Chapter (non-refereed)

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Forestry and water quality

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11.1 Introduction

Interpretation of the term 'water quality' varies with geographical location and the use to be made of the water. Different criteria will be applied by fishermen, water supply engineers and industrial plant operators, for instance. In this paper, we attempt to take a wide view of the term and we consider water quality as the chemistry, colour and sediment content of streams, rivers and lakes.

The impact of forestry on water quality can be seen as the result of two sets of interacting processes: those which are due to the growth of trees, as opposed to other vegetation types, and those due to forest management practices. Trees, as a result of their tall growth form, 'capture' more particulate and aerosol material from the atmosphere than low-growing vegetation types. Moisture losses through evapotranspiration are greater from forests than grassland, agricultural crops or moorland, especially at higher altitudes. The root systems of trees can create a network of macro-pores which act as pathways for rapid water movement to depth. The surface soil horizons developed below forests differ, both chemically and physically, from those formed under other vegetation types – this difference can influence water pathways and chemistry. Forestry management practices which can influence water quality include ploughing, drainage, application of fertilizers, use of pesticides, creation of forest roads, harvesting and timber extraction. Whether or not these practices are used, and, if used, the intensity of their use will vary with location and conditions. On the more fertile, better-drained soils of the lowlands, cultivation, drainage and fertilizer applications may not be required. Selective harvesting may be used in broadleaved woodlands, while clear-felling is normally used in coniferous forests. Herbicides may be needed to suppress competing vegetation on some sites but not on others.

In the lowland areas dominated by intensive agriculture, drainage waters from woodlands generally have lower contents of sediments and lower concentrations of nitrate, phosphate and calcium than streams draining agricultural land. This situation reflects the greater inputs of fertilizers and the more frequent ploughing of agricultural land. In this intensive agricultural zone, coniferous and broadleaved woodland is often seen as protecting water quality, limiting erosion, and preventing pollution by fertilizers or pesticides. In upland areas dominated by extensive sheep farming, forestry may represent the more intensive land use, particularly as ploughing, drainage and fertilizer additions may be needed to give satisfactory forest growth on the acid, poorly drained soils. Upland rivers and streams commonly have low contents of solutes, so that even a small change in solution chemistry, as a result of forest activities, may be significant.

In this paper, we consider the likely impact of the main forest management activities/stages on water quality and the link between forestry and the acidification of streams.

11.2 Site preparation

Afforestation in the uplands, particularly on soils grouped as stagnopodzols, stagnohumic gleys and peats (Avery 1980), generally involves ploughing and drainage. The ploughing (Thompson 1984) is designed to improve rooting conditions: it increases aeration and temperature, improves drainage, leads to increased rates of organic matter breakdown, and provides an elevated planting position. Ross and Malcolm (1982) studied the impact of ploughing on a peaty ferric stagnopodzol soil in south-east Scotland: the tilled soil had a lower bulk density, was better aerated, showed faster infiltration and had higher mean annual temperatures than untilled soil. The tilled soil also showed intimate mixing of the organic and mineral horizons to a depth of 60 cm. Drainage ditches, linked to the plough furrows, are intended to remove surface water rapidly (Thompson 1979). Drainage produces some disruption of soil horizons, exposes subsoil and drift material, and deposits subsoil material on the surface alongside the ditch. The combined results of the ploughing and drainage can produce changes in drainage water quality.

