Study of the Potential Impacts on Water Resources of Proposed Afforestation

Ian R. Calder, Ian Reid, Tom Nisbet, Adrian Armstrong, Julian C. Green & Geoff Parkin.

November 2002

Study of the Potential Impacts on Water Resources of Proposed Afforestation

Department for Environment, Food and Rural Affairs
Contracts CWO 633-I and CWO 633-II

Trees and Drought Project on Lowland England – TaDPoLE

Ian R. Calder[1], Ian Reid[2], Tom Nisbet[3], Adrian Armstrong[4],
Julian C. Green[2] & Geoff Parkin[1].

1 Centre for Land Use and Water Resources Research, Newcastle University.
2 Department of Geography, Loughborough University.
3 Forestry Commission Research Agency.
4 ADAS.

The authors of this report are employed by Loughborough University, Newcastle University, the Forestry Commission and ADAS. The work reported herein was carried out under Contracts CWO 633-I and CWO 633-II placed with Loughborough University on 19/11/97 and 1/4/00 respectively by the Secretary of State for the Environment Transport and the Regions. Any views expressed are not necessarily those of the Secretary of State for Environment, Food and Rural Affairs.

Executive Summary

The British Isles constitute one of the least wooded areas of Europe. This is the result of successive periods of deforestation. These began in earnest with the arrival of Neolithic cultures around 7000 B.P. and continued through the historical period, as exemplified by the exploitation of wood for pig iron production and bark for tanning in the 16th and 17th centuries A.D., and the expansion of agriculture during the Agrarian Revolution and increase in ship building in preparation for the Napoleonic conflict in the 18th century (Simmons, 1989). England has been particularly denuded of trees, so that, despite the efforts of agencies such as the Forestry Commission and the Woodland Trust over the last 50 years, only 8.4% of the national territory could be mapped as woodland at the close of the 20th century (Smith, 2002). In view of the benefits to amenity and biodiversity and in the context of European Commission directives on 'set-aside' (EEC, 1992) whereby farmers receive payments for taking agricultural land out of production, the UK Government's White Paper on Rural England (HMSO, 1995) proposed a doubling of the area of woodland within England by the year 2045.

Whilst acknowledging the multitude of benefits that would accrue to an increase in woodland, questions were raised concerning the possible impacts on water resources of such a large change in land use (House of Commons Environment Committee, 1996). Initially these questions were directed at the impacts on water quantity. It was believed that, although lowland forests might reduce groundwater recharge, they would help to protect water quality by reducing inputs and, therefore, leaching of fertilisers and pesticides. More recently, this latter assumption has also been questioned.

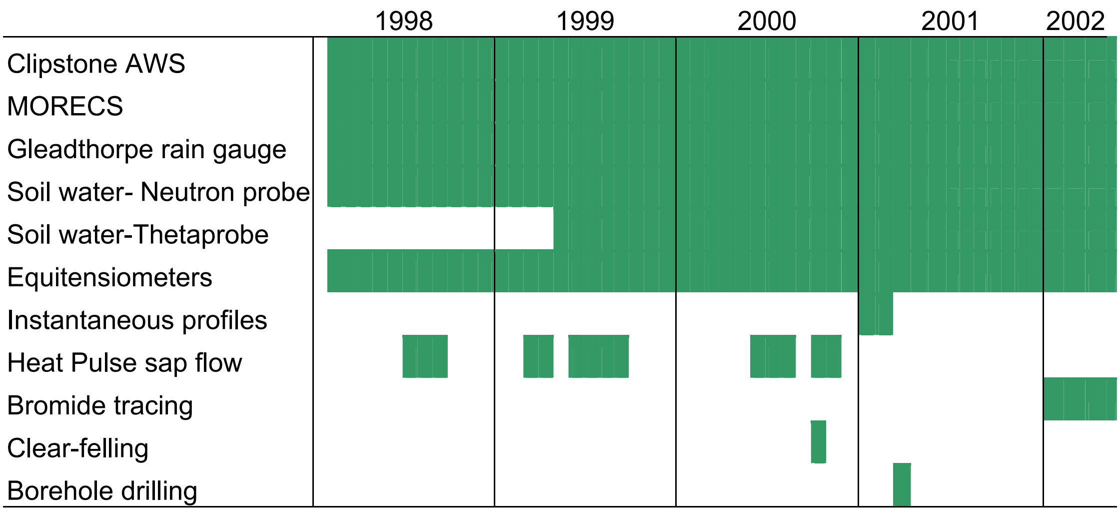
The Trees and Drought Project on Lowland England (TaDPoLE) arose initially as a desk-based scoping study carried out for the Department of the Environment in association with the Environment Agency and the Forestry Commission to assess the likely range of impacts on water quantity. As part of this study, the GIS-based HYLUC (HYdrological Land Use Change) soil water model was used with previously published values of model parameters in order to assess the potential impact of forest expansion on groundwater recharge of the second most important aquifer in England - the Triassic Sherwood Sandstone. This initial scoping study predicted that the average reduction in annual recharge in the Greenwood Community Forest (Nottinghamshire) as a result of a projected three-fold increase in woodland cover from 9 to 27% would be 11%. This implied serious consequences for an aquifer which is already fully exploited and where future abstractions are being restricted.

