content was then expressed as a percentage of the oven dry weight. A set of control data were obtained from sample batches of logs that came from trees that were felled in July/August of 1992.

Moisture content changes during water storage

After just 6 months in the wet store, logs of Corsican pine, Sitka spruce and beech had a significantly higher moisture content, both in the sapwood and the heartwood ($p<0.001$), than did the control logs. This effect was most pronounced in Corsican pine and least pronounced in beech. However, subsequent sampling at 12, 18, 24 and 36 months provided no evidence of any significant further change in moisture content. This point is illustrated in Figure 4.2 which shows data for control logs and for logs stored for 18 and 36 months. The figure also

Figure 4.1 Sampling scheme applied to boards cut from the centre of each experimental log showing the location of the blocks and the position of sampling points for fungi (crosses) and for moisture content (rectangles) on the bottom block. Routine fungal isolations were always attempted from the non-exposed end of the top and butt end blocks. Samples of wood removed for moisture content assessment measured 1cm (tangential) by 2cm (radial) by 4-5cm (longitudinal).



shows that in pine and spruce the heartwood at the ends of the logs became water saturated much more readily than the heartwood in the middle of the logs. Indeed in Sitka spruce, a species of timber widely recognised as impermeable to preservative treatments (Lincoln, 1986), the heartwood samples from the middle of the stored logs were only slightly wetter than those from the control logs.

The other conifers, placed in the wet store for 18 months, showed a similar pattern of moisture content increase to Corsican pine and Sitka spruce (Figure 4.3), with ANOVA revealing highly significant differences ($p<0.001$) in mean moisture content between controls and wet stored logs and between heartwood and sapwood samples. For the hardwoods, sycamore was broadly similar to beech with a fairly uniform moisture content throughout the sample logs, confirming the very permeable nature of this timber (Wilkinson, 1979). In contrast, ash resembled the conifers and revealed only a limited wetting of the heartwood in the middle of the logs.

The beneficial effect of the high moisture content on sawing has been described for pine in Chapter 2. It also applied to the other species, especially beech which was found to saw much more easily and accurately than freshly felled material (Thompson *et al.,* 1991).

Stain and decay after water storage

All the research logs placed in the wet store were inspected for any visible signs of stain and decay after processing at the sawmill, but inevitably particular emphasis was given to pine because of its susceptibility to bluestain.

Corsican pine

The extent of bluestain in logs placed in store within 0-2 weeks of cutting and then removed after different storage periods is shown in Table 4.2. Data for the period 18-36 months are

Table 4.2 Extent of bluestain in windblown Corsican pine placed in the wet store within 0-2 weeks of felling, and sampled after varying periods of storage.

Storage time (months)	*Number of logs*	*Proportion of boards with bluestain (%)*	*Mean area of stain as % of board surface (range in parentheses)*
6	20	– [a]	2 (<1-6)
12	20	– [a]	4 (<1-5)
18	20	15	2 (<1-5)
24	20	13	3 (<1-7)
36	20	13	2 (<1-5)

[a] No figures presented because of incomplete assessments.

the most reliable as the systematic sampling procedure was in full operation by then. Only some 15% of the centre boards showed stain and the mean area of stain never exceeded 4% of the total board surface. There was no indication of any increase in the amount of stain with storage time and the overall incidence of decay was negligible.

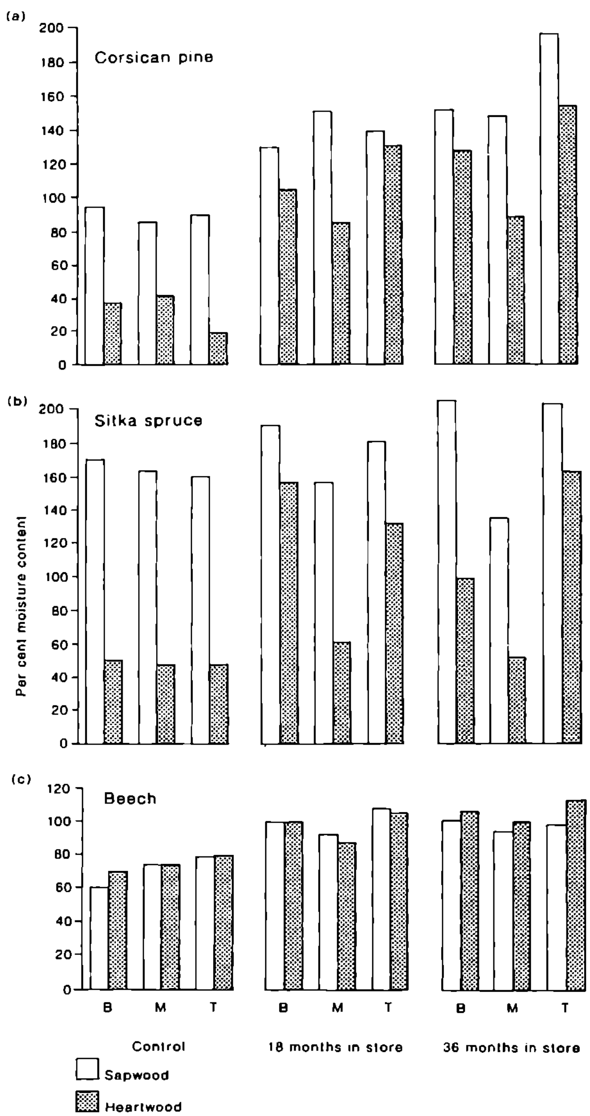


Figure 4.2 Mean moisture content of logs after 18 months and 36 months of water storage compared with control logs: (a) Corsican pine, (b) Sitka spruce, (c) beech. Moisture content measured at butt (B), middle (M), and top (T) positions on each log, with 10 logs sampled for each species.

In contrast, holding the logs for various periods between felling and placing in the wet store had a marked effect on the extent of visible stain (Table 4.3). As the holding time increased there was clear evidence of a substantial increase in the percentage of boards showing bluestain and the average area of stain also enlarged. With the logs held for 9-10 weeks it was also evident that much of the stain was distributed erratically along the length of the logs and not limited to the log ends as it usually was in logs held for 0-2 or 4-5 weeks. Closer inspection of the 9-10 week pre-stored logs revealed that the stain was invariably associated with colonisation of the logs by the pine shoot beetle *Tomicus piniperda*. The larval galleries were well developed and this accorded well with the fact that these logs had been cut in April. Shortly after this, during mid-April to mid-June they must have been colonised for breeding by *T. piniperda,* with the resultant galleries developing until the logs were placed in the wet store in mid-June. *T. piniperda* is known to be a vector of the bluestain fungus *Leptographium wingfieldii* (Gibbs and Inman, 1991).

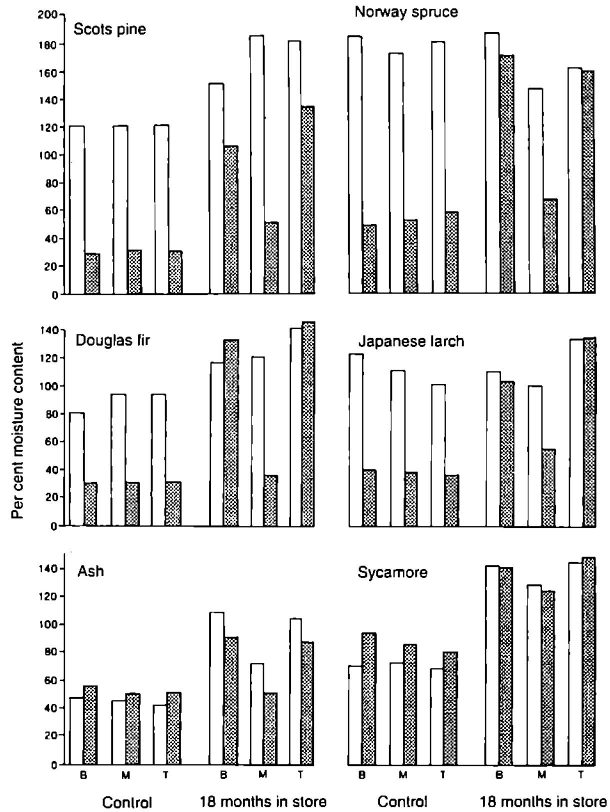
The vast proportion of the isolation attempts gave negative results, whether undertaken routinely from the top, middle and butt blocks or from definite areas of stain. After 12 months of water storage, more than 500 isolations were attempted from various sections of bluestained board but less than 1.4% of these yielded bluestain fungi. Those that were isolated usually corresponded to species of *Ophiostoma (O. piceae)* and *Leptographium (L. procerum* and *L.*

Table 4.3 Extent of bluestain in Corsican pine subject to varying periods of pre-store and assessed after 18 months of water storage.

Treatment	*Number of logs*	*Proportion of boards affected (%)*	*Mean area of stain as % of board surface (range in parentheses)*
Freshly felled	20	0	0
0-2 weeks pre-store	20	15	2 (<1-5)
5-6 weeks pre-store	20	50	3 (<1-8)
9-10 weeks pre-store	20	85	7 (<1-30)

Figure 4.3 Mean moisture content of a range of hardwoods and softwoods after 18 months of water storage compared with control material. Moisture content measured at butt (B), middle (M) and top (T) positions on each log, with 10 logs sampled for each species.

□ Sapwood
▩ Heartwood



wingfieldii). Isolations from logs stored for 18 months followed a similar pattern. Over 170 attempts at culturing from sapwood yielded six cultures of *O. piceae* and one of *L. truncatum.* Seventy-nine heartwood isolations yielded one culture of *O. piceae* and one of *L. procerum.* Thirty-six isolations were attempted from sapwood on stained boards, and of these, two yielded *L. truncatum.* Mould fungi capable of causing superficial discoloration to wood, such as species of *Trichoderma* and *Penicillium,* were isolated sporadically.

