Review of the effects of energy crops on hydrology

William Stephens
Tim Hess and
Jerry Knox

Institute of Water and Environment
Cranfield University
Silsoe
Bedford MK45 4DT

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Executive Summary

1) MAFF has recently launched a scheme to support the expansion of the area of energy crops grown in England in order to meet the nation's Kyoto targets for the reduction in CO_2 emissions. This has highlighted concerns about the possible effects of willow short rotation coppice (SRC) and Miscanthus on the hydrology of catchments in which they are grown. High levels of water use by these crops could result in less surface runoff, decreased aquifer recharge and hence reduced stream flow (Chapter 1).
2) This report reviews the available literature on the water use of energy crops and their effect on hydrology. It then presents the results of a sensitivity analysis to determine the relative importance of the various components of the water balance and the implications of different growing conditions for water use. A possible method for scaling up this approach to a catchment scale is discussed and future research requirements are suggested.
3) A simple conceptual model was developed to allow the main components of the water balance in energy crop production to be identified. The key components in terms of the hydrological effects of energy crops are the surface runoff and deep percolation below the root zone. These are affected by the water use of the crop and the proportion of the rainfall intercepted by the foliage and subsequently lost by evaporation. (Chapter 2).
4) Considerable research has been carried out on the water use of short rotation coppice. Much of this work has been in Sweden but, in England, there was a substantial project on the water use and hydrological effects of coppiced poplar undertaken by the Institute of Hydrology for the DTI. Less information is available on the water use of Miscanthus but an indication of the likely effects can be found by analogy with other tall C_4 grasses such as sugar cane (Chapter 3).
5) The results of the research to date indicate that a consequence of high biomass production by energy crops is a concomitant use of large amounts of water. These crops grow very rapidly and have a large leaf area for most of the growing season.
6) The large leaf area means that the foliage may intercept 20 to 30% of rainfall, which then evaporates directly from the leaves. Whether water intercepted by the canopy substitutes for transpiration will depend on the canopy height and structure.
7) Transpiration from tall crops with small leaves and rough canopies tends to be dependent primarily on wind speed and the humidity of the air above the crop. In these cases, where crops are said to be closely "coupled" to the atmosphere, interception losses tend to be high. By contrast, short crops with uniform canopies of larger leaves tend to be "decoupled" from the atmosphere and transpiration is dependent predominantly on the intensity of incoming solar radiation. The two extremes are pine forests, which are very well coupled to the atmosphere, and short grass, which is largely decoupled. Energy crops appear to be well coupled to the atmosphere early and late in the growing season when they have few leaves but are decoupled for the majority of the time when they have a large uniform canopy. The implication, though this has not been shown in the literature, is that intercepted water may not be a "loss" during the main growing season.
8) The siting and size of the area of crop grown can also affect water use. Isolated patches or thin strips of vegetation are able to transpire at up to 2.5 times the potential rate because of the availability of additional energy from surrounding areas. This advective or "clothesline" effect is potentially very important where crops have access to unlimited water supplies from ground water. Strips of energy crops grown in riparian zones could use up to twice as much water as the same crop grown in the same spatial arrangement on an upland site without access to ground water.
9) The scale of water use by energy crops depends on the demand from the atmosphere and the ability of the crop to satisfy that demand by extracting water from the soil. Evidence

from a number of studies suggests that Miscanthus and SRC are able to extract water from as deep as 2 and 3 m respectively and that trees are able to supply much of their water requirement from ground water where this is within the root zone.

10) Deep rooted energy crops grown on soils with a large available water content will cause substantial reductions in the amount of water percolating below the root zone. Soil water deficits of up to 250 mm may develop over the growing season and, in drier eastern areas, there may be insufficient rainfall during the winter months to rewet the soil to field capacity. The consequence of this is that there would be no deep percolation below the crop in that hydrologic year.

11) On the other hand, where the roots of energy crops are restricted by soil conditions, such that there is a limited available water capacity in the root zone, their water use will be much lower and will be primarily determined by the amount of rainfall during the growing season. In these circumstances, deep percolation may well be similar to that beneath annual crops or permanent grass grown at the same site. The biomass production of these crops, however, would be substantially reduced by water stress at a rate of 5 and 9 g kPa kg^{-1} for SRC and Miscanthus respectively. This is equivalent to a loss of 50 to 90 kg of biomass per ha for each millimetre of water stress.

12) The largest reduction in hydrologically effective rainfall (HER) would occur where energy crops are grown in small blocks in a riparian zone with good access to groundwater (i.e. a natural habitat for willow). Here biomass production would be very high but the annual water use could approach or even exceed annual rainfall in the drier eastern parts of England.

13) The range of effects of different crop and soil parameters on hydrologically effective rainfall was simulated using WaSim, a simple water balance model, with 30 years of daily weather data from Silsoe, Bedfordshire, which is situated in the driest area of the country. The predicted annual evapotranspiration varied little for a wide range of soil types and was between 400 and 500 mm in most years. The amount of runoff depended on the infiltration capacity of the soil and was between 0 and 50 mm in most years. Little deep percolation was predicted, however, for any soil type except sand (Chapter 4).

14) Variations in the date of canopy emergence had little effect on the predicted annual ETa of willow SRC since water stress restricted transpiration once the available soil water was used up. Late canopy development resulted in greater HER mainly because the shorter canopy duration resulted in smaller interception losses.

15) The importance of interception losses will depend on the extent to which the canopy is coupled to the atmosphere. Losses of 2 mm per rainy day and 10% any further rain falling led to a reduction of about 20% in net rainfall and this translated directly into lower HER and a larger proportion of years with no HER.

16) In crops grown in small patches the availability of advective energy can result in considerably higher transpiration (without necessarily increasing biomass production). In WaSim this is modelled by increasing the crop coefficient from 1.2 to 1.5. There was only a small proportional effect on ETa unless the crop had access to the watertable in which case the seasonal ETa was linearly related to the crop coefficient and increased to about 700 mm. This highlights the likely high water use and important impacts of energy crops grown in riparian areas.

17) Root depth also had a clear effect on both ETa and HER. Where the root depth was restricted ETa was reduced and HER increased. This effect was linear for root depths up to 2.5 m. Thereafter ETa increased only slightly as it was limited by the annual rainfall.

18) Comparing the water use of winter wheat, permanent grass, Miscanthus and willow SRC grown with no restrictions at three sites in different agroclimatic zones in England revealed

that both energy crops consistently used more water than the crops they might replace. HER from Miscanthus was predicted to be greater than from willow SRC as the canopy duration is likely to be shorter leading to lower interception losses and the root depth is less, resulting in a smaller soil volume to rewet before deep percolation occurs (Chapter 5).

19) The reduction in HER as a result of replacing wheat and grass with energy crops was 100 – 120 mm for Miscanthus and 140 – 180 mm for willow. This represents a reduction of 50 – 60% for Miscanthus and 75 – 90% for willow with the greatest proportional reductions in the drier areas. These simulations suggest that Miscanthus may be more appropriate than willow SRC in drier regions where the effects on HER are greatest.

20) The implications of these reductions at national level is that the establishment of 100,000 ha of energy crops would result in a reduction of the total freshwater resource of about 1.5×10^{8} m^{3} $annum^{-1}$, equivalent to 0.2% of the national freshwater resource or 12% of annual freshwater abstractions.

21) Around individual power stations the 40 km maximum radius for energy crop delivery defines a catchment of about 500,000 ha. The 2500 ha required to provide fuel for the power station would result in a reduction in HER of about 0.5% within this area. Compared with the 28% range around the mean HER beneath wheat in six years out of ten the reduction due to energy crops would be difficult to detect.

22) At a sub-catchment scale, however, the proportion of the catchment covered by energy crops might be greater and thus detectable reductions in aquifer recharge and stream flow might occur.

23) Biomass production is intimately related to water use in crops and this study reveals that, in the drier eastern areas of England, water stress is likely to reduce biomass production below the climatically determined potential in many years (Chapter 6).

24) Upscaling to catchment level can be achieved by using a GIS based approach to relate the one dimensional water balance model to a spatial database of soils and climate data. This approach has been used successfully for MAFF and the Environment Agency to predict the water requirements of irrigated crops and would be applicable for energy crops as well (Chapter 7).

25) Changes to landuse within individual catchments and sub-catchments could be investigated to identify the likely impacts for different combinations of soils, land use and climate.

26) Four main recommendations for further research arise from this study (Chapter 8):

    a) breeding to improve the biomass water ratio of willow;

    b) field scale studies on factors affecting hydrologically effective rainfall in energy crop systems;

    c) the development of energy crop biomass production models; and

    d) the development of a GIS approach for evaluating potential energy crop production sites

Contents

List of Figures

List of Tables

1 INTRODUCTION

Over the past ten years there has been an increasing recognition of the need to develop reliable sources of renewable energy. These were formalised in the 1992 Kyoto Convention on Climate Change as targets for reductions in greenhouse gas emissions. In the UK, the five Non Fossil Fuel Orders (NFFO1 – 5), made under the Electricity Act 1989, have led to three contracts awarded for short rotation coppice (SRC) under NFFO3 and a further seven contracts for energy crops and forest waste under NFFO4.

NFFO has now been succeeded by the New & Renewable Energy policy (DTI, 2000). Under this policy, energy crops are recognised as being an important component in meeting the 10% renewable energy target in the medium term (by 2010).