In view of these implications, the Department of the Environment, Transport & the Regions, supported by the Environment Agency and the Forestry Commission, commissioned a field study of the water use of pine forest, oak woodland, grassland and (later) heath at Clipstone Forest (part of the Greenwood Community Forest) in order to test the initial model predictions, to calibrate the model locally, and to derive revised predictions of the impact of different vegetation types on the recharge of the Sherwood Sandstone aquifer. The effect of pine, oak and grass on drainage water

quality was also to be investigated. The work was carried out in close collaboration with a number of different stakeholders through meetings of a Stakeholders' Advisory Group. Part way through this study, the commissioning authority, which had then become the Department for Environment, Food and Rural Affairs, together with the Forestry Commission, funded additional studies on the water quality implications of one of the vegetation types – Corsican pine woodland.

Four field sites – one for each targeted land use – were instrumented in February 1998 and data were collected up to April 2002. In all cases, a soil and rock moisture record was established using two independent methods: the profile to 9 m below surface was measured fortnightly using a neutron probe; while the profile to 1.5 m was logged quasi-continuously using capacitance probes to determine both moisture content and moisture energetics. These records were complemented by local and near-local measurements of rainfall and other meteorological variables that allowed the calculation of potential evaporation. Regional estimates of potential evaporation were also obtained from the Meteorological Office.

Field data collection programme for grass ley, heath, oak and Corsican pine woodlands at Clipstone Forest, Nottinghamshire, England.



AWS = automatic weather station. MORECS = Meteorological Office Rainfall and Evaporation Calculation System.

On a more occasional basis, the relation between soil moisture content and energetics (the 'instantaneous profile') was established at each site following flood irrigation, while soil wetting-front dynamics were confirmed by introducing a bromide tracer and analysing for the tracer in water samples taken subsequently from a number of horizons in the soil profile. Also occasionally, sap flow velocities were measured in specimens of oak and Corsican pine using the heat pulse (or compensation) method in order to estimate rates of transpiration. Soil water quality measurements were established on samples collected at intervals throughout the four-year programme using shallow tensionless lysimeters under grass, oak and Corsican pine, while, in the spring of 2001, pore-water quality was measured on samples extracted from bore-holes drilled to 36 m under Corsican pine.