Decay fungi were also isolated but only rarely. For pine taken out of storage after 12 months, *Phlebia gigantea* was isolated from two boards which showed visible signs of decay and *Heterobasidion annosum* from one. After 24 months water storage, *P. gigantea* was isolated from one board with visible decay. However, one of the most striking and unexpected features of the investigation involving basidiomycete colonisation was the appearance from spring 1990 onwards of large numbers of circular 4-7 cm diameter colonies of the honey fungus *(Armillaria)* growing in the bark of many of the logs (Plate 8). Although the fungus was evidently alive, all attempts to isolate it into pure culture were unsuccessful, because of very high levels of bacterial contamination. No invasion of wood was observed and this was especially interesting when contrasted to a situation recently described from Germany. There, Metzler (1994) and Gross and Metzler (1995) observed peripheral sapwood decay caused by *Armillaria* in logs of Norway spruce and silver fir stored under sprinklers for three years; this process of colonisation was associated with localised drying and oxygenation of the woody tissues. Gross and Metzler (1995) suggest that the infection they observed may have originated from bark at the base of the tree killed by the fungus prior to felling. However, this explanation certainly would not fit the situation observed in Thetford. Here, spore infection seems the only possible explanation, and the studies of Shaw (1981) suggest that basidiospores lodged in the outer bark may have been the source. This is an area that requires further study, particularly in view of the fact that significant sapwood decay caused by *A. gallica* occurred in the sycamore samples (see below).

Sitka spruce

No visible stain was recorded at any time. Despite this, the bluestain fungus *O. piceae* was isolated occasionally from some of the spruce, especially from the sample blocks taken from the end of logs. At 18 months, isolations from these blocks yielded 16 cultures of *O. piceae* from 63 sapwood samples and 19 cultures from 32 heartwood samples; no *Leptographium* cultures were ever obtained. Throughout the work, occasional examples of decay were recorded and *Sistotrema brinkmanni* and *Stereum sanguinolentum* were isolated from several boards. This decay was usually in the heartwood and was often advanced, suggesting it might have been present in the logs prior to their placement in store.

Beech

The beech logs placed in the wet store tended to be of very variable size and poor form. No bluestain was ever visible but boards with incipient decay were encountered from time to time. Extensive isolation attempts were made on samples removed after 12 months storage but few viable fungal cultures were obtained. Among decay fungi the Ascomycete *Hypoxylon fragiforme* was obtained from one log and a species of *Stereum* from another.

Other species

About 10% of the sawn boards of Scots pine had small areas of bluestain but, generally, there was little sign of degrade in the other species placed in the store. The main exception to this was the sycamore logs, many of which showed bark colonisation by *Armillaria* similar to that observed in the Corsican pine. In contrast to the pine, however, partial colonisation of the sapwood had occurred in some of the logs and quite extensive decay had taken place, with the wood containing numerous zone lines (Plate 9). Isolations from the colonised wood yielded isolates which were identified as *A. gallica* (S. C. Gregory, personal communication). This species is probably the most common *Armillaria* in the UK, occurring mainly as a saprophyte and often causing butt-rot in broadleaved species (Rishbeth, 1985).

Pre-existing bluestain in water stored pine

From the time of setting-up until additions to the store ceased in April 1989, it was possible to obtain stain-free pine logs from windblown trees that were still partially rooted in the ground and had escaped bark beetle attack. However, despite efforts at quality control, some stained logs were delivered to the wet store from time to time, particularly after late summer 1988 (see Chapter 2). To determine whether the bluestain in such logs progressed during storage, a number were labelled on entry to the store in May 1988, and the amount of stain visible at the log ends recorded. In February 1990, two of these logs (both Corsican pine) were removed for examination. A 5 cm disc was cut from the end of each log and then additional 5 cm discs were taken at 25 cm intervals until no more stain was visible. Samples were removed from the discs for fungal isolation and moisture content determination.

When it was placed in the store the first log was assessed as having heavy bluestain occupying a quarter of the sapwood on the butt end. On sampling, the 5 cm butt disc showed no increase in the amount of stain over that originally recorded (Plate 10(a)). No stain was evident in the disc taken at 25 cm (Plate 10(b)). Moisture contents ranging from 123 to 183% were recorded in the sapwood of both discs and no bluestain fungi could be isolated. For the second log, stain had been estimated to occupy 30% of the sapwood of the butt end initially. Just the same percentage of stain was visible when the log was removed from the store and the 5 cm disc examined in February 1990. A small amount of stain was visible on the 25 cm disc but none at all on the 50 cm disc. Sapwood moisture contents ranged from 120 to 165%

and no bluestain fungi could be isolated from any of the stained regions.

Six further logs (four Corsican pine, two Scots pine) which had shown stain at the log ends in May 1988 were removed from the store in March 1990 and sawn into boards. The extent of stain was quite variable (16–80 cm from the log end) but, again, there was no evidence for any increase during storage. Moisture content determination revealed mean sapwood figures of 139% for the Scots pine and 154% for the Corsican pine, and isolation attempts failed to yield any cultures of bluestain fungi.

Development of wood-rotting fungi during water storage

From the outset, it was intended that careful selection should prevent logs with existing decay from being placed in the wet store. It was recognised, however, that there was a high likelihood that the ends of many logs would become infected by wood-rotting fungi such as *Heterobasidion annosum, Stereum sanguinolentum* and *Phlebia (Peniophora) gigantea* during the period between cutting and incorporation into the store. This was particularly likely, as the store was located in the middle of Thetford Forest where the air spora usually comprises a high proportion of *H. annosum* and *P. gigantea* spores (Rishbeth, 1959). Confirmation of such infection came when some logs in the store were examined in early March 1988, just before the sprinkler system was brought into operation. Discs were cut at intervals along the length of 15 logs (10 Scots pine, 5 Corsican pine) and radially-orientated oval columns of pale dry-looking wood, extending up to 12 cm from the log ends, were observed in the sapwood of all but three of them. Culturing from these pale areas yielded either *H. annosum* or *P. gigantea*. It was evident from this that a significant proportion of the logs entering the store were likely to have incipient infections by decay fungi, and there was a natural concern that these might develop to cause serious decay during subsequent water storage.

Appearance of decay fungi

The first external sign of decay occurred in autumn 1989, when fruit bodies of *H. annosum, P. gigantea* and *S. sanguinolentum* were observed on the ends of some logs (Plate 11). These were most conspicuous in the short bay at the extreme south-west of the stack (see Figure 2.1) which included logs that had been added to the stack during the previous May. No direct irrigation of the log ends on this side of the stack had been conducted at this time, although a ground sprinkler line was instituted shortly thereafter (see Chapter 2). In this bay it was estimated that about 25% of the logs had visible fruit bodies of decay fungi. Elsewhere on the southern side of the stack it was estimated that about 10% of the logs carried fruit bodies, while on the northern side of the stack, very few fruit bodies were observed. Overall, it was estimated that about 1% of the visible logs showed signs of decay fungi.

Following this, regular monitoring of the store was maintained. Moreover, with the progressive removal of material from the research bay, the opportunity arose for examination of logs within the interior of the store. Here, fruit bodies, almost exclusively of *H. annosum,* were found principally as brackets at the log ends but occasionally also in resupinate form on the bark. When the third batch of research logs was removed after 18 months storage, in February 1990, *H. annosum* was found on about 3% of the logs on the south-facing side of the bay and on about 1% of the logs on the north-facing side. Later on it was noticed that many of the fruit bodies were no longer fresh and, by mid-summer of that year, very few live fruit bodies could be found.

Assessment of logs carrying fruit bodies of decay fungi

In March 1990, the extent of decay was assessed in 10 pine logs bearing *H. annosum* fruit bodies. These logs were cross-cut at 0.5 m from the end of the log carrying the fruiting fungus and then at 1 m intervals. The basal 0.5 m length was split longitudinally and the extent of visual decay recorded. Samples were then incubated in polythene bags at 18°C to determine if the decay causing fungi were still viable and to confirm identification. Likewise, in October 1990, 10 logs, which had been marked as carrying fruit bodies the previous February, were removed and similarly sampled together with 10 additional logs which were showing fruit bodies at that time. In June 1991, 10 more logs which had also been marked in February were sectioned along with six logs identified as possibly suspect during routine dispatch from the store.

Table 4.4 Extent of decay in logs showing fruit bodies of *Heterobasidion annosum.*

Date logs removed from store	*Number of logs*	*Range of decay/ stain column lengths (m)*	*Mean length of decay column (m)*
March 1990[a]	10	0.15-0.80	0.57
October 1990[a]	10	0.20-0.95	0.55
October 1990	10	0.75-5.50	1.96
June 1991[a]	10	0.00-2.50	0.70
June 1991	6	0.60-2.80	1.80
Overall	46	0.00-5.50	1.01

[a] Logs marked as showing *H. annosum* fruit bodies in February 1990; further details in text.

The outcome of these assessments is shown in Table 4.4. The average length of the decay columns was just over 1 m but this varied considerably, with decay extending up to 5.5 m in one 7.2 m length log. In this case, *H. annosum* was observed fruiting on the side of the log as well as at the end and the decay was in the outer sapwood. More commonly it was found in the heartwood zone while the sapwood remained fresh and clean. In at least two logs, the decay of the heartwood was sufficiently advanced to suggest that, despite instructions on log selection, butt-rot had been present in the standing tree. As expected from the presence of the fruit bodies, incubation and isolation confirmed that *H. annosum* was the most important cause of the decay (Rishbeth, 1979). *P. gigantea* and *S. sanguinoletum* were recorded in a few logs.

It is difficult to extrapolate from data on a sample of the logs to the store as a whole, but it seems possible that between 0.1 and 0.2% of the wood volume suffered degrade as a result of the activity of decay fungi which entered the logs after cutting. The amount could probably have been reduced significantly if the ground line of sprinklers along the southern edge of the store had been introduced earlier.

Conclusions

The results of these studies show that the wet store was almost wholly successful in preventing fungal degrade over more than three years in a wide variety of species. An amalgamation of a substantial body of data for Corsican and Scots pine indicate that not more than 2% of the wood coming from the store showed any evidence of bluestain and that the equivalent figure for decay was probably a tenth of this. The experiments with beech and Sitka spruce provide valuable evidence on the satisfactory storage of these species. Useful data have also been obtained on Norway spruce, Japanese larch, Douglas fir, ash and sycamore, although with the last species some decay was encountered. More work would need to be done to establish the true position. Regardless of species, the water stored wood was found to saw more easily and accurately than freshly felled timber.

One of the most important results to emerge from the work is the strong evidence that good water storage can not only prevent bluestain from occurring but can also stop the development of existing stain. This was demonstrated, not only by quantifying the effect of storage on logs with known amounts of stain (as illustrated in Plate 9), but also through the fact that only a tiny proportion of isolations from stained wood yielded possible causal fungi. The evidence presented here is the more important because of suggestions that water storage under sprinklers might even accelerate the development of pre-existing stain (see Söderström, 1986).