The implementation of the government energy policy will lead to the establishment of between 100,000 and 150,000 ha of energy crops in England and Wales. The primary objective in growing energy crops is to optimise the harvestable biomass in relation to agronomic inputs. The low value of biomass combined with high transport costs to power stations means that crops must be grown within a small radius of the power station (about 40 km). The species chosen should also be efficient at intercepting solar radiation, converting it into dry matter and partitioning a large proportion to the harvested parts of the plant. In Europe, the main crops being considered for renewable energy production are willow (*Salix* spp.) and poplar (*Populus* spp.), grown as short rotation coppice (SRC), and C_4 perennial grasses[1] such as *Miscanthus* spp.

The link between water use by crops and biomass accumulation has long been established. Whilst absorbing the carbon dioxide (CO_2) necessary for photosynthesis, plants also lose water vapour through stomata on their leaves. This relationship is modified by the evaporative demand from the atmosphere so that in hot, dry climates plants lose more water per unit of assimilation than in cool humid areas. High biomass production, a prerequisite for commercial energy crop production, therefore equates to high water use, especially in warmer and drier regions where the evaporative demand is greater.

Within a catchment, increasing the area of crops that have a high water use may change the hydrological balance with marked effects on river and stream flow. Therefore, whilst there are palpable benefits in terms of the reduction in fossil fuel usage, the environmental impacts of this change in land use need to be evaluated. In particular, the potentially greater water use of energy crops may have impacts on water users or natural ecosystems downstream. In this regard, the Environment Agency (EA) are developing and implementing Catchment Abstraction Management Strategies (CAMS). It is proposed that CAMS will be developed for every catchment, or group of catchments, in England and Wales. Issues relating to the catchment's resource availability, licence commitments, water management policies, Agency actions and future strategies will be addressed. At present CAMS do not quantify changes in the use of water within a catchment due to changes in land use.

Clearly for CAMS to be implemented successfully, potential new abstractions from the environment within each catchment need to be considered. These can be direct abstractions through pumping or indirect abstractions arising from changes in land use to crops that use more water. At a local level, a spatially integrated and balanced assessment of the environmental impacts and hydrological implications of energy crops on water resources (e.g. via aquifer recharge and river flows) would be beneficial and, in fact, an Environmental Impact

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[1] C_4 refers to the photosynthetic pathway used by the crop. In tropical climates, C_4 crops are more efficient at converting solar radiation to dry matter than temperate species that mostly use the C_3 photosynthetic pathway.

Assessment is now required by MAFF before establishment grants for energy crops are awarded.

This report addresses the issues and uncertainties surrounding the water use and consequent hydrological impacts of energy crops. We first propose a simple conceptual model of water use. Based on this model we review the available published literature on the water use and likely hydrological impacts of energy crops.

This information is then used to parameterise an existing one-dimensional water balance model (WaSim) and test the sensitivity of water use and hydrologically effective rainfall to changes in the key crop, soil and climate variables. Comparisons are then made between the hydrological effects of energy crops, winter wheat and permanent grass at three sites where NFFO power stations are, or may be, built.

The challenge of scaling up to catchment level is addressed by proposing a methodology similar to that used for other water requirement studies.

Finally we identify areas where further research is required in order to increase our understanding of the systems involved and suggest management strategies to minimise any adverse impacts.

2 CONCEPTUAL MODEL

2.1 MODELLING CATCHMENT HYDROLOGY

Modelling the hydrology of a catchment in response to climate and land cover can be considered a two-stage process. Firstly, the hydrologically effective rainfall is estimated from the recorded rainfall and estimated actual evapotranspiration. This may be partitioned in to surface runoff and groundwater recharge. Hydrologically effective rainfall is a function of land cover, soil type and climate and is often modelled empirically by calibration against observed hydrological data. However, with empirical approaches the impact of changes in land cover cannot be predicted. This requires a more mechanistic approach.

Secondly, the hydrologically effective rainfall is routed through the catchment to produce predicted river flows. The routing of hydrologically effective rainfall through the catchment is a largely a function of topography, soil type and geology. Thus, the impact of a change in hydrologically effective rainfall on the distribution of flows in a water course is very catchment specific. For this reason, the present study will concentrate on the impact of land cover on hydrologically effective rainfall.

2.2 A ONE-DIMENSIONAL CONCEPTUAL MODEL FOR HYDROLOGICALLY EFFECTIVE RAINFALL

Figure 1 presents a graphical illustration of the key components of the water balance of energy crops. To understand the impact of energy crops on runoff and baseflow, it is important to be able to quantify how differences in land use affect these components.

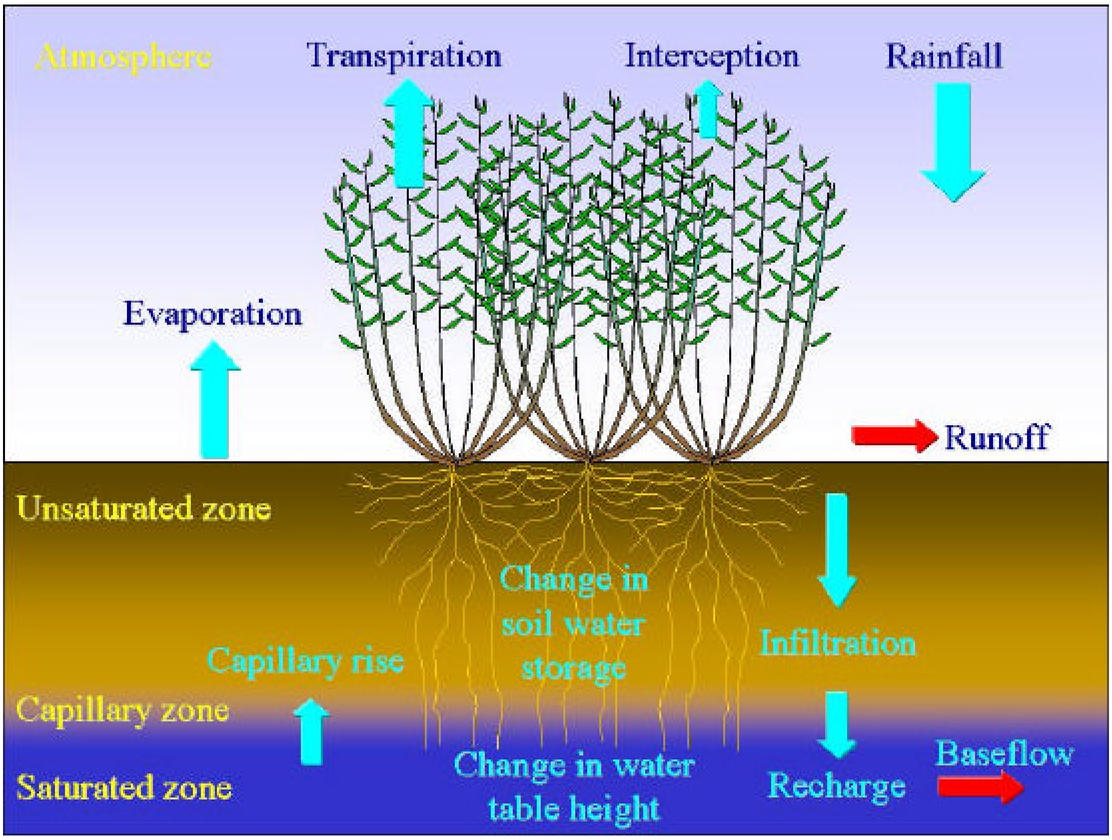

Figure 1. A conceptual model of the water balance and hydrology of energy crops.

Precipitation is either intercepted by the foliage of the crop or falls through the canopy to the ground. At this point the water infiltrates into the soil or, if the rate of infiltration is lower than the rate of precipitation, it runs off the surface to a water course.

Infiltrating water increases the soil water content and, once the soil has reached the upper drainable limit, contributes to recharge of the aquifer. The increase in water table height and subsequent lateral movement of water in the saturated zone contributes to the baseflow of streams.

The other half of the balance is driven by the evaporative demand of the atmosphere. This demand comprises a component related to the amount of incoming solar radiation, which either heats the environment (sensible heat) or evaporates water (latent heat). There is also an aerodynamic component that depends on the ability of the air to absorb water vapour (saturation deficit) and on wind speed, which causes turbulent mixing, moving humid air away from the land surface. The relative importance of the radiation and aerodynamic components depends on how well the crop is “coupled” with the atmosphere. Tall, sparse crops, especially trees, tend to be well coupled and their transpiration is more dependent on the aerodynamic component than on incoming radiation. By contrast, short uniform crops are “decoupled” by a thick boundary layer of humid air and the radiation load is the primary determinant of transpiration with the dryness of the air and wind speed having little effect over a wide range of values.

Evaporation from the soil surface and from intercepted water on vegetation is entirely dependent on the evaporative demand. Whereas transpiration from plants is, to a large extent, under physiological control in that plants can modify the rate of water vapour movement through their stomata. These two components are collectively referred to as evapotranspiration, which is commonly estimated from standard meteorological data using the Penman-Monteith equation.

The balance between evaporation and transpiration depends primarily on the vegetative cover. Similarly, interception losses depend on the storage capacity of the canopy and increase with leaf area and with the frequency of rainfall events. Once the crop covers more than 70 – 80% of the ground then transpiration is the dominant component.