Robinson (1980) examined the changes in hydrology and water quality during site preparation in a catchment drained by the Coal Burn, a headwater tributary of the River Irthing. Although located just over the county border, in Northumberland, the site is typical of much of northern Cumbria. The vegetation was dominated by purple moor-grass (*Molinia caerulea*) on peats and stagnohumic gley soils and underlain by glacial till. Concentrations of suspended sediments in the stream increased as a result of the ploughing and drainage, peaking during and immediately after the operations, and then declining. Before site preparation began, sediment concentrations ranged from 1 mg l^{-1} to 28 mg l^{-1} with a mean of 3.6 mg l^{-1}. During drainage operations, concentrations reached a peak of 7720 mg l^{-1} and a mean of 207 mg l^{-1}. Most of the very high concentrations occurred towards the end of the operations, when link and cross drains were being dug and when a bucket drainer was used to widen part of the main channel. Seven years after drainage, the sediment concentrations ranged from 1 mg l^{-1} to 5 mg l^{-1} in low flows and up to 40 mg l^{-1} in floods; the discharge weighted mean was 15 mg l^{-1}. Burt, Donohoe and Vann (1983) reported a similar increase in sediment yields during forestry drainage operations at a site in the southern Pennines where the soils were peaty gleys, podzols and brown soils. The maximum sediment concentrations recorded were 5384 mg l^{-1}, and total sediment yields were large enough during a storm to pollute a local reservoir. At most sites, increased sediment levels seem to decline rapidly after ploughing and drainage, but Newson (1980) has shown that they can continue for at least 40 years in certain drift materials, due to erosion of drainage channels.

Robinson (1980) also reported increased solute concentrations of calcium (Ca), magnesium (Mg), nitrogen (N) and potassium (K) following drainage. There was also a change in the relative abundance of the four main cations, from Na>Ca>Mg>K before drainage, to Ca>Na>Mg>K after drainage. Two years after cultivation and drainage, solute concentrations were similar to pre-treatment levels. Robinson suggests that the changes in solute concentrations were probably due to the exposure of till in the drains. Drainage of peats can also produce increased concentrations of ammonium and nitrate, due to increased mineralization of organic nitrogen compounds.

The increased solute concentrations will have a very limited impact; they are not high enough to necessitate additional treatment of water supplies for public use, and downstream dilution would rapidly take place. They are also unlikely to affect freshwater biota directly. The increased sediment yield may be a greater problem. It can lead to pollution and sedimentation of adjacent small reservoirs and damage to fish spawning beds. Road building can also produce large increases in sediment yield, and caused a major pollution problem at the Cray Reservoir in south Wales (Stretton 1984).

The impact of site preparation on water quality can be reduced by the careful planning of drainage schemes and by minimizing cultivation. The drainage schemes used by the Forestry Commission today are very different from those used 30–40 years ago. Thus, the design of drainage schemes used at the sites referred to in these examples are unlikely to be used today: these sites can be seen as 'worst possible cases'. New approaches to cultivation and drainage are giving very encouraging results; at a study site near Llanbrynmair, in mid-Wales, the increase in sediment yields during ploughing and drainage were insignificant (M D Newson pers. comm.). Research is also continuing on the potential of techniques such as mole-drainage, and in Cumbria scarifiers and rippers are beginning to replace ploughs. The careful planning and siting of roads are also reducing their impact.

In lowland areas or on better-drained, more fertile soils, the amount of site preparation may be minimal. Ploughing and drainage may not be necessary and the planting will, therefore, have little or no impact on water quality. Similarly, restocking existing woodland or plantations generally involves little ground disturbance, although the cleaning of existing drains may have a short-lived impact on water quality.

11.3 Fertilizers

Fertilizers have been widely used in forestry on the less fertile soils and particularly, therefore, in the new forests planted on the acid soils of the uplands. Phosphorus has been, and still is, the most widely used fertilizer (Mayhead 1976); it is generally applied as rock phosphate and at rates of about 50 kg P ha^{-1}. As described by Voysey (see page 18), application may be at establishment or at pole stage, or both. Nitrogen, as prilled urea or ammonium nitrate, has been used on heather (*Calluna vulgaris*)-dominated sites planted with Sitka spruce (*Picea sitchensis*): rates of application are usually around 150 kg N ha^{-1}. However, tree species mixtures, as described by Brown and Dighton (see page 65), are becoming increasingly attractive for overcoming nitrogen deficiencies, particularly because of the high cost of nitrogen fertilizers. Controlling the competing heather is another option. Potassium, as potassium chloride, is used at the establishment phase on deep peats at rates of approximately 100 kg K ha^{-1}. Fertilizer applications at establishment are often (but not solely) by hand, while aerial application is now most common for additions at pole stage. If any of these fertilizers find their way into drainage waters, they will clearly have an impact on water quality.