With decay fungi the real threat comes from the fact that, unlike the bluestain fungi, basidiomycetes can develop in the heartwood, and this often remains relatively dry except at the log ends. Given the likelihood that most logs will be infected at the ends via basidiospores before they are introduced into the store, it suggests that even short periods of drying out caused by, for example, faulty sprinkling may have adverse consequences.

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Chapter 5

Non-decay fungi in water stored pine following sawmill conversion

Michael Powell and Rod Eaton

Introduction

Under normal conditions of storage, the sapwood of sawn timber is susceptible to infection by microfungi which cause blue-black staining of the wood and mould growth on the wood surface. Internal staining is due to the presence of pigmented fungal hyphae in the wood cell lumina which grow into adjacent cells via the pits or produce very fine hyphae which penetrate through the wood cell walls. These sapstaining fungi form numerous, minute, dark-coloured fruiting bodies on the wood surface, which along with the sporulating structures of the superficial mould fungi contribute to the overall defacement of the timber. The timber can also be colonised by basidiomycete decay fungi, which cover the surface with fine wefts of white to creamy-coloured mycelium often forming a network of strands associated with zones of softening and slight discoloration of the wood. Infection of softwoods, particularly pine, by these three groups of fungi is common in situations where the wood is not rapidly air dried, kiln dried or treated with anti-fungal chemicals.

The high initial moisture content of freshly felled timber which can be up to 160% and the high nutrient status of the wood, particularly the residual non-structural carbohydrates, are thought to contribute to its infection and subsequent disfigurement by microfungi. These ascomycete and deuteromycete fungi grow rapidly at optimum temperatures and during the warmer periods of the year are able to spread extensively through stored lumber causing internal disfigurement and surface defacement. Although it is generally accepted that decay and strength loss do not occur in wood infected by sapstain fungi and moulds, loss in the appearance grade of the converted timber has commercial significance.

Following the October 1987 storm and the need to protect a sudden glut of windblown pine logs from deterioration by fungi (Evans *et al.*, 1989), water storage under sprinklers was chosen as a simple yet effective option for the long-term conservation of 70 000 m^3 of timber. An experimental study, begun during June-August 1988, monitored the incidence of active sapstain fungi in logs stored under water sprinklers and found that less than 2% of all isolations taken from 12-month stored logs yielded viable cultures (Thomson *et al.*, 1990 and Chapter 4). Following on from this work it was decided to investigate the effect of prolonged water storage on the fungal defacement of converted timber derived from wet stored logs in order to compare defacement with freshly felled lumber. Logs of Scots and Corsican pine were placed in the wet store for 6 months. At the end of this period, logs which had been stored under sprinklers for approximately 4 years were removed along with the 6-month stored logs. The logs stored for 4 years were identified as pine and were selected randomly from the store. All the wet stored logs were then converted into boards at the same time and at the same sawmill as freshly felled logs.

Evaluation of sawn timber

All logs were sawn into identical-sized sapwood boards (100 x 10 x 1.5 cm). The board trial was set up at a sawmill near Salisbury, Wiltshire and was regularly monitored for a 14-week period during June–September 1992. Mean monthly temperature maxima and minima

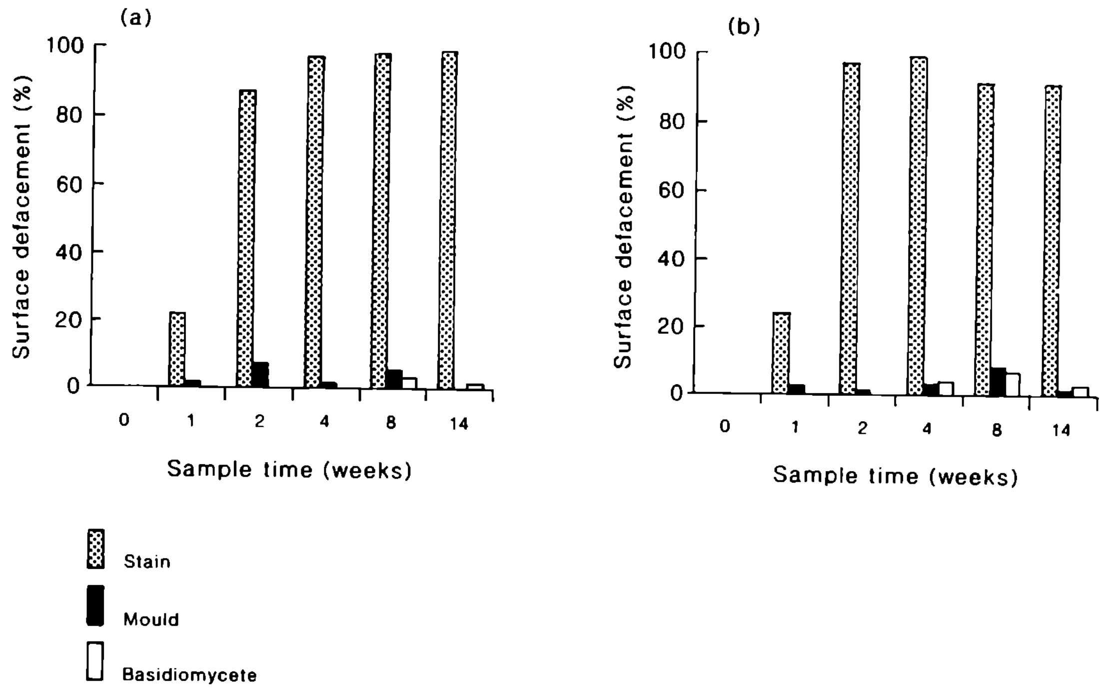

Figure 5.1 Mean fungal defacement scores of boards cut from freshly felled logs and exposed for 14 weeks: (a) Corsican pine, (b) Scots pine.

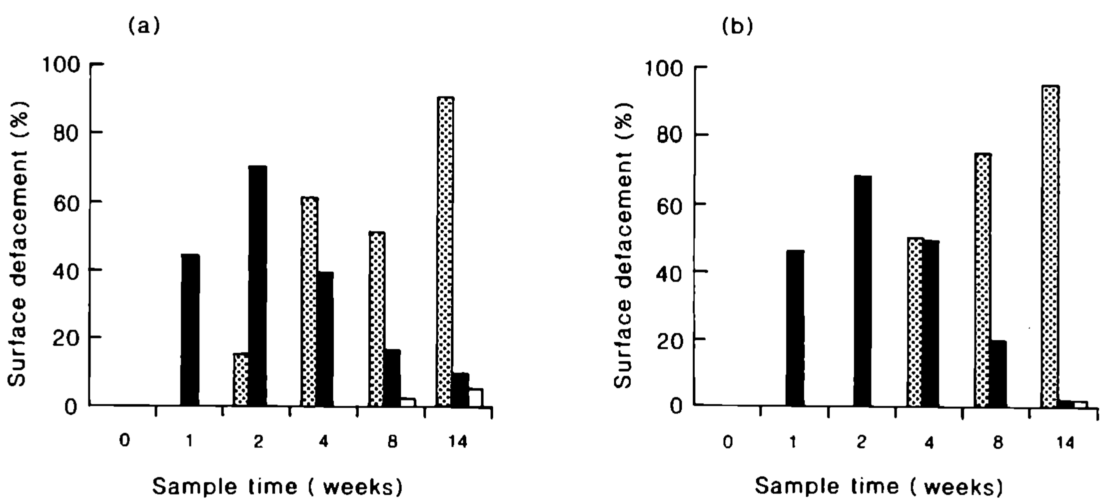

Figure 5.2 Mean fungal defacement scores of boards cut from 6-month wet stored logs and exposed for 14 weeks: (a) Corsican pine, (b) Scots pine.

were 17.9–22.5 and 10.4–13.0°C respectively, and mean monthly rainfall during this period ranged between 23.0 and 109.0 mm, June being a particularly dry month. Boards cut from the freshly felled, 6-month wet stored and *c.* 4-year wet stored logs were separately close-stacked. Each stack, composed of five columns of *c.* 70 boards, was erected 5 cm above the ground. Close-stacking rather than sticker-stacking was chosen to promote the biological hazard associated with fungal infestation by reducing the rate of moisture loss from the wood during the course of the trial.

Defacement of boards was measured by removing replicates at random from each of the three stacks, and scoring the per cent surface defacement by sapstain, mould and basidiomycete fungi. The stacks were sampled at 0, 1, 2, 4, 8 and 14 weeks but no boards were sampled from the outer columns or the upper or lower surfaces, where drying of the wood might have occurred. The moisture contents were determined by the oven dry weight method in all sampled boards which were then discarded.

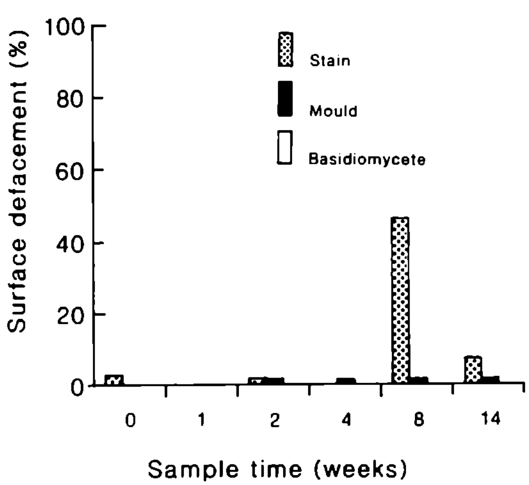

Figure 5.3 Mean fungal defacement scores of boards cut from *c.* 4-year wet stored pine logs and exposed for 14 weeks.

Despite the relatively dry weather at the start of the trial, boards from the freshly felled logs of Scots and Corsican pine were badly infected by sapstain fungi after only 2 weeks (Figure 5.1). The mean per cent defacement was 97% on Scots pine and 87% on Corsican pine. Sapstain defacement remained at *c.* 90% throughout the remainder of the 14-week trial on both species while mould and basidiomycete infection was slight, scoring less than 10% at each inspection. The mean moisture contents (MC) of the Scots pine boards ranged between 114 and 134% MC and between 104 and 153% MC in the Corsican pine.

Boards cut from logs which had been stored under sprinklers for 6 months showed a different pattern of defacement from the control boards (Figure 5.2). In both Scots and Corsican pine boards the type and extent of defacement was similar, producing mean scores of 68% and 70% mould defacement, respectively, after 2 weeks exposure in the board trial. During the remainder of the trial the incidence of mould defacement declined and was less than 10% after 14 weeks. In contrast, sapstain infection, which was only slight after 2 weeks, increased as the trial progressed so that by 14 weeks the mean values for defacement were 95% on Scots pine and 90% on Corsican pine. Basidiomycetes were hardly recorded at all on both species, the maximum mean score being 5% after 14 weeks on Corsican pine boards. Despite the similarity in the pattern of the fungal infestation of each wood species, the mean moisture content of Corsican pine (157–165% MC) was higher than Scots pine boards (113–145% MC).