The amount of water transpired will also depend on the crop in terms of its ability to conserve water, its structure and the duration of the growing season. In the absence of physiological control, tall crops with large leaf areas and non-uniform canopies will lose more water than short, uniform canopied crops. Crops with longer growing seasons also tend to use more water than those with a short season and a long fallow period though when calculating the annual water balance evaporation from the bare soil must also be taken into account.

The evaporative demand causes a water potential gradient in the soil and plant. This results in soil water movement along the gradient towards roots and the soil surface. As water is taken up the soil water content will decrease, reducing the rate of water movement and increasing water stress within the plant. Where there is a water table close to the surface of the soil, water can move up the soil profile through capillary action and become available for abstraction by roots. If recharge to the water table is less than the baseflow and capillary rise then the water table level will fall.

A review of the relative importance of the components of the hydrological cycle in energy crops is presented in the following Chapter.

2.3 SPATIAL AND TEMPORAL VARIABILITY

A model of the type described above is one dimensional, dealing primarily with vertical flows of water. In addition, there will be spatial variability in the hydrological balance, which can be investigated by assuming alternative soil and groundwater conditions and climate. These need to relate to the range of conditions in which energy crops are likely to be grown. In a study of this kind it is useful to establish the limits to the likely impacts and to identify the critical conditions that lead to maximum impact.

In this case the maximum impact will occur when there is no restriction to the water use of the energy crop. In areas with deep soils with large water holding capacities or where there is a permanent water table close to the root zone then the water supply may not be restricted during the growing season. The maximum water use will then occur where the evaporative demand is greatest, typically in the warmer, drier areas of the UK. It is in these areas that the hydrologically effective rainfall (i.e. that which contributes to river flow) is least and small changes in baseflow or runoff will have the largest relative effect on hydrology.

In wetter areas, two factors reduce the possible impact. Firstly, the evaporative demand of the crop will probably be lower due to the cooler, moister conditions. Secondly, the impact may be relatively minor if the reduction in hydrologically effective rainfall is small in relation to the total amount.

By contrast, where the soil type or depth limits the available water in the soil, water use is restricted by stomatal control of transpiration then the actual water use is determined not by the evaporative demand but by water supply. The effect on hydrology may be similar to that of annual crops in these circumstances.

Spatial diversity is compounded by further variability in weather both within- and between-seasons. Whilst the average effect provides some information on impact, the extreme years, and particularly drought years, may well be more important in the long term. Quantifying the effect of changing land use to an energy crop should therefore be undertaken for a large number of years in order to characterise the probability of any particular level of impact. Plausible climate change scenarios may also need investigation to determine the likely future impact but are not part of the remit of this report.

3 WATER USE BY ENERGY CROPS

3.1 INTRODUCTION

This Chapter sets out to review the available literature on the water use of energy crops and their effects on the water balance in the context of the conceptual model described in Chapter 2. The first five sections concern the development of the canopy, its connection to the atmosphere, crop water use relative to a reference crop, the loss of water intercepted by the canopy and the seasonal water use by energy crops. The effect of roots is then reviewed followed by the overall effects of trees on catchment hydrology and river flow.

3.2 CANOPY DEVELOPMENT

The timing of canopy development and the leaf area duration are important factors determining the potential water use of energy crops. Ceulemans *et al.* (1996) noted that there are few data in the literature on the time course of leaf development of short rotation crops. For Poplar cv Beaupré SRC in southern England, Hall *et al.* (1996) recorded leaf emergence in mid-April with the canopy reaching a Leaf Area Index[2] (LAI) of 2 by about mid-May, peaking at LAI 4 from mid-June to mid-September with leaf fall complete by the end of November. Souch *et al.* (2000b) report *Salix viminalis* cv Q683 in the third year of growth after coppicing at Kettering, Northamptonshire[3], reached LAI 3 by mid-April, peaked at LAI 6.9 in late June and then declined to LAI 2 by mid-October (Figure 2). On a drier site at Silsoe, Bedfordshire[4], the same cultivar, in the first year after coppicing, rapidly developed to LAI 4 but further leaf are development was then restricted by drought stress.

In the absence of water or other stress, canopy development depends on the accumulation of thermal time above a base temperature for growth which, for *Salix viminalis*, is 5 °C (Cannell *et al.*, 1987; Perttu and Kowalik, 1989). Cannell *et al.* (1987) suggest that, once a threshold value has been exceeded (180 d °C > 5 °C), accumulated thermal time contributes directly to increasing leaf area until the maximum leaf area index of about 4.5 is reached. During autumn (September-November) leaf area reduces linearly at a rate of 2% per day (Cannell *et al.*, 1987).

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[2] The Leaf Area Index is the ratio of leaf surface area per unit ground area. Thus an LAI of 6 represents 6 m^2 of leaf per m^2 ground area.

[3] Kettering is in Agroclimatic area 22e (661 and 494 mm annum^{-1} mean rainfall and potential evapotranspiration respectively).

[4] Silsoe is in Agroclimatic area 28, the dries in the country (574 and 523 mm annum^{-1} mean rainfall and potential evapotranspiration respectively).

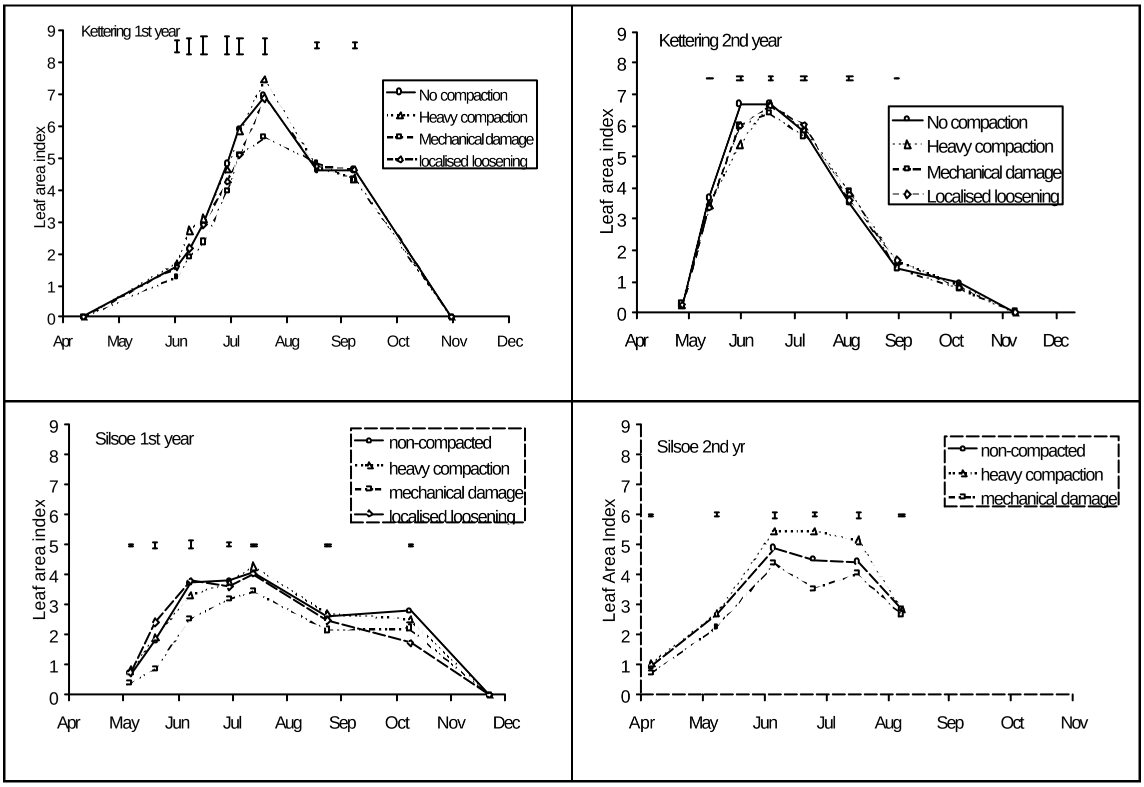

Figure 2. The effect of harvesting damage on leaf area index development of *Salix viminalis* cv Q683 in the first year of growth after harvesting at Kettering (top) and Silsoe (bottom) and in the first (left hand side) and second (right hand side) years of growth after harvesting. Error bars are the standard error of the difference between means, n = 30 (Souch *et al*., 2000a).

In *Miscanthus x giganteus*, grown in England, leaf emergence occurred from early to mid-April and the canopy intercepted 20% of incoming solar radiation by mid- to late-May. Canopy closure occurred by late August to late September, depending on the age of the crop, and the green LAI reduced steadily thereafter until November (Bullard *et al.*, 1997).

Different rates of canopy development between stages of development, years and sites will have an effect on water use by energy crops. For example at Silsoe, in one of the driest areas of the country, the maximum LAI for willow SRC in the first year after cutback was only 4 compared to almost 7 for the same cultivar at the same stage of growth on a wetter site near Kettering (Souch *et al.*, 2000a). Thus drought might limit the leaf area duration and, where the canopy does not develop sufficiently to allow full ground cover, then transpiration will also be reduced.

3.3 COUPLING TO THE ATMOSPHERE

McNaughton and Jarvis (1983) showed that the height and canopy structure of vegetation had a considerable effect on the relative importance of the radiation and aerodynamic terms of the Penman-Monteith equation and hence the key drivers for evapotranspiration from plants. The movement of water vapour from within the leaf to the bulk atmosphere is governed by the stomatal resistance (collectively referred to as the canopy resistance) and the resistance of the boundary layer of air surrounding the leaves and canopy (the aerodynamic resistance).