Nutter (1979) has suggested that, on a world-wide basis, application of fertilizers to forests has little impact on water quality when proper safeguards are used, and in the absence of overland flows of water. The direct input of fertilizer to streams during aerial application is said to be often the sole reason for fertilization affecting streamwater quality. Both Nutter (1979) and Tamm *et al.* (1974) do, however, stress that care is needed when using readily leachable forms of nitrogen. Despite comments of this nature, there is considerable concern in the UK water industry about the possible impact of forest fertilization, particularly phosphorus, on the chemistry of otherwise unpolluted streams and rivers in the uplands (Youngman & Lack 1981). A small increase in phosphorus levels in these waters can lead to a large increase in biological production, as the biological populations in the streams, lakes and reservoirs are generally phosphorus limited. The water industry's main concern is with reservoirs, where a build-up of phosphorus, leading to algal blooms, would necessitate additional treatment.

Phosphate fertilizer has been used extensively in forests in north Cumbria, but only on a limited scale in other parts of the county. Potassium has been used fairly widely in north Cumbria but there has been little use of nitrogen fertilizers in any Cumbrian forests to date. To obtain data on the impact of forest fertilizers on water quality it is necessary to look beyond Cumbria. Ground rock phosphate was applied to the Coal Burn catchment from the air some nine weeks prior to planting. Before fertilization, PO_4-P concentrations in the drainage waters ranged from 0.01 mg l^{-1} to 0.06 mg l^{-1}, with a mean of 0.016 mg l^{-1} (Robinson 1980). Immediately after application, the concentrations rose to 0.27 mg l^{-1}, probably as a result of rock phosphate falling directly into the drainage channel. Between storms, phosphate levels remained at 0.25–0.35 mg l^{-1}, but reached 1.5 mg l^{-1} during storms. Concentrations increased again when drainage operations started, ranging between 0.7 mg l^{-1} and 2.2 mg l^{-1}, and again during drain cleaning. Fiedler and Richter (1981) reported a similar rapid response to aerial application of fertilizers: peak values of 2.6 mg $PO_4-P\ l^{-1}$ were recorded after heavy rain. In a lysimeter study in southern Scotland, Malcolm and Cuttle (1983) found that phosphorus losses began 24 weeks after hand application of fertilizer, and were continuing, with little apparent decline, some three years after application. Harriman (1978) also reported that phosphate was still being lost to streams some three and a half years after aerial application to pole-stage Sitka spruce: measured concentrations reached about 0.3 mg P l^{-1} shortly after fertilization and up to 0.1 mg l^{-1} three years later. He also found that nitrate levels doubled, to 0.4–0.5 mg N l^{-1}, after fertilizing with urea, declining to pre-treatment levels after about three years. The same study found that potassium concentrations declined to pre-treatment levels two years after applying potassium chloride.

It is clear from the above studies that fertilizers do find their way into drainage waters and may, in the case of phosphorus, influence water chemistry for up to three years. Although leaching of phosphorus occurs, there have as yet been no reported occurrences of algal blooms in reservoirs which could be directly linked to forest fertilization. Thus, it is likely that the worst fears of the water industry will not be realized. In many cases, the removal of phosphate by organisms in the stream channel and downstream dilution probably reduce concentrations to acceptable levels before they reach upland lakes or reservoirs. The biggest danger would seem to lie with small upland water supply reservoirs; however, careful management of phosphate fertilizer applications in these catchments can almost certainly overcome any potential problems.

Use of fertilizers is uncommon in forests and woodlands on the more fertile soils of the lowlands. Inputs of nitrogen, phosphorus and potassium to lowland waters from agriculture and sewage effluents will also be much greater than any possible contribution from forested land or woodland.

11.4 Herbicides and pesticides

Several of the more widely used pesticides are toxic substances which may have adverse effects on freshwater biota and, at higher levels, on human health. The chemicals can also produce an unpleasant taste in drinking water at levels much below those which would cause a risk to health. The European Community regulations covering drinking waters set a limit on total pesticide concentrations of 0.5 μg l^{-1} and for any individual pesticide of 0.1 μg l^{-1}. Pesticides are rarely used in Cumbrian forests, but they are used in other parts of Britain in response to specific pest outbreaks on conifers. Aerial application of pesticides would increase the risk of contamination of streams, as the chemicals can fall directly into surface waters.