Estimates of recharge, based now on detailed measurements of soil moisture change recorded by both neutron and capacitance measurement methods and on the locally calibrated HYLUC model, broadly support the rank order of the scoping study recharge predictions – grassland > heath > oak woodland > pine forest. However, they indicate that recharge under grassland and pine forest had been overestimated, while that under oak woodland had been underestimated. The four-year observation period covered by this study (1998-2002) was endowed with higher than average rainfall. Under such conditions, estimates of average annual recharge derived with the HYLUC model are 201 mm under grassland, 189 mm under heathland, 136 mm under oak woodland and 48 mm and 63 mm under Corsican pine woodland. Although the ranking remains the same, an alternative method of calculating recharge gave smaller values of 140 $\pm$ 18 under grassland, 120 $\pm$ 14 under oak woodland and 69 $\pm$ 12 mm under Corsican pine woodland. Expressed as a percentage of rainfall, the HYLUC estimates of recharge are 25% for grass, 23% for heath, 17% for oak woodland and 6 and 8% for Corsican pine woodland. Using the same model for a 32.5-year period (1969-2002) that includes a number of significant droughts, calculated values of average annual recharge under each land-use are understandably lower, though, again, the rank order remains.

With some important exceptions, studies in a number of locations and environments worldwide have concluded that evaporation from forests is higher, reducing groundwater recharge when compared with shorter vegetation such as grass and heath. This can largely be explained by just two processes: increased transpiration in dry periods because of deeper rooting, permitting greater access to soil water reserves; and increased interception losses in wet conditions. Increased interception from forest is brought about by enhanced rates of heat and water vapour exchange from the tall, aerodynamically rough surfaces of the woodland when the canopy is wet. Over an annual cycle, evergreen coniferous species such as pine exhibit higher interception losses than deciduous species such as oak, which drop their leaves in winter. Long-term estimates of the ratio of interception loss to rainfall derived with the HYLUC soil moisture model indicate a value of 44% for pine. Although higher than most published values, it lies within a range established by recent measurements on comparable stands of conifers elsewhere in the UK and in Denmark. The long-term value for oak woodland at Clipstone is 23%, while those of each year of the four-year period of field observations range narrowly between 21 and 26%. Allowing for experimental error, these are relatively close to values recently reported for direct measurements on stands of oak that have been made by the Forestry Commission at Alice Holt, Grizedale and Savernake.

In addition to the soil moisture and HYLUC-based studies referred to above, other methods have been investigated as an alternative means of determining and confirming evaporation and recharge rates. A study of transpiration from the woodlands - oak and pine – using sap flow heat pulse methods was carried out. However, uncertainties regarding calibration of the probes remain unresolved and this has so far prevented the calculation of transpiration rates on a plot basis using this method. In lieu of this, arrays of continuously recording capacitance probes have provided estimates of short-term changes in profile soil moisture on rainless days and these have been used successfully to corroborate the values of the transpiration parameters optimised by the HYLUC model for the growing season. The nature of the soil water regime at Clipstone, where annual recharge rates may be only a small fraction of the annual rainfall, especially under Corsican pine, has presented unforeseen difficulties in the use of a numerical, finite-difference model (SHELUC – Système Hydrologique Européan Land Use Change) to calculate long term recharge. At present, although an assessment of the soil-rock water balance using moisture data provided by the neutron probe indicates that predictions of flux are approximately correct, interpretation of the results is confounded by the presence in the model of a significant cumulative numerical error associated with the prediction of recharge and further work is required. As a consequence, it is not possible to have the same level of confidence in the long-term recharge estimates as it is in those derived with HYLUC. However, an independent check on the results of the soil moisture and HYLUC modelling has been provided, at least for pine forest, by a chloride mass balance method. Through a comparison of the concentration of chloride in rainfall and in soil-rock water samples within and beneath the root zone, long-term recharge rates of 25-30 mm per year have been derived. These compare with equivalents of 29 ± 8 and 33 ± 3 mm per year that have been derived with the HYLUC model.