Short grass and agricultural crops with large boundary layers tend to be poorly coupled to the atmosphere. Their transpiration and evaporation rates are principally governed by incoming radiation and respond only slightly to canopy resistance. By contrast, transpiration from tall vegetation such as trees is driven predominantly by the saturation deficit of the air in the boundary layer and plants can exert considerable stomatal control over transpiration. In addition, direct evaporation from wet foliage on tall well coupled vegetation can be several times greater than open water evaporation rates because of the additional energy available from warm, dry air blowing through the canopy, a process known as advection (McNaughton and Jarvis, 1983). It is therefore important to determine to what extent energy crops are coupled to the atmosphere as this will have important implications for their water use and the hydrologically effective component of rainfall.

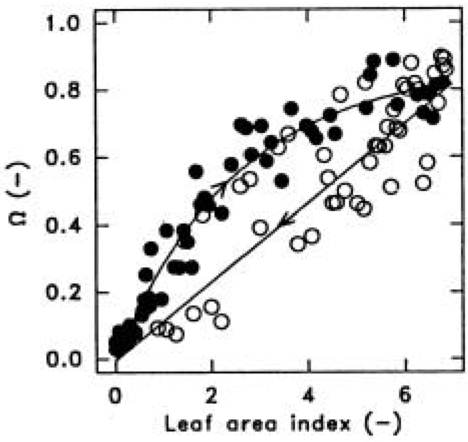

Figure 3. Effects of canopy development in willow short rotation coppice on the decoupling factor (W) in Sweden: 1988 (Persson and Lindroth, 1994).

The decoupling factor (W) described by McNaughton and Jarvis (1983), ranges from 0 when the vegetation is fully coupled to the atmosphere up to 1 when it is fully decoupled[5]. In an experiment to determine the degree of coupling for a stand of *S. viminalis* SRC, aerodynamic resistance was found to vary solely because of variations in leaf area indices (Lindroth, 1993; Persson and Lindroth, 1994). W for the stand was found to increase from zero at Leaf Area Index (LAI) zero to about 0.7 for LAI 2, and in the range of 0.6 to 0.8 for larger LAIs (Figure 3). The stand was therefore well coupled to the atmosphere for low LAIs (<1) and was practically de-coupled for LAIs above two. Thus the willow stand responded to evaporative demand like a tall forest when the leaf area was small and like an agricultural crop when leaf area was large. During the majority of the season, there was little stomatal control over transpiration, which would have been primarily determined by net radiation receipts.

In Miscanthus, the dense nature of the canopy (Figure 4) would also suggest that the crop will be largely decoupled from the atmosphere, with transpiration driven predominantly by net radiation. Unlike SRC, the canopy of Miscanthus develops as a short, dense layer close to the ground, which then increases in height as the stems elongate. By contrast in SRC, the canopy in the second and third years of the coppice cycle is already several metres tall so that, until the canopy closes, it is closely coupled with the atmosphere.

The water use of C_4 grasses, such as Miscanthus, is likely to be analogous to similar species that are widely grown crops. In particular sugar cane (*Saccharum officianarum*), is closely related to Miscanthus (Hodkinson *et al.*, 1997). In Mauritius, between 75 and 80% of the variability in annual yields of well irrigated sugar cane was due to fluctuations in solar

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[5] The coupling factor, W is related to the ratio of canopy (r_c; s m^{-1}) to aerodynamic resistance (r_{as}; s m^{-1}) as follows:

$$\Omega = \left[1+\frac{g}{(\Delta+g)}\frac{r_c}{r_{as}}\right]^{-1}$$

where: Δ is the slope of the saturation vapour pressure temperature curve (kPa °C^{-1})
γ is the psychrometric constant (kPa °C^{-1})

radiation receipts (Cheeroo-Nayamuth *et al.*, 2000) and this suggests that transpiration is determined primarily by the radiation component of the Penman-Monteith equation.

Figure 4. Mature stand of *Miscanthus x giganteus* approximately 3.5 m high. Photograph taken September 1996, about 30 km south of Ulm in southern Germany, by Dr. I. Lewandowski, University of Hohenheim (Scurlock, 1998).

In Poplar, there does not appear to be a strong link between stomatal conductance and saturation deficit (Hall *et al.*, 1996). Stomatal conductance was reduced below the optimal when the fraction of available water in the soil reached 0.3; lower than the 0.6 found for pot-grown poplar plants by Braatne *et al.* (1992). Willow stomata seem to be more sensitive and close with increasing saturation deficits. This effect is greater at higher radiation intensities (Cienciala and Lindroth, 1995).

The size of the plantations and of the individual trees will obviously have a large effect on Ω. Zhang *et al.* (1999) found that poplar trees (*P. trichocarpa* x *tacamahca*) were well-coupled to the atmosphere with Ω between 0.35 and 0.5. The transpiration rate was shown to be highly sensitive to stomatal control. The poplars were, however, grown in two rows of 11 trees and therefore the boundary layer conditions would not be the same as for a much larger stand such as that studied by Hinckley *et al.* (1994) who reported Ω for poplar of 0.66 indicating much more de-coupled conditions. Zhang *et al.*'s (1999) findings should not therefore be applied to larger plantations but are indicative of how the effects of plantation size and shape could affect total water use and hence hydrologically effective rainfall.

The theoretical basis for quantifying the effects of advection on evapotranspiration has been described by Philip (1987) who showed that surface resistance is important for small patches of vegetation surrounded by dry areas, where the boundary layer is small. As the area of vegetation increases surface resistance becomes a smaller component in the total resistance to water vapour transfer from plants to the bulk atmosphere.

The importance of advection will be most marked when small patches of coppice are surrounded by dry bare soil. Lindroth and Iritz (1993) showed that for a closed canopy stand of SRC the sensible heat flux was negative, i.e. the trees used heat from the air for evaporation. This advective effect occurred in July and August but was most pronounced (-3 MJ m^{-2} d^{-1}) in September and October when it was equivalent to about 15 - 20% of the daily incoming solar radiation. Advection can therefore contribute markedly to the total water use of energy crops where the water supply is sufficient to meet the seasonal demand.

3.4 CROP COEFFICIENT

A simple procedure to predict the effects of advection is to modify the crop coefficient (K_c) that is used to estimate crop evapotranspiration from reference evapotranspiration (ET_0) (Allen *et al.*, 1998). If all incoming solar energy were used to evaporate water, rather than heating the air, soil and crop, then the maximum crop coefficient would be about 1.2. This corresponds closely with average values for irrigated sugar cane (Allen *et al.*, 1998). Irrigated Miscanthus grown in Essex, during April to August had an average crop factor of about 1.3 (Beale *et al.*, 1999). During the majority of the period after canopy development, however, the crop coefficient was above 1.5, reflecting the availability of advective energy from dry ground surrounding the small (8 x 6 m) plots. In an irrigation experiment in Italy, Ercoli *et al.* (1999) used Kc values rising from 0.33 at 20 days after emergence to 1.23 at anthesis. They applied these coefficients to Class A pan evaporation, which is 15 – 100% greater than the ET_0 values more commonly used. Whether this was intentional or not is unclear but the effect would be to increase the predicted water requirement.

For very narrow and tall strips of vegetation, K_c can be as high as 2.5 but this rapidly decreases as the width of vegetation increases. For strips of tall vegetation, the following formula can be used to estimate the appropriate K_c value:

$$K_c = \min\left(1.2 + \frac{F_r\, h_{canopy}}{Width}, 2.5\right)$$

where:	F_r	stomatal resistance correction factor
	h_{canopy}	mean vertical height of canopy area (m)
	$Width$	width (horizontal thickness) of vegetation (m)

The stomatal resistance factor, F_r, adjusts for differences between vegetation types as follows:

$$F_r \approx \frac{\Delta + g\,(1 + 0.34\,u_2)}{\Delta + g\left(1 + 0.34\,u_2\,\frac{r_l}{100}\right)}$$

where:	Δ	slope of the saturation vapour pressure temperature curve (kPa °C^{-1})
	u_2	wind speed at 2 m (m s^{-1})
	γ	psychrometric constant (kPa °C^{-1})
	r_l	bulk stomatal resistance (s m^{-1})

The upper limit is imposed to represent the maximum stomatal capacity of the vegetation to supply water vapour to the air stream under advective conditions and could be lower on plants with small leaf areas or large hydraulic resistances.

The importance of vegetation height is obvious especially for narrow vegetation strips (Figure 5). A strip of vegetation 10 m high and 50 m wide might transpire 45% more than a similar width of short grass. Though the effect decreases rapidly, it is still noticeable even for vegetation widths of 200 m. The implications for design of coppice planting in sensitive areas could be significant and suggests that narrow strips of coppice planted across the prevailing wind direction should not be recommended.