Herbicides are used in Cumbria to suppress vegetation which is competing with young trees. They are applied from the ground as liquids using knapsack sprays or wick applicators, or as granules using pepperpot type applicators. The risk of contamination of watercourses is small, provided that published guidelines are followed (Sale, Tabbush & Lane 1983). In dry conditions, and with freely drained soils, most of the herbicide will be absorbed in the vegetation or soil. In wet conditions and poorly drained soils, surface flows could carry the chemicals into watercourses. It is suggested, therefore, that spraying be carried out in periods of dry, settled weather, particular care being taken in areas of poorly drained soils. In water catchment areas, it is suggested that, when using 2,4–D, the area treated at any one time may have to be restricted to allow for the effects of expected rain and surface runoff.

11.5 Harvesting

Clearfelling is the normal method of harvesting coniferous plantations in Britain. There have been many overseas studies of the impact of clearfelling on water quality, but none have been completed in Britain.

The impact of clearfelling is currently being investigated in Kershope Forest on the Bewcastle Fells (Pyatt *et al.* 1985; Adamson *et al.* 1987). The site lies at 225 m and is dominated by stagnohumic gley soils developed in clay-rich glacial till derived from the underlying Carboniferous rocks. The joint study, between the Institute of Terrestrial Ecology and the Forestry Commission, uses four two ha plots, three of which have now been felled. Each plot is isolated by deep drainage ditches and the drainage water from each is gauged using V-notch weirs. Drainage water is sampled at weekly intervals for chemical analysis. Data from this site show marked increases in the concentrations of nitrate, ammonium and potassium following felling (Figure 1), but a reduction in the concentration of most other solutes. Because of the large increases in water output following felling, the total outputs of most solutes increased, nitrate, ammonium and potassium showing the most dramatic rises. These changes in solute chemistry and solute outputs can be seen as a consequence of one or more of the modifications to the forest ecosystem which take place at felling.

Interception and transpiration are reduced as a result of canopy removal, leading to an increased flux of water through and out of the system. The removal of the canopy also reduces the 'capture' of particulate and gaseous material from the atmosphere. In the absence of ground vegetation, root uptake ceases following felling. Changes in microclimate at ground level may produce changes in decomposition rates, and the resultant release of elements from organic materials. The lop and top left on the site produce a sudden large input of material and a rapid release of some of the elements they contain. The increased nitrate and ammonium concentrations and fluxes probably result from the reduction in root uptake plus the increased rates of decomposition of needles already on the ground before felling.

Reductions in the concentrations of sulphate, chloride, and sodium will result from a combination of reduced 'capture' from the atmosphere plus dilution due to the increased throughput of water.