The defacement scores derived from boards which were cut from pine logs stored under sprinklers for *c.* 4 years (Figure 5.3) were considerably lower than boards from freshly felled and 6-month wet stored logs. Defacement by sapstain, mould and basidiomycete fungi was minimal throughout the trial except at week 8 when a mean value of 46% sapstain defacement was recorded. Even after 14 weeks close-stacking, defacement was limited to only 7% by sapstainers and 1% by moulds. This dramatic difference in the susceptibility of freshly felled and 6-month wet stored wood compared with the resistance to fungal defacement found in long-term wet stored wood is illustrated in Plate 12. Indeed the boards which are shown represent samples removed from the stacks at week 8 when the incidence of fungal defacement in the 4-year wet stored logs was the highest. The relatively clean state of wood surfaces after 4 years of wet storage was therefore indicative of some form of biological control mechanism which inhibited the growth and sporulation of those fungi which would normally cause defacement. This inhibition of fungal activity on the boards was not attributed to the wood moisture contents which ranged from 81 to 135% MC and were similar to those of the other two treatments.

It is worth recording that at the end of the 14-week trial, the residual boards cut from the 4-year wet stored logs still present in the stack were in a sufficiently clean condition to be acceptable for pallet manufacture. All the boards from the other field trial stacks were rejected.

Absence of fungal defacement

In attempting to explain the reasons for the relative absence of fungal defacement on boards from long-term (4-year) wet stored logs, two factors were considered:

- the availability of non-structural carbohydrates
- the bacterial population in the wood.

Carbohydrate effects

It is known that carbohydrates and other extractives are leached from softwood logs under sprinklers, particularly during the first 6 months of storage (Liese and Peek, 1984; Webber, 1990). The pattern of fungal infestation which was recorded on boards from 6-month wet stored logs, i.e. the early flush of mould fungi followed by a progressive increase in sapstain defacement, may therefore reflect a difference in the nutrient status of the wood compared with the predominance of sapstain in freshly felled material. In addition, other authors working with pine roundwood have recorded losses of wood extractives such as turpentine, tall oil, rosins and fatty acids over short periods of water storage (Volkman, 1966) which may also account for differences in the pattern of fungal defacement in sawn wood.

In our study, preliminary analyses of carbohydrates in the expressed sap of long-term wet stored Corsican pine indicated that the concentration of available sugars was less than 20% of the sugar levels analysed from sap in freshly felled wood. This marked reduction in available nutrients in the sap may be due in part to leaching under water sprinklers, but may also result from assimilation by bacteria in the log during the course of prolonged storage. It is well known that water storage, particularly ponding of softwood logs, increases permeability and therefore the preservative treatability of the wood which has been used in the treatment of spruce (Dunleavy *et al.,* 1973). Bacterial degradation of bordered pits is primarily responsible for this (Dunleavy and McQuire, 1970), and in our investigations, attack of the torus and margo in bordered pits from Scots pine wet stored for 4 years was repeatedly observed. Examples of pit degradation by bacteria are shown in Plate 13.

The role of bacteria

In a preliminary study to enumerate the bacteria present in the expressed sap from a freshly felled Scots pine log and a pine log (probably Corsican pine) kept in the wet store for *c.* 4 years, it was found that the bacterial population in the water stored wood was significantly larger than in the fresh Scots pine (Clark, 1992). The difference in the bacterial counts ranged from 23 to 85 times more in the wet stored log compared with the freshly felled wood, although the method of enumeration did not take account of any obligate anaerobic bacteria which may have been present in the samples of expressed sap. Using non-selective microbial techniques, it was also noted that the highest concentrations of bacteria in the 4-year wet stored log were present in the outer sapwood zones adjacent to the bark and at the cut ends of the log. Storage of logs under sprinklers for periods of up to 4 years often results in separation of the bark from the sapwood. The outer sapwood is therefore more accessible to any invading bacteria carried in the water

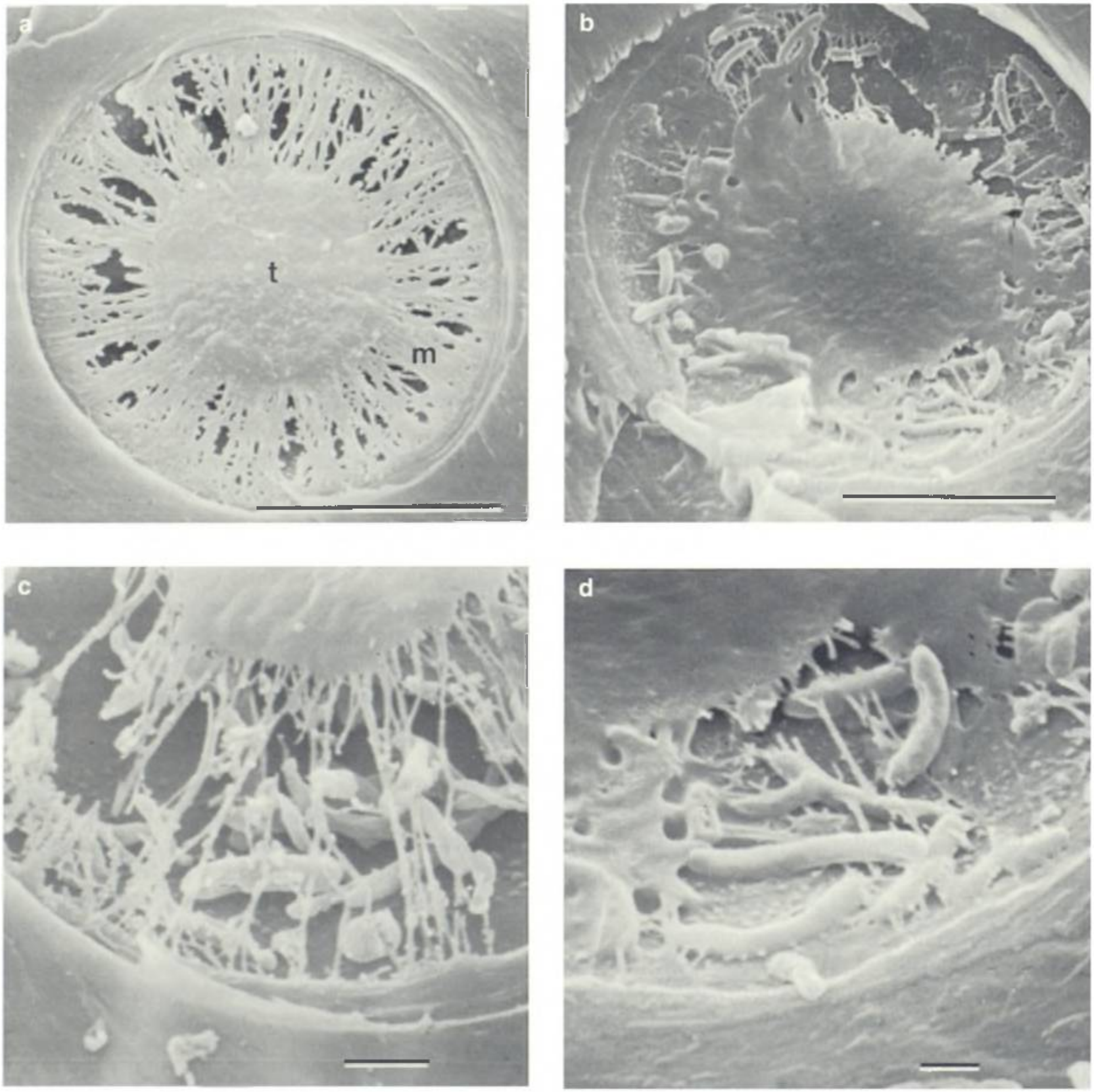

Plate 13 Scanning electron micrographs of bordered pits in softwood tracheids showing (a) intact pit from freshly felled Scots pine log and (b)-(d) bacterial degradation of the torus (t) and margo (m) in pits from a *c.* 4-year wet stored log. Bar lines for (a) and (b) are 10 µm, (c) and (d) are 1 µm. (VANESSA CLARK)

spray and additionally the enhanced level of aeration in this region will promote bacterial growth. This sometimes appears as a brightly coloured slime which can be found over the cut ends of logs and is presumably associated with the release of soluble leached nutrients from the wood. The slime can be pink-orange to purple in colour and is composed not only of bacteria but also fungi and other microorganisms all of which may contribute to the colour. The build up of slime on the surface of the wood undoubtedly provides a constant source of inoculum leading to repeated infection of logs in the store.

In addition to their potential for assimilating soluble nutrients and degrading pit structures in the wood, high numbers of bacteria may also exert inhibitory effects on the germination of fungal spores and the subsequent hyphal growth and sporulation of fungi on the surface of boards from wet store wood. Recent work by Benko (1988; 1989), Benko and Highley (1990), Bernier *et al.* (1986), Croan and Highley (1991) and Seifert *et al.* (1987) has shown that bacterial antagonism can affect the growth of sapstain fungi. Laboratory studies using culture media tend to demonstrate fungal inhibition by bacteria quite successfully, but sometimes this effect can be difficult to reproduce in wood in the laboratory and in artificially inoculated field specimens. In this study, agar plate assays using bacteria (*Chromobacterium* and *Vibrio* spp.) isolated from a pine log wet stored for 4 years produced hyphal inhibition of three species of the sapstain fungus *Leptographium,* which had been previously cultured from local softwoods (Cavell, 1992).

The possibility that bacteria present in wet stored logs can affect the susceptibility of the wood to sapstain, mould and basidiomycete defacement after conversion is not the only effect that bacteria may have on the disfigurement of sawn lumber. Hedley and Meder (1992) described brown staining of wood cut from water stored logs of radiata pine. The brown stain is a tannin-like substance which is produced from the breakdown of flavanoid glucosides by bacteria in the wood. Although brown staining of pine boards was noted occasionally in the present study, the levels of defacement were slight.

Conclusions

The relative absence of sapstain, mould and basidiomycete infestation on boards cut from long-term (4-year), wet stored logs may be due directly to the antagonistic behaviour of bacteria in the wood, to the depletion of soluble nutrients in the wood caused by continuous leaching and bacterial assimilation, or to a combination of both of these factors.