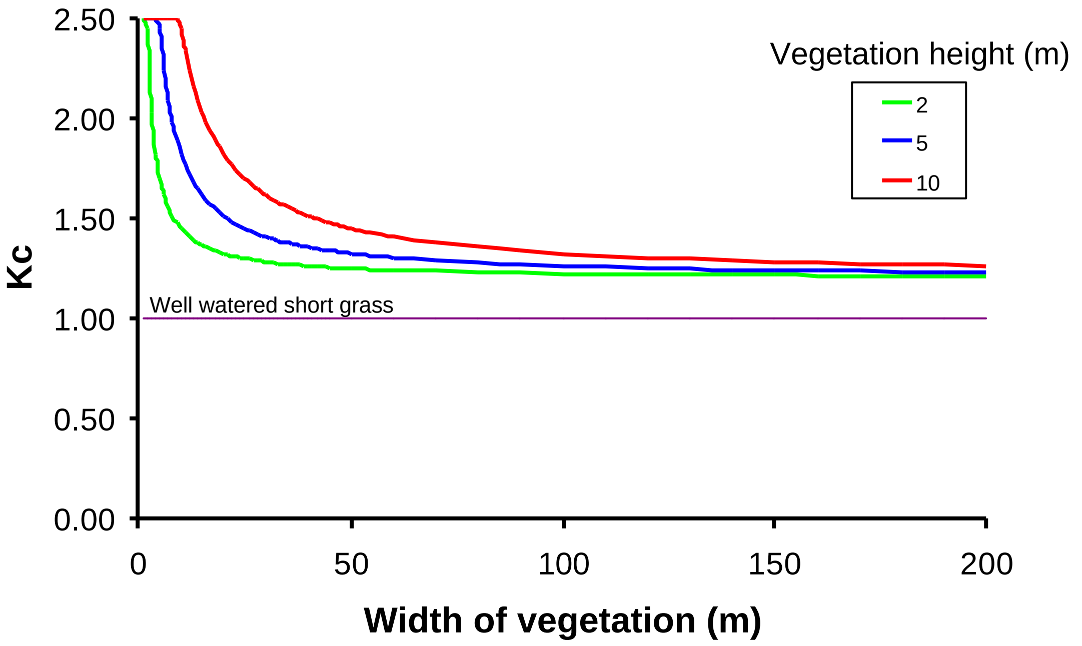

Figure 5. The theoretical effect of vegetation height and width on crop coefficient (K_c) for conditions where: mean temperature = 22 °C; bulk stomatal resistance = 40 s m^{-1}; wind speed = 2 ms^{-1}. Adapted from Allen *et al.* (1998).

3.5 INTERCEPTION OF RAINFALL BY FOLIAGE

The rate of evaporation of rainfall intercepted by the foliage of a crop is related to the amount of advection and the extent to which the canopy is coupled with the atmosphere. High rates of interception losses can be maintained from well-coupled forest canopies even at reasonably low wind velocities provided that a saturation deficit exists. Small but significant saturation deficits exist above wet canopies often as a result of dry-air advection from surrounding land areas, or by the supply of heat directly and studies in UK and New Zealand have shown that between 30 to 85% of the interception loss from canopies occurs as evaporation during rainfall with the remainder resulting from the evaporation of water stored in the canopy (Gash *et al.*, 1980; Pearce and Rowe, 1981). Indeed, evaporation rates from temperate forests under rainfall conditions are often similar to transpiration rates in good weather (Jarvis, 1985).

In Finland, Ettala (1988) measured interception, stem flow and evapotranspiration from *Salix aquatica* grown on a landfill site. Interception was about 31% of rainfall and irrigation during a period when the foliage was wet on 103 out of 153 days. In the UK, Hall and Allen (1997) recorded interception losses of 21% of gross rainfall during May to October. These may be more representative of unirrigated coppice plantations as the canopy would be wet on fewer occasions. The utilisation of advective energy by well-coupled forests is much higher than for shorter vegetation and is the principal reason for higher evaporative losses from forests compared to shorter vegetation (Calder, 1998b).

Larsson (1981), working with individual willow branches in a growth room, showed that transpiration rates in willow were reduced by 95% when leaves were wetted, but that evaporation rates were very high and total evapotranspiration was double the rate of transpiration from dry leaves when the leaves were saturated. These results, however, may not be representative of a complete canopy with a thick boundary layer where evapotranspiration is driven primarily by solar radiation receipts.

There is therefore a question mark over the implications of interception losses from energy crops that may well be virtually decoupled from the bulk atmosphere. In arable crops, control of transpiration by stomata is poor until the crop becomes very drought stressed (McNaughton and Jarvis, 1983). This effect is also true of perennial woody plants grown with very compact canopies (Stephens and Carr, 1991) where water evaporating from the canopy substitutes directly for transpiration and therefore allows assimilation and biomass production to continue.

When Ω is large for energy crops, as seems to be the case for most of the season when the LAI exceeds about 2 (Persson and Lindroth, 1994), then evaporation of intercepted water may not be a hydrological "loss" but substitute for transpiration and thus reduce soil water extraction. Where there is less water extraction from the soil then there will be more water available later for growth. One consequence could be that, if the canopy is wet frequently and evaporation of this intercepted water substitutes for transpiration, then the soil would be wetter at the end of the growing season and the profile would take less time to refill to the point when deep percolation would occur.

When Ω is small, evaporation of intercepted water will not substitute for transpiration to any great extent and hence the amount of water percolating below the root zone and contributing to groundwater recharge will be lower by up to the total amount of interception loss. This would have implications for small, narrow strips of coppice. Further studies are needed to determine the conditions under which intercepted rainfall substitutes for ET in commercial scale field conditions.

3.6 EVAPOTRANSPIRATION

Evapotranspiration (ET) is the combination of soil evaporation and transpiration from plants. In energy crop cultivation systems, soil evaporation will be a small component of total ET as the evaporative demand of the atmosphere is low for most of the time that the soil is exposed. Once the canopy cover exceeds about 10% then ET is increasingly dominated by transpiration and soil evaporation is negligible when the canopy cover is about 70 – 80%.

Hall *et al.* (1998) measured transpiration rates of SRC poplar (Beaupré: *Populus deltoides x trichocarpa)* and willow (*Salix burjatica*) on a freely draining clay loam in the South-west of England. In June and July, when there was no water stress, transpiration (T) from individual stems was up to twice reference evapotranspiration (ET_0) on a daily basis, reaching a peak of almost 11 mm d^{-1}. The mean transpiration rate was about 5 mm d^{-1} (Allen *et al.*, 1999). As water stress increased through the dry summer, the transpiration ratio (T/ET_0) decreased to almost zero at the end of July and remained there for most of August.

The peak values measured by Hall *et al.* (1998) seem to be very high in comparison to rates recorded elsewhere. For example, Hinckley (1994) measured a maximum rate of 4.8 mm d^{-1} from single stem *P. trichocarpa* x *deltoides* in Washington, USA. Similarly, in a well irrigated stand of hybrid poplars grown as SRC, evapotranspiration was between 4.4 and 4.8 mm d^{-1} from June until August in North America (Hansen, 1988).

In many studies, transpiration is assumed to occur only during the day but, in willow, night time evapotranspiration has been measured, though it was only 4% of the total seasonal ET (Iritz, 1994). This could prove to be an important feature of willow SRC where water availability limits biomass production.

For an isolated strip of (*P. trichocarpa* x *tacamahca*), Zhang (1999) measured transpiration rates of up to 5.4 mm d^{-1} in June, decreasing to 3 mm d^{-1} in August. These rates were sustained by advection of sensible heat from surrounding farmland, as they exceeded the water equivalent of daily total net radiation.

For most crops, the ratio of actual to potential evaporation (E_0) increased with Leaf Area Index (LAI) up to about 3 - 4 but, in willow SRC the ratio stabilised at LAI 1.5 (Iritz and Lindroth, 1996). Above LAI 1.5 – 2 there is a strong relationship between actual evaporation and available energy, corroborating other evidence of the decoupled nature of extensive SRC canopies for most of the growing season.

Over the growing season, energy crops have been reported to use large amounts of water. The largest amount was reported by Ettala (1988) who estimated that the evapotranspiration from a small (0.15 ha) stand of *Salix aquatica* was 710 – 900 mm during the growing season (1 May to 30 September). However, this may be lower on agricultural fields as there is additional advective energy available on landfill sites.

Mean daily rates of water use by rainfed *M.* x *giganteus* and *Spartina cynosuroides,* another C4 perennial grass, were found to be less than 2.5 mm d^{-1}. In irrigated crops the values were greater at about 3.4 mm d^{-1}, giving an annual water use of between 250 and 450 mm depending upon the availability of water (Beale *et al.*, 1999). Over the growing season in Italy from mid-April to the end of September, irrigated Miscanthus used between 360 and 620 mm (Ercoli *et al.*, 1999). However, the authors did not report changes in soil water storage over the season so these results need to be treated with a degree of caution.

Overall, there is a wide range in the amount of evapotranspiration reported in the literature. Many studies do not report ET out of season when soil evaporation will dominate though there may be enhanced evaporation from water stored on stems in coppice crops. In England, the potential evapotranspiration during the period November to March inclusive is about 50 mm in many areas of England and, whilst this is considerably less than rainfall, it must be taken into account in determining the hydrologically effective rainfall.

3.7 ROOT DEVELOPMENT

The study of roots and root soil interactions is fraught with difficulty and, though this topic area is now making progress, we still do not have a clear understanding of the processes involved, especially for trees grown as short rotation coppice (Dickmann and Pregitzer, 1993).

In *Populus,* large diameter woody roots grow radially away from the taproot, which is established from the original cutting. These roots extend in proportion to the height of the tree and are generally found in the top 0.2 m of the soil profile. Vertical roots or “sinkers” branch from the horizontal roots and can reach depths of more than 3 m (Dickmann and Pregitzer, 1993; Heilman *et al.*, 1994). In South West England, Hall *et al.* (1996) have also identified roots of three-year-old poplar at depths from 1.6 to at least 3 m depending on soil depth and clay content.