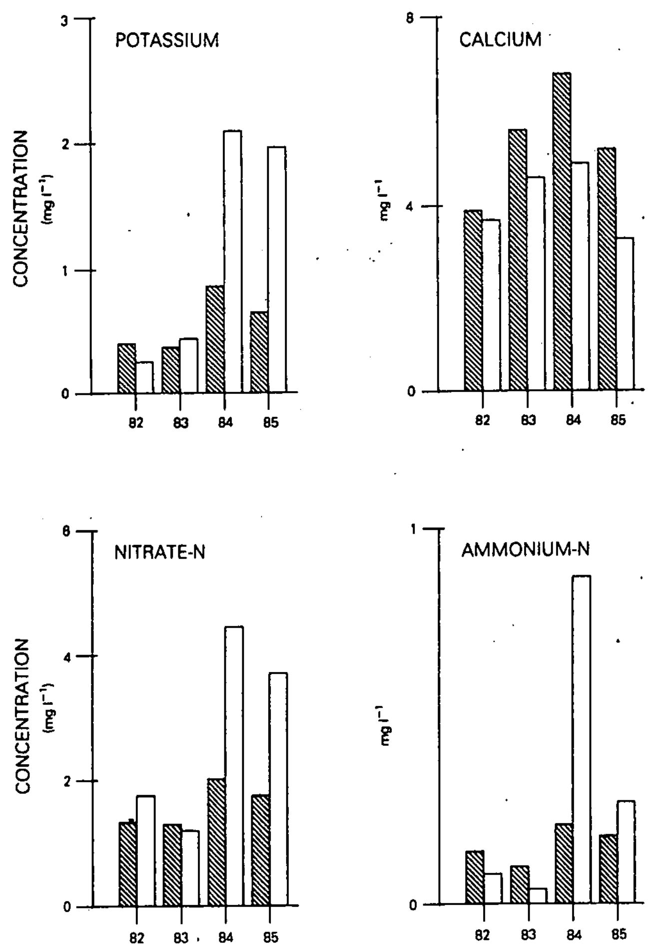

Figure 1. Annual mean concentration (mg l^{-1}) of four ions in drainage water, Kershope Forest, 1982–85. The hatched bars represent the drainage water from a control plot and the open bars an adjacent experimental plot. Felling took place on the experimental plot in 1983 (Adamson et al. *1987)*