However, the pattern of early moulding followed by sapstain development on boards cut from the 6-month wet stored logs is more difficult to explain in terms of a bacterial effect. Although these boards were as badly defaced after 14 weeks as boards from freshly felled logs, the slower rate of infestation and the change in composition of the fungal flora from moulds to sapstain fungi might suggest that different responses by these fungi to available nutrients in the wood or competition between fungi occurs. Indeed, it has been shown that selected sapstain and mould fungi are inhibited to a similar degree by a mixed suspension of bacteria (Benko and Highley, 1990). This work indicates that neither sapstain nor mould fungi would be selectively advantaged or disadvantaged in the presence of bacteria.

It is clear that the length of time that logs are stored under sprinklers determines the susceptibility of converted lumber to fungal defacement and that in long-term storage the bacterial population in the wood can exert a significant effect. Over the short-term, this effect may be less pronounced and the parasitic/saprophytic behaviour of sapstain fungi and moulds in relation to the living or dead status of water-stored wood may assume greater importance. This aspect is currently receiving further attention.

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Chapter 6

Changes in the properties of timber during water storage

Keith Maun and Joan Webber

Introduction

In the wake of the severe gale in October 1987, which caused extensive damage to forest and woodland in the south-east of England (Grayson, 1989), the Forestry Commission set up a long-term water sprinkler system to store windblown timber. The bulk of the timber in the store comprised more than 70 000 m^3 of pine (Corsican and Scots), but a range of other softwood and hardwood species were also included because the store provided a unique opportunity to examine the effect of long-term water immersion on timber quality. For the purposes of scientific assessment, a special area of the wet store was carefully stacked to allow for the extraction of batches of logs at fixed time intervals. Most of these samples consisted of Corsican pine, Sitka spruce and beech, with small quantities of other softwoods and hardwoods also present.

Previous knowledge predicted that logs continuously sprayed with water over many months would suffer attack by bacteria, leading to changes in the porosity of the wood (Ellwood and Ecklund, 1959; Banks, 1970; Dunleavy and McQuire, 1970). However, the extent of this type of degrade and its effect on the strength of commonly grown British timbers such as Corsican pine and Sitka spruce was largely a matter of speculation. The Building Research Establishment (BRE) was therefore commissioned to assess the effect of water storage on timber quality over increasing time. The main objectives were twofold.

- To assess the extent of biological degrade, by measuring the porosity of timber sawn from water stored logs.
- To determine if the strength of the timber changed during prolonged water saturation and, in particular, to assess any changes in the yield of sawn battens meeting the requirements of structural grade timber.

Material under test

As already indicated in Chapter 4, batches of experimental logs consisted largely of Corsican pine, Sitka spruce and beech (Table 6.1). All the Corsican pine was drawn from windblown stock in Thetford Forest, whereas the Sitka spruce consisted of windblown trees from Grizedale and Kielder Forest. Windblown beech was collected from three forests - Donnelly (Suffolk), Thetford and the New Forest. Smaller batches of ash, sycamore, Scots pine, Norway spruce, Japanese larch and Douglas fir were obtained from a variety of locations (Table 6.1).

The main assessment focused on logs cut and removed from windblown forests and placed into the wet store no more than 2 weeks after felling; this corresponded to the commercially desirable time interval between harvesting and transfer into wet storage. Controls consisted of logs that had not been water stored, and these were mainly drawn from freshly felled material that had not been windblown. As a check of the comparability of windblown versus freshly felled logs, a small number of freshly felled logs were also added to the store.

All logs destined for evaluation at BRE were sawn through and through into 50 mm and 25 mm waney edge boards for softwood and hardwood respectively (Figure 6.1). The logs were sawn at a commercial mill with the

Table 6.1 Summary of test material.

Species	*Time in wet store (months)*	*Windblown* [a]	*Freshly felled* [a]
Major species			
Corsican pine	0 (control)		✔
	6	✔	
	12	✔	
	18	✔	✔
	24	✔	
	36	✔	
Sitka spruce	0 (control)		✔
	6	✔	
	12	✔	
	18	✔	✔
	36	✔	
Beech	0 (control)		✔
	12	✔	
	18	✔	✔
	36	✔	
Other species			
Scots pine	0 (control)		✔
	18	✔	
Norway spruce	0 (control)		✔
	18	✔	
Japanese larch	0 (control)		✔
	18		✔
Douglas fir	0 (control)		✔
	18		✔
Ash	0 (control)		✔
	18		✔
Sycamore	0 (control)		✔
	18		✔

[a] Windblown and freshly felled material was placed in the wet store 0-2 weeks after harvesting.

exception of some of the controls, which were converted at BRE. Two boards were then selected from each converted log for assessment (Figure 6.1). The first board having a minimum width of 100 mm, was sawn from the outside of the log; these boards are referred to as side boards. The second sample board was cut from the centre of the log and referred to as the centre board. All the waney edged softwood boards were then converted into 100 mm battens (Figure 6.1) and subsequently kiln dried to 15% moisture content. However, the hardwoods were not converted into battens; instead entire waney edged boards were kiln dried to 12% moisture content.

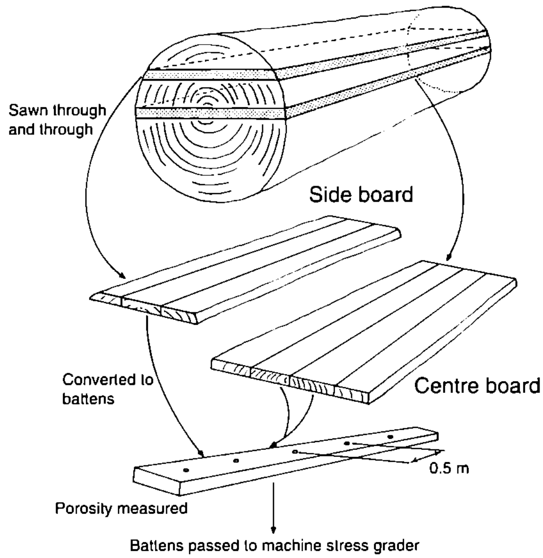

Figure 6.1 Conversion process from logs to sawn battens. Porosity measurements were taken along the length of each batten at fixed intervals indicated by •. Hardwood boards were not converted to battens or stress graded but porosity measurements were made along the length of the entire board.

Measuring changes in porosity

Biological degradation caused by bacterial action is known to occur during prolonged water immersion and results in increased porosity of wood. A relatively simple and, more importantly, a rapid method for measuring porosity was devised and used to collect over 20 000 porosity values. The system used a pressurised bell which was clamped and sealed against the wood surface being assessed (Figure 6.2). Compressed air was applied to the bell and a measure of porosity determined from the amount of air leakage. Further details of the method are given by Maun (1993).

Strength assessment

Successful marketing of timber sawn for construction use relies on the timber meeting structural classification grades of SC3 and above. Lower grades, SC2 and SC1, are not sufficiently strong to be used in construction,

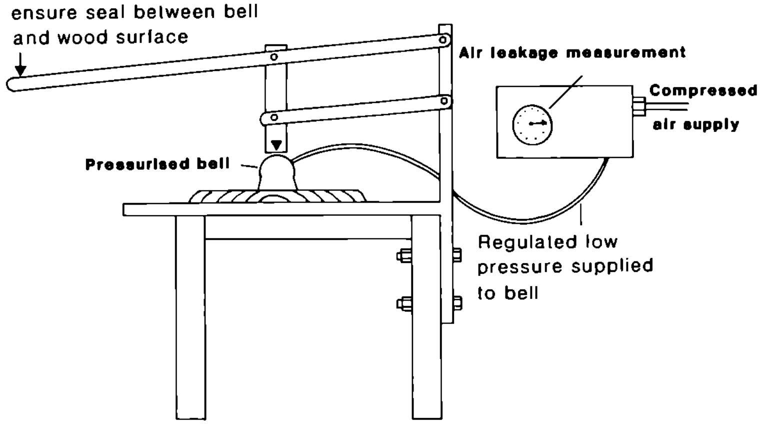

Figure 6.2 Apparatus employed to assess porosity using the air leakage method.

although the grades are recognised for other uses. In Britain sawn softwood is routinely graded by machine, using settings which test each batten for compliance with two strength classes at any one time. These are usually SC1 and SC3 or more occasionally SC2 and SC4, with SC3 and SC5 applied to intrinsically stronger timber species such as larch and Douglas fir.

To examine whether yields of construction grade timber (passes at SC3 or above) were reduced because of strength loss caused by water storage, the 2 m and 4 m length battens previously used for porosity tests were graded using a Cook-Bolender stress grading machine. In allocating strength class grades ranging from SC1 to SC5 to individual battens, this machine measures the load required to deflect battens a fixed amount at 10 mm intervals over a span of 900 mm along the length of each batten. The minimum deflection load along each batten can then be used to calculate the Modulus of Elasticity (E) which is a measure of stiffness and an indicator of strength.

Results of porosity assessments

Initially it was anticipated that the extent of air leakage, and hence porosity values, would be influenced by the grain orientation of the wood; this proved to be unfounded. However, there was considerable variation in the porosity of material sampled from the wet store. Despite this, a clear pattern emerged of increasing porosity over the three years of water storage (Figures 6.3 and 6.4). Data were analysed using Student's t-test to compare significance between material stored for different times and the controls. Particularly with the softwoods, increases in porosity were most striking in the side battens and differences were often apparent after only 6 months of storage.

Corsican pine

The porosity of water stored material was calculated against baseline values taken from the control logs. In general, the wood in the side battens was more porous than that of the centre battens (Figure 6.3(a)). Student's t-test indicated that the increase in porosity with 6 months storage was not significantly different from the freshly felled material but after 12 months of water storage, the porosity of both sides and centre boards had increased significantly ($p > 95\%$). There were also significant differences between the porosity of 12 and 24 month samples and 24 and 36 month samples ($p > 95\%$). Combining values from both edge and centre battens revealed an increase in mean porosity of more than 50% over the 36 month period of water storage, with over half of the increase occurring in the first 12 months of storage.

Sitka spruce

Porosity values derived from control samples of Sitka spruce indicated this species was at least 50% less permeable than Corsican pine before any water storage. The wood of the side battens had a slightly higher porosity than the centre battens but this was not statistically significant. However, after the first 6 months of water storage there was a 30% increase in the porosity of the side battens and this had doubled at the end of three years water storage (Figure 6.3(b)). At 12 and 18 months, the porosity of both the side and centre boards was significantly increased ($p > 95\%$) compared with the 6 month samples. There was also a significant difference between the porosity of 18 and 36 month samplings ($p > 95\%$). Combining porosity values for side and centre boards, the mean overall increase after 36 months of water storage was 53%, two-thirds of which occurred within the first 12 months. The pattern of change was similar to Corsican pine (Figure 6.3(a)) although the porosity of spruce remained four times lower than the pine at the final sampling.