Willow is often considered to have a very different rooting pattern to Poplar, with a preponderance of surface roots but, in soils where there are no constraints to downward growth, they may be able to extract water from a similar depth. Souch *et al.* (2000b) have shown that water was being extracted from a depth of 1.8 m below two-year-old *Salix viminalis* cv Q683 grown in a sandy loam soil at Silsoe, Beds, suggesting that roots had reached at least to this depth.

The majority of roots are, however, concentrated in the topsoil where the nutritional resources are greatest (Elowson and Rytter, 1984; Ericsson, 1984; Heilman *et al.*, 1994). The root distribution will be modified by site characteristics and management practices. For example, soil compaction between the double rows of one-year-old *Salix viminalis* cv Q683 resulted in reduced numbers of roots in the top 0.3 m of the soil (Souch *et al.*, 2000b). In another study in a willow plantation in Sweden, most fine roots were found in the upper 0.5 m of the soil profile but drought caused a reduction in the number of fine roots and an increase in the mean root depth (Rytter, 1996). Soil moisture has been found to be the major determinant of root biomass accumulation in poplar with most produced in well-watered pots, intermediate amounts in droughted pots and the least in flooded pots (Liu and Dickmann, 1992).

As Liu and Dickmann showed, waterlogging can cause reductions in root growth and water uptake because of the poor aeration status around the roots. Biomass production in a range of poplar varieties varied in response to waterlogging (Hallgren, 1989). In general, root growth was restricted in flooded soils, although the capacity to grow roots in waterlogged soil was associated with total dry weight production. Some varieties showed an increase in biomass allocation to stem wood when grown in waterlogged soil. Root elongation in poplar was promoted by water table decline, as the trees maintained contact with a declining water table (Mahoney and Rood, 1992).

Growing trees in close proximity to each other can greatly affect their root morphology. For example in apple (*Malus domestica*), close spacing resulted in a less wide spreading root system (Atkinson *et al.*, 1976) and could result in a greater depth of soil being exploited where there are no barriers to root development. The root systems of close spaced willow or poplar may therefore be deeper than similarly aged single trees grown at wider spacings.

The root morphology of grasses is, of course, very different to that of trees but the effects of different rooting depths and densities on hydrology will be similar. Miscanthus roots have been found throughout the soil profile to a depth of beyond 2.5 m (Neukirchen *et al.*, 1999). More than half of the roots were found below 0.9 m. This is a greater rooting depth than most annual crops and Neukirchen concluded that Miscanthus would therefore be able to overcome periods of low nutrient and water availability. On a site in eastern England, 90% of the roots of three-year-old Miscanthus growing in a soil with a good water holding capacity were found in the upper 0.5 m of the soil profile (Beale *et al.*, 1999). The soil water content profiles below the crop also indicated the presence of roots to at least 1.2 m. At the other end of the spectrum, sugar cane is sometimes grown in very poor soils, which may be only 0.3 m deep and consist of 50% stone. In these conditions the total available water capacity may be used within one to three days but, with access to water from irrigation, the water use and biomass production is similar to crops on much deeper soils. There therefore seems no reason why Miscanthus should not be able to utilise available soil water to the same extent as willow SRC.

3.8 GROUNDWATER UPTAKE

Trees and other crops are very responsive to differences in water content in the root zone. In apple, the roots had the capacity to transfer water from locally wet areas at much higher rates than normally occurs when the whole root zone is wet (Green *et al.*, 1997). This ability is particularly important when trees have access to groundwater and they have been shown to be very capable of extracting large quantities of water in these circumstances. In Australia, for example, trees have been planted to increase the depth of water tables to help control salinity. Cramer *et al.* (1999), working in an area with shallow saline groundwater, showed differences in the ability of tree species to take up groundwater at depths of around 1.5 m. At another site in Australia, a high density *Eucalyptus* plantation started to lower the water table four years after planting with water table uptake accounting for 430 mm of the annual 720 mm water use of the trees (Heuperman, 1999).

In a comprehensive study of water use by phreatic vegetation in semi-arid western North America, the ability to use groundwater was also shown to be species dependent (Snyder and Williams, 2000). *Salix goodingii* was dependent on groundwater for all of its water supply, even when the water table was at 4 m, whereas *Populus fremontii* also used water from the upper soil layers when it was available after rainfall. Goodrich *et al.* (2000) indicate the importance of seasonal riparian evapotranspiration, which can be an important component of the overall water balance in semi-arid regions. They report that *S. goodingii* and *P. fremontii* in contact with the capillary fringe above groundwater transpired twice as much as those dependent on soil water.

Closer to home, over a three month period in the UK, poplars grown in a flood plain with their roots in contact with the water table transpired 213 mm of which about 90 mm was from groundwater. The percentage extracted from the groundwater increased from 15 to 63% as the soil moisture was depleted (Zhang *et al*., 1999). Transpiration was closely linked to evaporative demand, and the shallow water table was an important water resource for the plants. Roots were found below the water table depth at 1.2 – 1.3m.

There was no direct evidence found in the literature of Miscanthus or other C_4 grasses extracting groundwater but in riparian areas, groundwater can provide a very important source of water, especially during the late summer in drier areas when water stress might otherwise restrict the transpiration and growth of energy crops.

3.9 MODELS OF GROWTH AND WATER USE

There have been a number of reviews of energy forestry models in recent years (Ceulemans, 1996; Isebrands and Burk, 1993; Isebrands *et al*., 1996; Perttu and Kowalik, 1989). Perttu (1989) concluded that, whilst the process modelling approach holds promise for use as research and management tools, greater emphasis would need to be placed on below-ground and whole-tree physiological processes in future. Similarly, when Ceulemans (1996) reviewed 10 tree and stand growth models (ranging from detailed simulation of leaf-level photosynthesis through three-dimensional radiative transfer approaches to general models of forest growth) to evaluate their potential within short rotation forestry systems he concluded that there was no single model readily available that could be used to model SRC growth. In another study, Isebrands *et al.* (1996) proposed a multi-scale modelling strategy for extrapolating from detailed mechanistic models up to regional level.

The main difficulty with the low-level process-based models is that they tend to require very detailed data at short time intervals to run them. When attempting to identify the hydrological effects of energy crops, however, more simple approaches can be used, such as the SIMWUCOP model used by Hall *et al.* (1996) in their comparative study of water use by agricultural crops and SRC. The main advantage of these approaches is that they work at a daily time step for which meteorological data is widely available. Comparative studies are therefore possible over a large number of years. Hall *et al.* (1996) showed that SIMUWUCOP predicted ET well for their site. They estimated that water use by coppice would exceed that of grass and wheat by 160 to 250 mm on average depending on the soil type and that this would result in a reduction in drainage of between 150 and 180 mm. However, in seeking to investigate the wider implications of energy coppice on hydrology it is necessary to explore the sensitivity of the outputs to changes in crop, soil and weather parameters.

In this study, we have used a simple water balance model (WASIM[6]) to simulate the water use, runoff and deep percolation under different environmental conditions. An earlier version of this model has been used for estimating water requirements for agricultural crops (Weatherhead and Knox, 2000) and is the basis for water resource planning for agriculture by the Environment Agency. There are pitfalls with adopting this approach related to the assumptions on crop responses to water stress made in the model. The effects of internal factors such as water stress feedback on leaf area and external factors such pest and disease attack are not modelled. For the purposes of this report, however, we consider that a simplistic approach should be sufficient to identify the key areas of uncertainty and the sensitivity of energy crop water use to variations crop, soil and climate factors.

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[6] This model has been developed by the Institute of Water and Environment, Cranfield University and HR Wallingford to simulate water use by agricultural crops (Hess and Counsell, 2000).

3.10 EFFECT OF FORESTS ON RIVER FLOWS

3.10.1 Annual yield

In wet conditions interception losses from forests are higher compared to shorter crops and in dry conditions, evapotranspiration is higher due to deeper rooting depths. Therefore, river flows from forested catchments are likely to be lower than from catchments with short vegetation. Newson and Calder (1989) suggested that forests may reduce stream flow by up to 20% compared to grassland and the majority of the world's catchment studies indicate decreased runoff from catchments under forests compared to those under shorter crops (Calder, 1998a).

At the upper end of the scale, Waterloo *et al.* (1999) estimated that in tropical maritime conditions reductions in annual water yield of about 500 – 700 mm could be expected if grassland was replaced with *Pinus caribaea* where ET was between 1700 and 1900 mm.

However, experimental results in UK are inconclusive. A major experiment comparing grassland and forest hydrology was carried out on the Plynlimon catchment in mid-Wales between 1969 and 1995, (Hudson *et al*., 1997). The evaporation losses from the forested area declined from 61% above that of the grassland in the early years to a level only 18% higher before the start of felling in 1985. Since 1990 the forest catchment losses appear to have stabilised at 5-10% below those of the grassland catchment. Similarly, Robinson *et al*., (Robinson *et al*., 1998) working in N E England, showed that the different stages of forest development can have very different environmental effects. Harding *et al.* (1992) (cited in (Calder, 1998a) found that broadleaf forests on chalk soils in S. England had lower water use compared to grass.