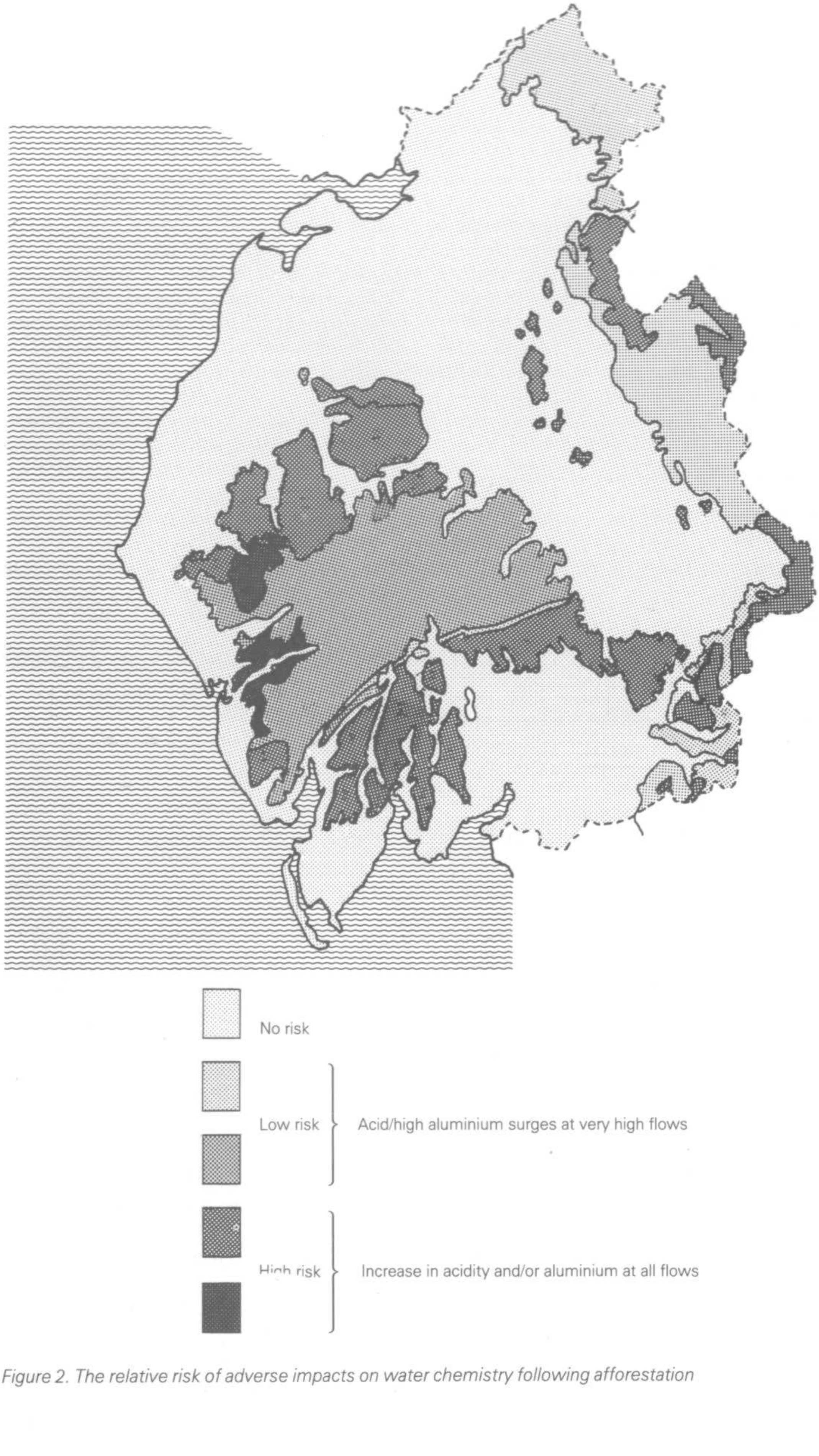

Figure 2. The relative risk of adverse impacts on water chemistry following afforestation

The increased solute concentrations are unlikely to have a significant effect on water supplies. Although maximum measured nitrate concentrations were close to the World Health Organisation's limits for drinking waters, these would be rapidly diluted downstream if felling coupes are not excessively large. Phosphate only leached into drainage waters during flood events, and again dilution would soon take place. Although the increased nutrient concentrations in drainage waters are unlikely to cause water treatment problems, they may lead to a undesirable increase in biological production immediately downstream of the felling.

11.6 Forestry and acid, high-aluminium waters

In recent years there has been much debate on the significance of atmospherically transported industrial pollutants. These pollutants have been linked to increased stream acidity and leaching of aluminium into streams (Underwood, Donald & Stoner 1987). These findings have, in turn, been linked to changes in the invertebrate populations of streams and reductions in fish populations (Crawshaw 1986). Several studies, from various parts of Britain, suggest that coniferous plantations can exacerbate the problem. Harriman and Morrison (1982), Stoner, Gee and Wade (1984), Reynolds *et al.* (1986) and Bull and Hall (1986) found higher acidity and greater concentrations of aluminium in streams draining established coniferous forest, than in adjacent streams draining unplanted moorland, on similar soils and geology. The apparent link between afforestation and increased acidity and aluminium concentrations is not found at all upland sites. It is most marked where acid soils overlie massive, base-poor bedrock. Here, acidity and aluminium concentrations are greater in forest streams at all levels of flow. The difference between forest and moorland streams will, however, be greatest during high stream flows. Where acid soils overlie non-acid drift and/or bedrock, there is little difference at low flows between forest and moorland streams. In these conditions, water which has been in contact with the neutralizing drift or bedrock predominates. Only during floods will acid water penetrate downstream from the forest, because a significant proportion of the streamwater will have passed into the stream without making contact with the drift or bedrock.

Figure 2 combines information on the occurrence of acid soils in Cumbria with a ranking of the relative buffering or neutralizing capacity of bedrock, in an attempt to identify those areas where afforestation may be expected to have adverse effects on streamwater chemistry. The areas dominated by acid soils are taken from the 1:250 000 scale soil map of northern England (Jarvis *et al.* 1984). The soil associations, and soil types, grouped as acid are Winterhill (peats), Wilcocks (stagnohumic gley soils), Anglezarke and Crannymoor (humo-ferric podzols), and Skiddaw (humic rankers). All these soils are naturally acid, and the podzols and stagnohumic gley soils have exchange complexes dominated by aluminium.

The acid soil areas are subdivided into four classes on the basis of the buffering capacity of the underlying bedrock, using a grouping of rock types proposed by Kinneburgh and Edmunds (1984) (Table 1). These authors classified the map units on the 1:635 000 scale geology maps of the UK into four classes according to the sensitivity of groundwaters to acidification. This classification can be used as an index of the buffering capacity of the various rock types. Rocks with groundwaters most susceptible to acidification (class 1) will have the lowest buffering capacity; those with waters not at risk to acidification (class 5) will have the highest

Table 1. Categories adopted for classification of the solid geology map (1:625 000) of the UK, according to sensitivity to acidification (Kinneburgh & Edmunds 1984)