Beech

Initially the porosity of the side boards was *c.* 25% greater than for the boards sawn from the centre of the logs, but after 12 months in the wet store the porosity of the centre boards had increased markedly (Figure 6.3(c)) and the porosity of both side and centre boards was significantly greater than the controls($p > 95\%$). After a further 6 months of storage, there was again a significant increase in porosity ($p > 95\%$) but mean values for side and centre boards were similar. In the last 18 months of storage, it was evident that the changes in porosity had slowed somewhat, although there were still significant differences between the data for 18 months and 36 months. At the end of three years of storage the increase in porosity for the combined side and centre boards was *c.* 70% but over half this increase occurred between 12 and 18 months.

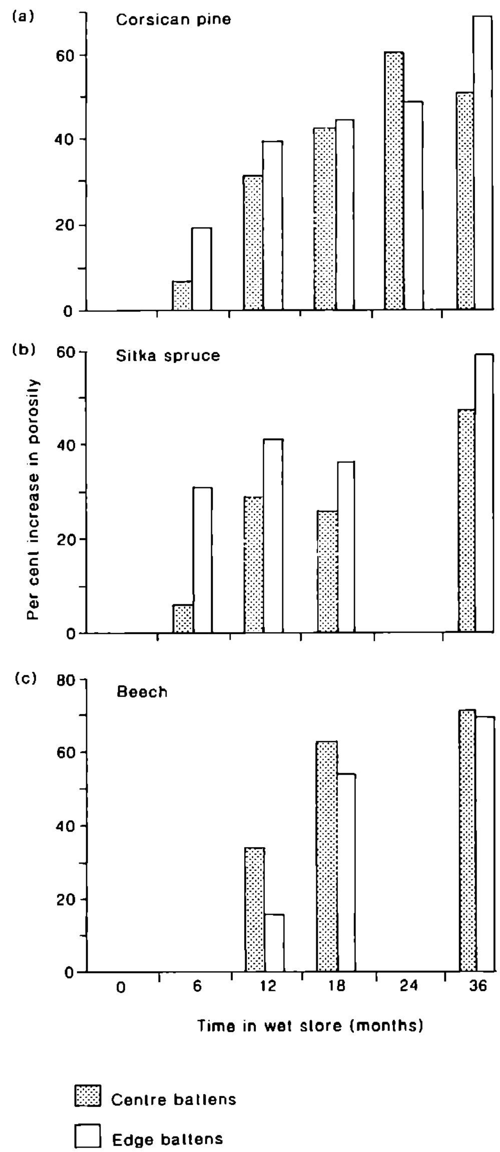

Figure 6.3 Changes in the porosity of timber over increasing periods of water storage: (a) Corsican pine, (b) Sitka spruce, (c) beech.

Other softwoods

Not surprisingly, the changes that occurred in Scots pine during storage mirrored the changes in Corsican pine. The porosity of the side and centre battens from control logs initially was similar but after 18 months in the store, side battens had a mean porosity three times greater than the centre battens (Figure 6.4). The increase in porosity of both the side and centre battens was significantly different from the control battens ($p > 95\%$) and overall there was an average increase of 36% for all battens of Scots pine sawn from water stored logs.

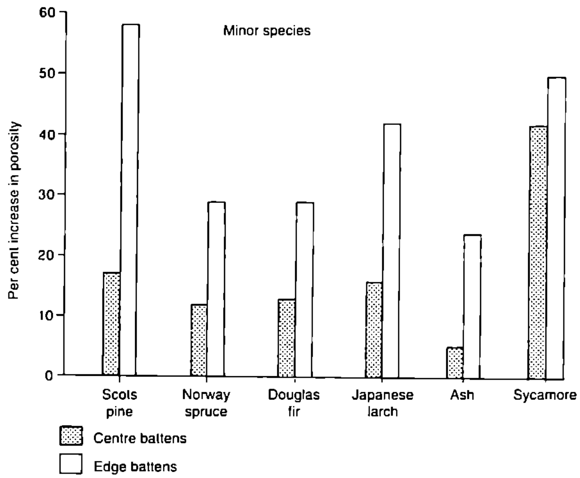

Figure 6.4 Changes in the porosity of a range of timbers after 18 months in the wet store.

Just as the two pine species were similar, the porosity of Norway spruce and Sitka spruce wood was also comparable both in the controls and after 18 months of storage. Overall the increases were 22% and 30% respectively, compared with an average increase in porosity of 40% for the pines. Student's *t*-test revealed both side and centre battens of Norway spruce were significantly more porous ($p > 95\%$) after 18 months of water storage (Figure 6.4).

The porosity of the side and centre battens of Japanese larch controls were almost identical, but after 18 months in the wet store the porosity of the side battens had increased by 42% and the centre battens by 16%. However, only in the side battens was the porosity found to be significantly increased compared with the controls ($p > 95\%$). Combining data from all the battens of Japanese larch, the average increase in porosity was 28% (significantly greater than the controls at ($p > 95\%$), and therefore in the same range as the increases for Sitka spruce and Norway spruce but somewhat lower than the pines.

For the final softwood species included for assessment, Douglas fir, the porosity of the control side battens was *c.* 25% more than the centre battens, but after 18 months of water storage the porosity of the side battens increased by 27% compared with an increase of 14% for the centre battens (Figure 6.4). Only the increase in the porosity of the side battens was significantly different from the controls ($p > 95\%$) and the 19% mean increase in porosity for all the wet stored Douglas fir battens did not differ significantly from the controls.

Other hardwoods

Sycamore responded to water storage in much the same way as beech (Figures 6.3(c) and 6.4), with significant increases in porosity of both side and centre boards ($p > 95\%$). In contrast, the changes in ash were much less; at the end of the 18 month storage period the porosity of ash centre boards had only increased by 5% which was not a significant change. Ash side boards, which came from the outer parts of the logs, were 24% more porous than the control side boards and although this was a significant change ($p > 95\%$) it was still only half that observed for beech and sycamore.

Freshly felled material

There were some small differences in porosity between freshly felled and windblown material (Table 6.2) after 18 months of water storage. However, the differences were only significant for the centre battens of Corsican pine ($p > 95\%$). When the data for both side and centre

Table 6.2 Comparison of the porosity of freshly felled and windblown Corsican pine and Sitka spruce after 18 months water storage.

Species	*Treatment* [a]	*Per cent increase in porosity*	
		Centre battens	*Side battens*
Corsican pine	Windblown	42.0	44.9
	Freshly felled	52.7	31.9
Sitka spruce	Windblown	25.6	36.1
	Freshly felled	17.6	46.2

[a] All logs aged for two weeks before placing in the wet store.

battens were combined, the change in porosity for both freshly felled and windblown material after 18 months in the wet store were almost identical for both Corsican pine and Sitka spruce. Therefore, the changes in porosity of windblown Corsican pine and Sitka spruce can be assumed to reflect what would happen to material not subject to windblow, but placed into water storage shortly after harvesting.

Results of strength assessments

Strength assessments were only carried out on the softwood species, as no machine grading settings are currently available for hardwoods. The tests revealed a higher than usual variability in the machine *E* values, which probably resulted from irregularities in batten thickness and the small sample sizes (see Table 6.3). Normally at least 200 battens would be used for each stress grading assessment but for the samples of wet stored material only 50-80 battens were available for each evaluation. For this reason, the results should be considered as indicative rather than absolute measurements. The tests also revealed that the mean machine *E* values were higher for the side battens than the centre battens in the controls. This is consistent with the centre battens containing weaker, faster grown juvenile wood, whereas the side battens comprise wood mainly from outside the juvenile core which tends to be slower grown and stronger.

Table 6.3 Strength assessment of major softwood species.

Species	*Time in wet store (months)*	*Mean E values (N mm^{-2}) ± SD*	*Per cent yields of stress graded battens*					
			SC3	*SC1*	*Rejects*	*SC4*	*SC2*	*Rejects*
Corsican pine	0	7700 ± 2600	95	2	3	83	14	7
	6	6800 ± 1900	89	8	3	79	18	3
	12	7100 ± 2600	84	7	9	73	18	9
	18	7300 ± 3200	92	5	3	75	22	3
	24	6500 ± 1500	95	3	2	79	19	2
	36	6900 ± 2100	89	8	3	73	24	3
Sitka spruce	0	7000 ± 2000	97	0	3	70	27	3
	6	6500 ± 1800	93	2	5	66	29	5
	12	6800 ± 2300	93	0	7	67	26	7
	18	6200 ± 1600	100	0	0	51	49	0
	36	6500 ± 1600	98	2	0	68	32	0

Table 6.4 Strength assessment of minor softwood species.

Species	*Time in wet store (months)*	*Mean E values (N mm^{-2}) ± SD*	*Per cent yields of stress graded battens*								
			SC3	*SC1*	*Rejects*	*SC4*	*SC2*	*Rejects*	*SC5*	*SC3*	*Rejects*
Norway spruce	0	7400 ± 1800	100	0	0	77	23	0			
	18	7200 ± 1400	97	3	0	87	13	0			
Scots pine	0	8400 ± 3200	85	13	2	79	19	2			
	18	7200 ± 1400	100	0	0	89	11	0			
Japanese larch	0	7100 ± 2000				49	10	41	10	90	0
	18	8600 ± 2200				78	5	17	27	69	5
Douglas fir	0	10200 ± 2000				96	4	0	74	26	0
	18	9400 ± 2200				90	9	1	58	40	2

Corsican pine

The general trend for E values indicated that water storage slightly reduced the strength of Corsican pine, but the pattern of strength loss was erratic (Table 6.3). There was a significant reduction in the mean E value after 6 months, which generally continued over the whole of the 36 months of water storage. However, only the mean E values of samples removed after 6, 24 and 36 months of storage were significantly different from the controls ($p > 95\%$).

The main factor causing the reduction in mean E values was the progressive loss of strength in the side battens. For these, there was a marked decrease in strength after 6 months which continued more slowly for a further 12 months before dropping markedly again after 24 months storage. This decrease correlated very strongly with the observed increase in porosity, having a correlation coefficient of 0.9.