3.10.2 Low flows

It is difficult to generalise on the impact of land use change on low flows due to the site specific processes controlling runoff. However it would be expected that increased dry season ET would reduce dry season flows whilst increased infiltration could lead to higher soil water recharge and higher dry season flows (Calder, 1998a). It is clear that the management of the woodland has a significant impact on the low flow regime. A review by Johnson (1998) highlighted that the stage in the forest cycle had important effects. Drainage and clearfelling increased low flows initially but forest growth decreased low flows in all but the driest years. In these years drift deposits and geology tended to control the low flow. Johnson suggests that these effects are most apparent when more than 25% of the catchment is forested. Field drainage associated with woodlands can increase dry season flows (Calder, 1993). On a river basin scale the effects can be further obscured by differences in catchments, land use and forest growth stage.

3.10.3 Floods

The general conclusion appears to be that there is little relationship between landuse and flood flows. Increased interception from forest, which has a marked effect on the runoff from small storms, has a relatively small effect during big storm events. Management of woodlands (roads, ditches, etc.) has a greater impact (Calder, 1993).

3.11 CONCLUSIONS

The key conclusion that arises from our review of the available literature is that there is considerable site specificity in the water use of energy crops and their consequent effects on runoff and deep percolation. There is considerably more information available on the water use and hydrological effects of willow SRC than for Miscanthus and other C_4 grasses. The limited information available does suggest, however, that the behaviour of SRC and energy grasses may be quite similar.

Within the hydrological cycle the importance of the connection between the foliage and the bulk atmosphere, the “coupling” factor, cannot be underestimated. This will determine whether transpiration is driven primarily by the saturation deficit or by solar radiation receipts. In the former case, the total water use per unit area could be substantially greater than where large contiguous areas are grown, especially if the crops are grown in soils with a large available water capacity or have access to ground water.

In well-coupled crops, interception losses may reduce net rainfall be 20 – 30% compared to decoupled crops with consequent reductions in hydrologically effective rainfall. It is not clear how the size and shape of energy crop plantations modifies the coupling factor.

4 MODELLED WATER USE

4.1 INTRODUCTION

The review of factors affecting the water use of energy crops highlights the complexity of the interactions between crop and environment. Site specific factors will tend to result in large differences in water use and hence the water balance can be expected to vary considerably.

4.2 THE WASIM MODEL

4.2.1 Introduction

The WaSim model is a one-dimensional, daily, soil water balance. It aims to simulate the soil water storage and rates of input (infiltration) and output (evapotranspiration and drainage) of water in response to climate. The input of water to the soil is net rainfall, defined as the gross amount, less interception losses, and surface runoff. The outputs of water from the profile are soil evaporation, plant transpiration and deep percolation. The model can be used to simulate water table fluctuations, but in this case free drainage from the root zone was assumed.

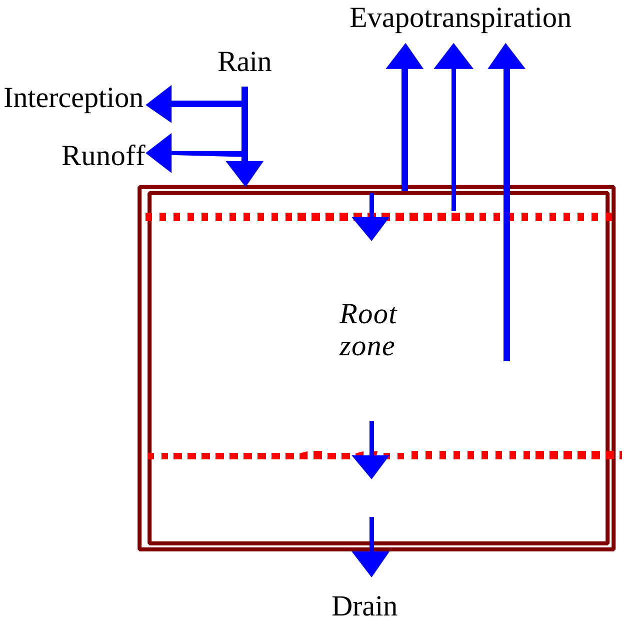

Figure 6. Schematic representation of the WaSim soil water balance model

4.2.2 Standard parameterisation

The predicted sensitivity of energy crops to changes in crop and environmental parameters was tested using a 30-year climate data set from Silsoe, Beds, which is situated in the driest area of the country. The WaSim model was set up to run for the whole of the available weather dataset using a standard set of parameters. For each sensitivity analysis, one parameter was modified within the range of potential values to determine the predicted effects on the components of the water balance.

The key factors identified in the literature review and from direct experience were taken to be:

- soil type;
- canopy emergence and development;

- interception losses;
- crop coefficient, used to represent the amount of advection;
- soil readily available water; and
- root depth.

The standard parameters were taken to be 2nd year rotation willow SRC grown at Silsoe on a sandy clay loam with canopy emergence on 1 April, 20% cover on 25 April, 100% cover on 1 June, beginning of canopy senescence on 25 September and total leaf fall by 15 November. The canopy had a storage capacity of 2 mm and intercepted a further 10% of all rainfall. The crop coefficient at full canopy was 1.2 (120% of reference evapotranspiration (ET_0). The crop was assumed to have a root depth of 2.5 m and an easily available capacity of 50%. This scenario represents a healthy, fast growing, mature coppice crop grown on a common soil type with a relatively low available water capacity.

4.3 SENSITIVITY

4.3.1 Introduction

In investigating the likely effects of energy crops on hydrology there are a large number of variables that might affect the results of the simulation. This section reports broad sensitivity analysis for canopy emergence, crop coefficient, root depth and interception losses. The sensitivity analysis was carried out using weather data for January 1970 to December 1998 from Silsoe, Bedfordshire (52 °N) with all other factors held constant.

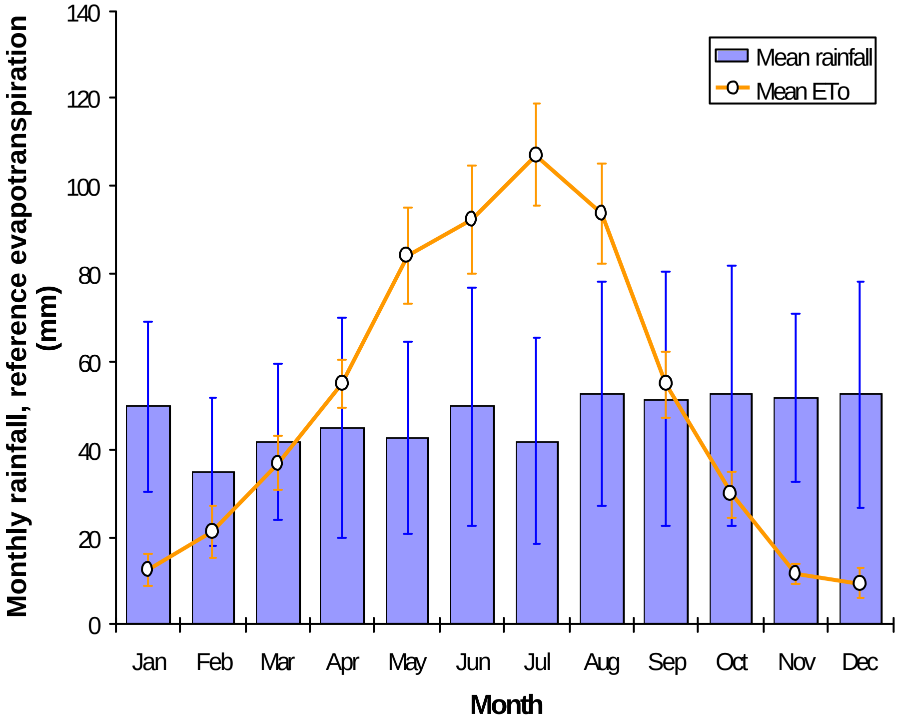

Figure 7. Mean monthly rainfall and reference evapotranspiration (ET_0) at Silsoe, Beds, for 1970 – 1998. Monthly variability is indicated with the 20% and 80% probabilities of exceedence.

At Silsoe there is an even distribution of rainfall across the year with about 40 to 50 mm falling in each month (Figure 7). The driest month is February, largely because it is shorter than the others. In two years out of ten there will be less than 20 to 30 mm in any given month and in two years the monthly rainfall will exceed 50 to 80 mm.

Reference evapotranspiration (ET_0) shows a strong seasonal pattern but is less variable from year to year than rainfall. In most years at Silsoe, ET_0 exceeds rainfall during April to September inclusive.