Category	Buffer capacity and/or impact on groundwaters	Rock type
1	Most areas susceptible to acidification, little or no buffer capacity, except where significant glacial drift	Granite and acid igneous rock, most metasediments, grits, quartz sandstones and decalcified sandstones, some Quaternary sands/drift
2	Many areas could be susceptible to acidification. Some buffer capacity due to traces of carbonate and mineral veining	Intermediate igneous rocks, metasediments free of carbonates, impure sandstones and shales, coal measure
3	Little general likelihood of acid susceptibility, except very locally	Basic and ultrabasic igneous rocks, calcareous sandstones, most drift and beach deposits, mudstones and marlstones
4	No likelihood of susceptibility. Infinite buffering capacity	Limestones, chalk, domomitic limestones and sediments

buffering capacity. A study by Adamson and Benefield (1987) in the Lake District clearly indicates the impact of variations in bedrock on streamwater chemistry (Table 2). Given similar vegetation and land use, streams draining areas underlain by Borrowdale Volcanic Group rocks were significantly less acid than streams draining areas underlain by Ennerdale granophyre. This result reflects the greater buffering capacity of the volcanic rocks.

Table 2. Mean annual pHs and calcium contents of headwater streams on three rock types in the Lake District (Adamson & Benefield 1987)

Rock type	pH	Ca (mg l^{-1})
Ennerdale Granophyre	5.1–6.0	0.6–1.1
Skiddaw Group	6.4–6.7	1.8–2.7
Borrowdale Volcanic Group	6.7–7.2	2.5–6.7

In areas where acid soils overlie rocks with low buffering capacity, Kinneburgh and Edmunds' (1984) classes 1 or 2 (labelled 1 and 2 on Figure 1), afforestation will probably produce an increase in acidity and/or aluminium concentrations at all flow levels. It must be stressed, however, that this is a very general assessment. Small, local variations in soils and bedrock can have a major influence, and any impact assessment on a specific catchment will require more detailed information. Afforestation of areas in which acid soils overlie rocks with a high buffering capacity (labelled 3 and 4 on Figure 2) can lead to surges of acid, high-aluminium waters at very high flows. This soil/rock combination occurs in the Bewcastle Fells, the Pennines, the Mallerstang-Baugh Fells area and the central Lake District fells. Data from our Kershope Forest study site provide an example. The waters draining from the upper horizons of the stagnohumic gley soils are very acid, and the E horizon waters also have a mean annual aluminium concentration of 1.5 mg l^{-1}. Drainage waters from the subsoil, drift and bedrock are much less acid and contain very low levels of aluminium. At low or average flows, the streamwater is buffered by the inputs from the drift and bedrock, but at high flows acid surges can reach up to one km downstream as the proportion of water derived from the upper soil horizons increases.

The causes of the increased acidity and aluminium concentrations in the forest streams are still unclear. The increased interception and transpiration of water by the forest, compared with moorland or grassland, will concentrate the solutes. There is greater deposition of pollutants on to forest canopies than on to grassy or moorland vegetation; this fact may be particularly important as occult precipitation (from mist and fog) contains higher concentrations of solutes (pollutant and non-pollutant) than rainfall (Lovett, Reiners & Olson 1982). The ploughing and drainage carried out at forest establishment will increase the amount of water reaching streams from the acid, upper soil horizons. The water is transferred to the stream more quickly, with less opportunity, therefore, for buffering. The growth of the forest also leads to the development of a very acid forest floor which gives rise to acid, near-surface flow. All these processes interact to influence drainage water acidity, although it is usual in forests planted today to leave riverside zones unplanted or, if planted, to use broadleaved species. The relative importance of the different processes producing acidification and high aluminium concentrations will vary from site to site. A series of studies is now in progress in Britain to assess their importance on a range of soils and bedrocks, and to investigate possible ameliorative forest management options.

11.7 Conclusion

Commercial forestry, particularly in the uplands, has a considerable potential for influencing water quality. However, guidelines exist to prevent catastrophic damage to streams. Continuing research is identifying the role forests play in the acidification of streams.

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