However, this decline in strength was not reflected in the yields of structural grade timber. The percentage yields for SC3 and SC4 were high and compared very favourably with the commercial yields expected from pine. Chi-squared analysis applied to the number of battens passing SC4 and SC2 or being rejected indicated no difference between any of the samples of wet stored pine timber. This also applied to the proportion of battens grading to SC3 and SC1 or being rejected, except for the battens derived from logs stored for 12 months which were significantly different in yield ($p > 95\%$; Table 6.3).

Sitka spruce

As expected, the mean E values for Sitka spruce were lower than those for Corsican pine, reflecting the inherently weaker nature of spruce timber compared with pine. Just as with the pine, the E values suggested that water storage slightly reduced the strength of Sitka spruce, although only the mean E value of the 18 month water stored material was significantly reduced compared with the control (Table 6.4). The main factor causing the reduction in E values was the progressive loss of strength in the side battens although this change was not as marked as it was in the side battens of Corsican pine.

The yields of battens grading to SC3 and SC4 were very high, and chi-squared analysis did not reveal any significant changes when the control and water stored samples were compared. Therefore, although there was some decrease in the strength of Sitka spruce associated with water storage, it was not enough to compromise the yields of battens grading to the structural classification of SC3 or the more demanding SC4.

Other softwoods

The machine E values for the control Norway spruce were slightly higher than the control Sitka spruce material, but after 18 months in the wet store a similar decrease in strength had occurred (Table 6.4). However, the strength of the Norway spruce side battens was only reduced by about half the amount observed in the Sitka for the same storage period. Chi-squared tests did not reveal any difference in the yields of structural grade timber after water storage; indeed the yield of material meeting the requirement for SC4 were higher for Norway than Sitka spruce (Table 6.4).

The strength assessment of Scots pine was broadly in line with the results obtained with Corsican pine except that the consignment of Scots pine material was more variable. Water stored material showed a slight decline in strength but this did not reduce the structural yields of the sawn timber at all (Table 6.4).

Unfortunately, the results for the Japanese larch were inconclusive (Table 6.4). The machine E values obtained for the control material were very low, probably 30% lower than would normally be expected from larch. (This conclusion is based on machine E values obtained for larch in previous testing programmes carried out by the Timber Structures Section at BRE.) However, using an estimated mean E value of 10 400 N mm^{-2} derived from previous testing, it is likely there was about a 17% decrease in the mean E value for larch after 18 months of water storage. Despite this, the yields of structural grade timber achieved from the wet stored material were very similar to those expected from freshly felled material, so it is probable that, as for the other species, water storage did not compromise yields of construction grade timber.

As with the pine and spruce, water storage had some effect on the timber strength of Douglas fir (Table 6.4), with the strength of the side battens reduced more than that of battens cut from the centre of logs. This significant decline in the strength of side battens contributed to the overall decrease of 8% for all Douglas fir battens after 18 months of water storage, but this did not result in significantly reduced structural yields of sawn timber.

Freshly felled material

Mean machine E values for both Sitka spruce and Corsican pine were approximately 10% higher for the freshly felled material compared with the windblown material, after 18 months in the wet store. However, these differences were not significant. In addition, when the yields of battens attaining the minimum requirement for structural classification SC3 were statistically analysed, no significant differences were revealed. In general then, all the strength assessments indicated that windblown and freshly felled logs were likely to react to water storage in a similar way.

Conclusions

Prolonged water immersion markedly increased the porosity of Corsican pine and Sitka spruce; with both species it was a 50% increase by the end of three years of water storage. As the wood of Corsican pine is naturally much more permeable than Sitka (Anon., 1985) and over half of the increase in porosity occurred during the first 12 months, it suggests that pine should not be stored for more than 6–12 months if very porous timber is unacceptable for certain end markets. This particularly applies for joinery end uses which require paints or other surface finishes. However, it should also be considered that enhanced permeability will result in the increased uptake of preservative treatments, perhaps in excess of what is required for effective protection, thereby adding to the cost of treating against stain and decay. In contrast to pine, Sitka spruce may be stored for much longer, and the increased porosity may be advantageous in this otherwise impermeable species which can be difficult to treat successfully with preservatives (Dunleavy and McQuire, 1970). Indeed, it was only following three years in the wet store that the average porosity of Sitka spruce approached the level of porosity that would be expected in Scots pine and Corsican pine timber without any water storage (Maun, 1993).

Not surprisingly, the results for Norway spruce and Scots pine were broadly in line with those for Sitka spruce and Corsican pine respectively. Of all the softwoods assessed, the consignment of Douglas fir showed the smallest increases in porosity and, as with spruce, this increased porosity could improve the treatability of the species (Purslow and Redding, 1978).

Some of the hardwoods also showed sharp increases in permeability associated with water storage. With beech, the porosity had increased by 69% at the end of three years in the wet store and half of the increase occurred between 12 and 18 months. This suggests that water storage should only be considered for a maximum of 12 months if markedly enhanced permeability is undesirable. This consideration also applies to sycamore which after 18 months in the store showed a *c.* 45% increase in porosity and was also found to be suffering from attack by the decay fungus *Armillaria* which had penetrated into the wood extensively (Chapter 4). The response of these species contrasted with ash which showed only relatively small changes in porosity. This was not unexpected as, unlike beech and sycamore which are classified as permeable species (Anon., 1985), ash is a moderately resistant timber. It also indicates that ash could be water stored for two or even three years without major (> 50%) changes in porosity.

Apart from making stored timbers more permeable to paint and preservative treatments, increased porosity in the softwoods was strongly associated with reduced strength, indicated by the lower E values recorded during stress grading. But these decreases in strength were clearly not sufficient to reduce the proportion of battens that would normally be expected to conform to commercial structural classifications of SC3, SC4 and SC5. However, it does suggest that long-term water storage for up to seven years, which has been practised in some other parts of the world, should be viewed with some caution if critical strength reductions are to be avoided.

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Chapter 7

Comparative experiences of emergency water storage and considerations for the future

John Gibbs and Joan Webber

As will be clear from the preceding chapters, the water storage operation set up in Thetford Forest would probably not have been conducted so effectively without the benefit of earlier experiences abroad. It is therefore useful to consider the UK operation in relation to other emergency water storage programmes conducted in northern Europe and identify additional points that should be borne in mind when any similar schemes are contemplated in the future.

The first major use of water sprinkling to protect storm-damaged timber was 1967 when 45 000 m^3 of Norway spruce and 30 000 m^3 of beech was stored in Denmark for a period of up to 4 years (Dalgas *et al.*, 1975; Moltesen *et al.*, 1974; Moltesen, 1971; 1977). This initial experience proved invaluable when, in November 1972, a gale with winds of up to 200 km h^{-1} blew down 17.6 million m^3 of merchantable timber in north-west Germany. A swift decision to mount a major water storage operation was made and 1.3 million m^3 of conifer logs (predominantly Scots pine) were stored in a total of 93 sprinkling yards and 5 ponds. A desire to minimise transportation costs meant that some stores held as little as 8000 m^3 of wood. Subsequently 235 000 m^3 of conifer logs, mainly Norway spruce, were stored in Denmark after a gale on 24-25 November 1981 blew down 2.7 million m^3 of conifer timber (Tingleff, 1991).

Guidance based on all these operations (with the exception of the most recent operation in Denmark) is provided in a general review by Liese and Peek (1984). The relevance of many of the points made by these authors has been made clear, particularly in Chapters 2 and 4, but there are some aspects of water storage that merit further discussion in the light of the UK experience.

Wet store operation

Reliability of water supply and the quality of the run-off water have been key issues wherever water storage has been conducted. At Lynford, the flooded gravel pit which served as both source and sink, was ideal, containing as it did, a very large volume of water with relatively little biological diversity. Changes in colour and BOD that were recorded in the run-off water (Chapter 3) were consistent with results obtained elsewhere (Peek and Liese, 1974) and no concerns arose over the effects on the quality of the ground water or the nearby river. Careful construction of the log stack is also a significant part of ensuring water storage works effectively. Liese and Peek (1984) emphasise the importance of close-stacking and Tingleff (1991) refers to the problems of logs on the top of a stack forming 'eaves' and preventing water from reaching the logs below. The use of logs of the same length in any particular bay (as practised initially at Lynford) reduces this problem and, coupled with the use of careful stacking, ensures easy handling and compact storage.

For successful water storage it is essential to maintain a water saturated atmosphere around the logs at all times. European practice recommends the application of 40-50 mm of water per day, but usually applied only during the daytime and only in summer. Since no charge was levied for the water used at Lynford, it was possible to maintain irrigation with negligible cost penalties for 24 hours per day throughout the year. Moreover, given the fact that winter temperatures in the UK are often high enough to permit very extensive fungal growth, there were also good reasons for not switching off the system until it became fully iced up.

In its general design and layout, the sprinkler system at Lynford closely followed that adopted in other countries and this proved satisfactory. However, it was clear that more effort should have been developed to provide a moveable line of sprinklers on the southern edge of the stack throughout the process of stack construction.

Stain and decay in wet stored logs

Previous workers have laid much emphasis on the point that only top quality logs should go into the store. This is clearly desirable on the 'rubbish in, rubbish out' principle. However, there has been rather less clarity over the question of whether bluestain and decay already present in a log can continue to develop during water storage. In particular, there is uncertainty in the literature about the fate of pre-existing bluestain (Söderström, 1986). One of the most useful features of our work has been to establish that, with proper sprinkling, existing stain can be prevented from developing further (Chapter 4). This applies both to stain developing from log ends and that developing from the galleries of bark beetles such as *Tomicus piniperda*. Furthermore, once logs have been water stored for a lengthy time the timber actually appears to be more resistant to attack by bluestain fungi (see Chapter 5).

In contrast, dealing effectively with decay fungi required a somewhat different approach. Moltesen (1977) and Liese and Peek (1974) both stress that existing decay caused by *Heterobasidion annosum* and other basidiomycete fungi should be cut from the logs before storage and this is clearly a sound recommendation. This point has a special importance on the continent, where Fomes butt-rot, caused by *H. annosum,* is common in Norway spruce, but it does also apply in the UK. As noted in Chapter 4, pre-existing *H. annosum* was probably present in two of the 46 pine logs assessed for decay (Table 4.4), and these may well have come from Thetford Forest where butt-rot caused by this fungus is quite common in mature pine on some sites (Greig, 1995). Pre-existing decay was also suspected to have been present in some of the Sitka spruce logs.