Before the field study began, there was an expectation that, even if the water resource beneath the predominantly Corsican pine forest at Clipstone were reduced in quantity, the quality of recharge water would be good. This appeared to be confirmed by the quality tests on water being abstracted by Severn Trent plc from boreholes located within Clipstone Forest. However, once the study had commenced, the soil water quality monitoring that was being carried out appeared to indicate otherwise. Indeed, some of the poorest quality water in terms of nitrate concentrations had been obtained from the soil profile under pine. These were above World Health Organisation recommended limits. In order to understand these results and to obtain samples from beneath the zone which is influenced by the abstraction of water by roots, a drilling programme was carried out in the spring of 2001 to obtain water quality profiles to depths of > 30 m beneath pine. The samples taken during the drilling programme showed that the high nitrate (and chloride) concentrations measured in the soil extend beneath the root zone to a depth of about four metres. These high concentrations result primarily from transpiration; it is suggested that significant dilution is unlikely to occur in future because recharge rates are very low. Modelling using SHELUC indicates that water with comparatively high concentrations could reach the present water-table within the next 30 years, but that the EU Drinking Water Directive guide value of 5.65 mg l^{-1} nitrate-N is unlikely to be exceeded until shortly after the middle of this century.

The implications for the UK's lowland water resources are that afforestation with oak or pine on sandy soils overlying the Sherwood Sandstone aquifer will reduce groundwater recharge. In the case of oak during comparatively wet years, such as those experienced throughout this study, recharge may be reduced locally by 14-32%

when compared with grassland. The impact of evergreen needle leaf species such as pine is even greater in that recharge is predicted to be about one quarter of that under grass and, essentially, non-existent in years with average or below average rainfall. However, over a wider area, the impact on groundwater recharge will depend on the scale of planting, on forest design and on the land cover that is being replaced. The woodland stands selected for this study were deliberately chosen to reflect the stage of maximum growth rate and, thus, water use. As a woodland matures, modern forestry practice involves a phased programme of thinning and felling that gradually converts it to a multi-age structure in which a range of growth stages are represented. Since younger components will have a lower water use than fully established stands, the impact of a forest of mixed age will be less. Another important consideration is that much of the non-forested land overlying the Sherwood Sandstone aquifer is used currently for potato, sugar beet and carrot production and this is subject to spray irrigation in summer. These other land uses have not been investigated and may have a higher or lower water use when compared with grass.

The implication for the quality of lowland water resources in drier regions of England is that afforestation of arable or grassland with pine will not bring about the expected benefit in terms of lower nitrate concentrations, although phosphate levels would be reduced. More importantly, nitrate levels in groundwater under existing pine forest could be expected to rise in the future, adding to the existing nitrate problem affecting waters draining agricultural areas. In contrast, woodland planted with broadleaves such as oak could be expected to greatly improve water quality by reducing both nitrate and phosphate levels to low values. This would help to offset the predicted reduction in recharge compared with grass. Heath vegetation, which provides quantities of groundwater not much reduced from those of grassland, is also expected to provide water of good quality because it is not subject to fertilizer applications, unlike grassland, and not associated with atmospheric scavenging of airborne pollutants, unlike pine forest.

The main aim of this study has been an assessment of the likely impacts on water resources of the increase in woodland that is embodied in Government planning for the countryside. Using the extreme values of groundwater recharge rates which have been derived for each land-use for the comparatively wet period 1998-02, future recharge beneath a tract of land that has a current mix of forest and non-forest land-use akin to that of the Greenwood Community Forest, Nottinghamshire, has been modelled for a number of land-use change scenarios. These all involve the target three-fold increase in the area of woodland from 9 to 27% and assumptions have been made that all short vegetations, including arable, act as grass and that the increase in woodland is at the expense of grassland. In the 'worst' case, where all new planting involves pine, recharge would be reduced by between 10 and 14%. In the case where all new planting involves oak, recharge would be reduced by between 3 and 6%.

The four-year period of study, 1998-2002, represents one of the wettest in the region within the last three decades. The autumn of 2000, the wettest on record, was particularly helpful in providing a reference value for 'field capacity' moisture content at the different sites under investigation. This has helped separate site effects from vegetation effects in the soil moisture record. What the four-year observation period has not provided is a drier than average year, which would be necessary in order to determine the evaporative responses of the different vegetation types under conditions of water stress and test the longer-term predictions of HYLUC. Further research and monitoring will be needed if this is to be achieved and if those questions surrounding the water regime of sandy soils in England and Wales are to be fully resolved.