A major problem related to the development of decay fungi, and of greater relevance to the UK situation, is the infection of log ends by basidiospores between the time of cutting and the time of insertion in the store. Any faults in the sprinkler system can be expected to allow these infections to develop and spread, particularly in the drier heartwood. In our experience, *H. annosum* was the most common cause of such decay, which was not surprising given the long history of disease caused by this fungus in Thetford Forest and the high spore counts known for the area (Rishbeth, 1959). However, given the similar frequency of spores of *Phlebia (Peniophora) gigantea* in Thetford (Rishbeth, 1959), this fungus was less abundant than might have been expected. Interestingly, and in contrast to the situation in both Germany (Liese and Peek, 1984) and Denmark (Tingleff, 1991), *Stereum sanguinolentum* was relatively rare. It should be recognised that, in the UK, basidiospores of decay fungi are likely to be present in the air at any time of year, and even the most rapid 'hot-logging' is unlikely to prevent infection. A total commitment to effective irrigation is the only solution.

Wood appearance and quality after storage

The presence of a bright orange stain in the outermost layers of the wood mentioned in Chapter 2 has frequently been observed in water stored material and was first described by Findlay (1959). Liese and Peek (1984) give less attention to the condition in pine than to an equivalent condition in spruce, where the coloration is attributed to tannins diffusing into the sapwood from the bark. Its development is said to depend on water temperature and time of storage although this appears to be largely a matter of conjecture. It is also well known that timber that is wet stored is intensively invaded by bacteria which selectively attack the border pits between tracheids, making the sapwood much more porous (see, for example, Ellwood and Ecklund, 1959). In addition, these bacteria produce organic acids which are responsible for the unpleasant odour often associated with water storage. As Chapter 6 shows, increases in porosity were marked, especially with the more permeable species stored at Lynford such as pine, beech and sycamore and could make the wood unacceptable for certain end uses which require paints or other surface finishes.

The increased porosity was also found to be associated with slight decreases in the strength of the softwood timber (Chapter 6), presumably as bacterial attack caused progressive weakening of the tracheid cell walls (Schmidt *et al.,* 1987). However, as most of these changes were confined to the outermost 'shell' of wood around each log, where the bacteria appeared to be most abundant, they are unlikely to have an impact on timber sawn for construction purposes. Timber destined for structural use is invariably sawn from the central cant of each log, and therefore will have suffered only minor exposure to the effects of bacterial degradation during water storage.

How does water storage work?

The mechanisms by which water storage prevents the development of stain and decay fungi are still far from understood. However, it is probable that it is the increase in bacterial populations and the creation of anaerobic conditions, rather than high moisture content *per se,* which is unfavourable for the growth of degrade fungi. Moltesen (1977) also referred to the beneficial effects of the formation of the 'mucous film' by micro-organisms, and Liese and Peek (1974) described the protective layer of brightly coloured slime fungi which can be observed on the cut ends of logs, and stated that this indicated that the logs were sound. Despite this, the nature of these slime fungi appears never to have been determined.

It is also worth noting that although moisture content is a useful measure of changes occurring in the wood over time, it is of little value when it comes to comparing the data from different studies because of the relationship between wood density and moisture content. A more comparable measure is the degree to which the wood is saturated with water, as this takes account of the varying density observed in wood from different species of tree or of different ages.

Costs of water storage

Table 7.1 gives details on the costs of the Lynford operation in comparison with the combined costs for many sites in north-west Germany (Liese and Peek, 1984) and one site in Denmark. This last was at Feldborg in Jutland where 18 000 m^3 of wood was stored after the 1981 gale (Tingleff, 1991). The various establishment and maintenance costs are expressed as a percentage of the average sale price achieved for the wet stored wood. Any comparisons drawn from this table must be tentative because of differences in the nature of the data. Thus with the accounting system employed in the Forestry Commission, some costs under maintenance include those used for the purchase of pump equipment (see Chapter 2) whereas in another system they would count as installation costs. Similarly it is almost certain that very different approaches to the question of overheads have been adopted in the various sets of figures. There is also the question of the final sale price that was achieved. A figure of £30 m^{-3} was achieved at Lynford but had a recession not developed at the end of the 1980s, the average price might have been nearer to £40 m^{-3} (see Chapter 2). Such a change would have a significant effect on the cost effectiveness of the water storage operation.

Despite these complications, it is noteworthy that the total cost of the German and Danish operations work out at 15% and 13% of the sale price, respectively, while the equivalent figure for Lynford is 35%. There is little doubt that this substantial difference is very largely accounted for in transport costs. It has already been noted that in the German experience the need to reduce transport was given a high priority and it seems likely that a similar approach was adopted in Denmark. A map in the report by Tingleff (1991) shows that there were three other storage sites within a 50 km radius of the Feldborg site. It therefore seems unlikely that much wood was transported to Feldborg over distances greater than 25 km. The contrast with the 85 km that separates Rendlesham from Lynford is striking. The conclusion from this must be that the option of using water storage should only be considered in extreme circumstances, but it can deliver value for money on those rare occassions.

Acceptability to the trade

With no previous experience of water storage in Britain, and with the unattractive appearance of water stored logs, it is not surprising that the first lots offered for sale were greeted with some suspicion. Although, as described in Chapter 2, these suspicions were largely allayed, there is a marked contrast between the situation in Britain and that existing in northern Europe where, with a long history of ponding, the trade was well prepared for sprinkler-treated logs. For the latter, the only point at issue seems to have been in respect of the extra weight of water stored logs and Liese and Peek (1984) record that some reductions in price were negotiated in relation to the extra costs incurred for transport.

As timber from the wet store was released into the market over a period of time, it was done alongside continuing supplies of freshly felled pine logs from Thetford Forest. Several purchases sought a mix of wet stored and fresh timber, but these appear to have been sawn and marketed together and were indistinguishable in most cases. The main factors ultimately influencing purchase of wet stored timber were:

- *Weight.* Haulage costs from the store to the mill were acknowledged to be significantly higher for wet stored compared with freshly felled timber.
- *Bark yield.* Bark has become a valuable by-product for purchasers in the UK. During loading a significant quantity of bark that had become loosened during storage tended to be lost.
- *Quality of chips.* Slab wood and off-cut chips have also become valuable by-products and some consumers viewed chips derived from wet stored logs with some suspicion, partly because of their dull colour, although there was no evidence of outright rejection.

Table 7.1 Comparison of various wet storage operations.

	Lynford wet store	*Many sites in north Germany*[a]	*One site in Denmark*[b]
Storage dates	1988-1992	1973-1977	1982-1986
Volume of wood in store (m^3)	63 340[c]	1 204 000	18 000
Species	Pine	Pine and spruce	Spruce
Sale price m^{-3}	£30	100 DM	396 Kr
Total cost of water storage operations m^{-3}	£10.4	14.6 DM	52 Kr
Cost of various operations (as % of sale price)			
Site preparation	1.2	2.0 (0.1-10.1)	6.2 (Site preparation and Installation of equipment combined)
Installation of equipment	1.0	2.9 (0.8-10.1)	
Log transport and stacking	19.6	7.2 (1.0-14.1)	4.9
Maintenance throughout life of store	8.7[d]	*c.* 2.5	2.0
Log dispatch	4.3	–	–
All activities	34.8	14.6	13.1

[a] Data from Liese and Peek (1984).
[b] Data from Tingleff (1991).
[c] Underbark.
[d] Cost of water not included (see text).

- *Preservative uptake.* Wet stored timber destined for the treated fencing market was recognised as consuming significantly more preservative because of the increased porosity.
- *Ease of sawing.* As noted previously, freshly sawn wet stored timber was acknowledged to be easier to saw than freshly felled material.

The first four of these factors undoubtedly resulted in wet stored timber being sold at a discount to fresh logs, and also being less sought after when adequate fresh supplies were available from elsewhere. Nevertheless, it was broadly accepted as marketable and the full volume in the wet store was sold without difficulty.

What species should be water stored?

Work in Europe has shown that satisfactory water storage can be conducted on Scots pine, Norway spruce and beech. Our experience at Lynford indicates that Corsican pine is just as good a candidate for storage as Scots pine and in consequence, given the right conditions, both these species can be recommended for any future water storage schemes. Our research confirms that beech can also be stored successfully, although the ability of much beech to remain alive after windblow, makes it doubtful if it is likely to be a necessary activity in this country. It should be noted that in Denmark, windblown beech is water stored only if it has been growing on clay soils on which the fallen trees often develop a blue iron-based stain (Moltesen, 1977). Acceptable results have also been obtained with Norway spruce, Japanese larch and Douglas fir among the conifers and ash among the hardwoods. The position with sycamore is somewhat uncertain: the discovery of *Armillaria* decay in the sapwood of some of the logs means that further studies on this species would need to be conducted before it could be recommended for storage.

The position of Sitka spruce is of special interest in view of the importance of this species to UK forestry. The results of the experimental storage operation were good, and no doubts should be entertained about the feasibility of water storage for this species. The necessity of so doing is a different matter, even following catastrophic gale damage. In Britain, Sitka spruce suffers much less from bluestain than does pine, although this situation might change if the bluestain-carrying bark beetle *Ips typographus* became established in this country. In addition, experience of windblown Sitka spruce in various parts of Britain provides evidence for the long-term survival of many blown trees and little indication that such trees are subject to decay or other degrade.

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Glossary

Scientific names and authorities of the main English names used in the text

Softwoods

Corsican pine	*Pinus nigra* var. *maritima* (Ait.) Melville
Douglas fir	*Pseudotsuga menziesii* (Mirb.) Fraco.
Larch, Japanese	*Larix kaempferi* (Lamb.) Carr.
Norway spruce	*Picea abies* (L.) Karst.
Scots pine	*Pinus sylvestris* L.
Sitka spruce	*Picea sitchensis* (Bong.) Carr.

Hardwoods

Ash	*Fraxinus excelsior* L.
Beech	*Fagus sylvatica* L.
Sycamore	*Acer pseudoplatanus* L.

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From time to time a major calamity such as violent storm or forest fire demands the rapid salvage of timber, which then has to be protected from deterioration and marketed in an orderly way. The dramatic windblow which occurred in England in 1987 and blew down 4 million m^3 of timber necessitated such a salvage operation. As part of the process, 70 000 m^3 of pine were placed in water storage using overhead sprinklers and successfully protected against attack from sapstain and decay fungi for up to four years. This Bulletin reports on the detailed investigation applied to all parts of the wet store operation including the construction and management of the store, the monitoring of water quality and the evaluation of timber quality throughout the period of storage.

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