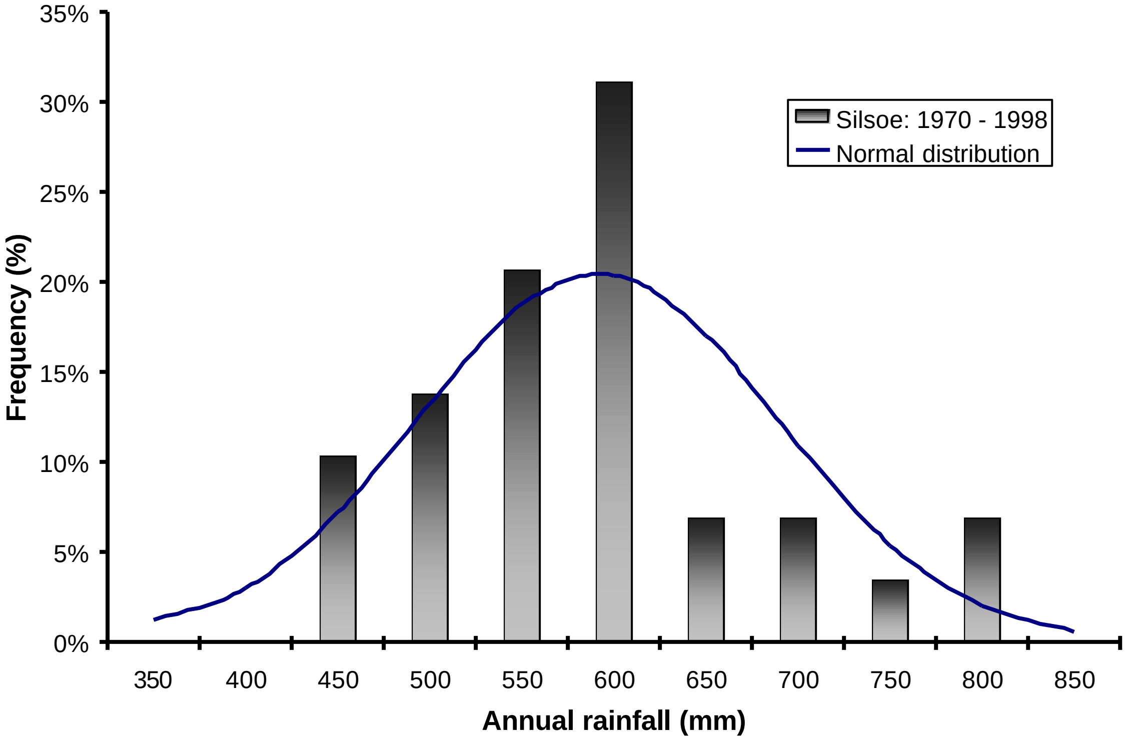

Figure 8. Frequency distribution for annual rainfall at Silsoe, Beds: 1970 – 1998.

The annual rainfall at Silsoe broadly conforms to a normal distribution with a mean of 570 mm and a standard deviation of 96 mm. By comparison, the mean annual ET_0 at Silsoe is 610 mm with a standard deviation of only 60 mm, reflecting the less variable nature of evapotranspiration.

4.3.2 Soil type

With the expansion of the area of energy crops, they are likely to be grown on an increasingly wide range of soils. To investigate the effect of soil type, WaSim was run using standard crop parameters for five soils with differing hydraulic characteristics (Table 1).

Table 1. Soil water characteristics for typical soils used in the sensitivity analysis for energy crop impacts on hydrology.

Soil type	Saturation water content (% v/v)	Field capacity (% v/v)	Permanent wilting point (% v/v)	Available water capacity (mm m^{-1})	SCS Curve Number[7]	Saturated hydraulic conductivity (m d^{-1})
Sand	43.7	11.5	3.3	82	36	15.0
Sandy Loam	45.3	24.5	9.5	150	60	2.0
Sandy Clay Loam	39.8	24.1	14.8	93	70	3.2
Silty Loam	50.1	32.4	13.3	191	73	0.1
Clay	47.5	36.8	27.2	96	79	0.1

Soil type had a small effect on simulated annual evapotranspiration (ETa; Figure 9). More than doubling the available water capacity from 82 to 190 mm m^{-1} only increased ETa by about 10%. In addition the year-to-year variability was limited with ETa in six out of ten years falling within a range of 7 – 9% of the mean value. Because rainfall and ETa are finely balanced at Silsoe, relatively small changes in either component translate into large proportional differences in runoff and deep percolation.

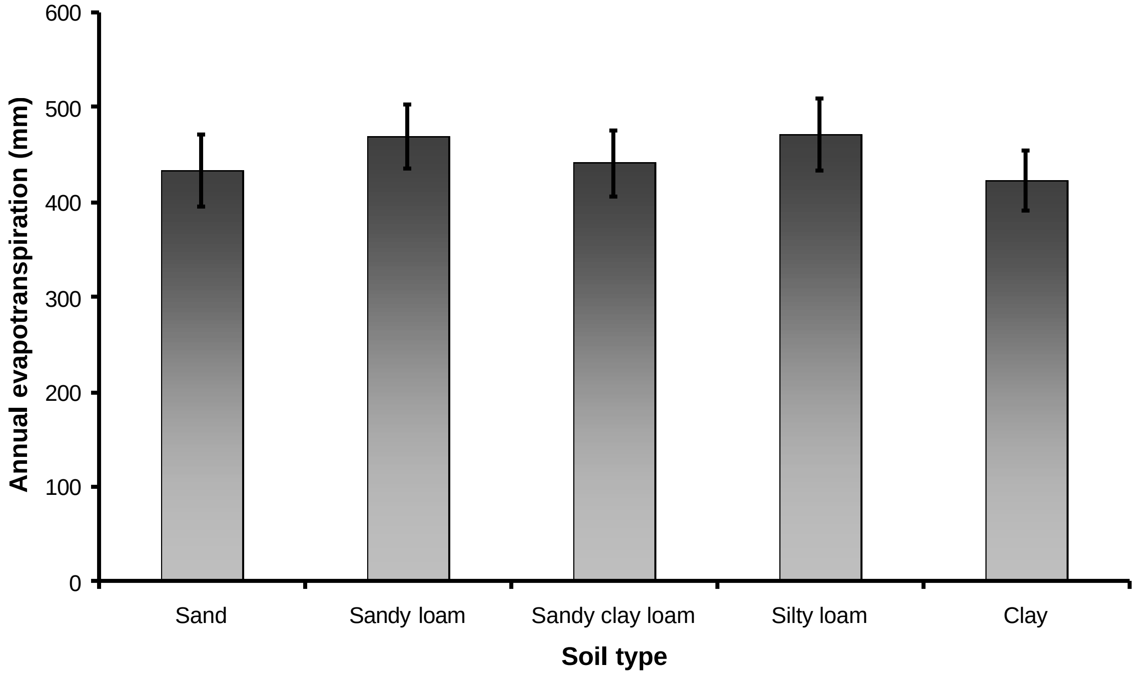

Figure 9. Effect of soil type on simulated annual evapotranspiration by willow SRC at Silsoe, Beds: 1970 – 1998. Error bars represent the 20% and 80% probabilities of exceedence.

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[7] The US Soil Conservation Service developed the empirical Curve Number method for describing rainfall-runoff relationships for different soil types, land uses, treatments and hydrologic conditions. The values used to parameterise WaSim reflect fair hydrologic conditions under woods based on a moderate depth of litter and humus.

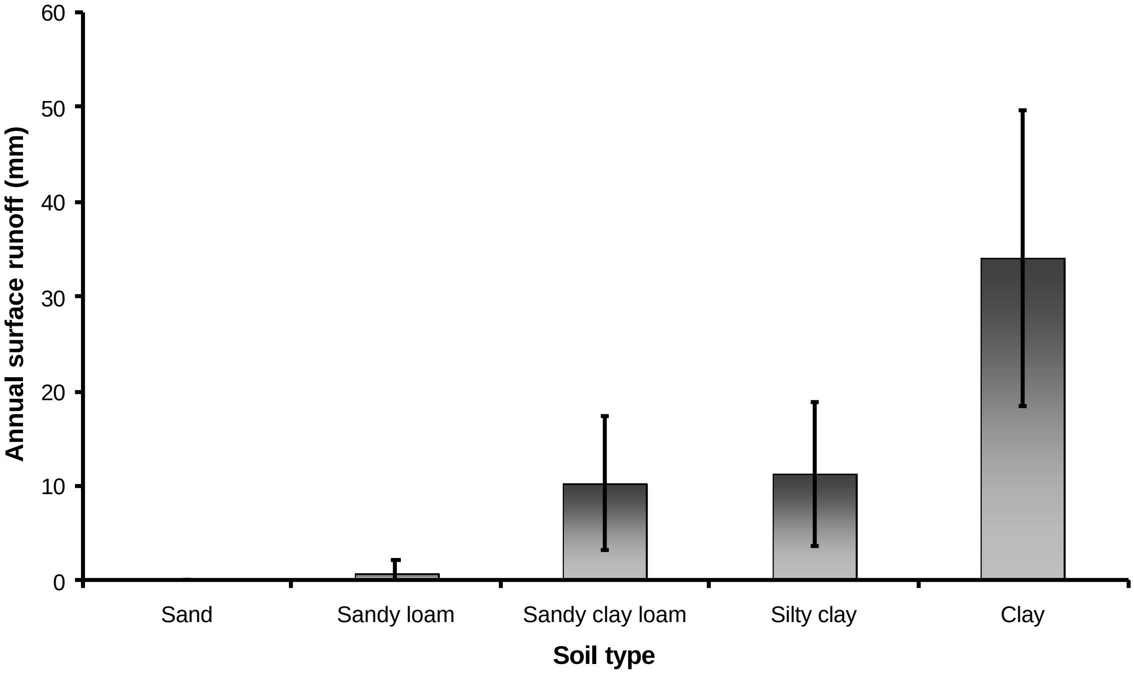

Figure 10. Effect of soil type on simulated annual runoff under willow SRC at Silsoe, Beds: 1970 – 1998. Error bars represent the 20% and 80% probabilities of exceedence.

The effect on runoff was very marked and reflected the relative ease with which water infiltrated into the soil (Figure 10). Unsurprisingly, there was greatest runoff on clay soils and none on sand reflecting the parameterisation of the model using the SCS curve numbers for different soil types.

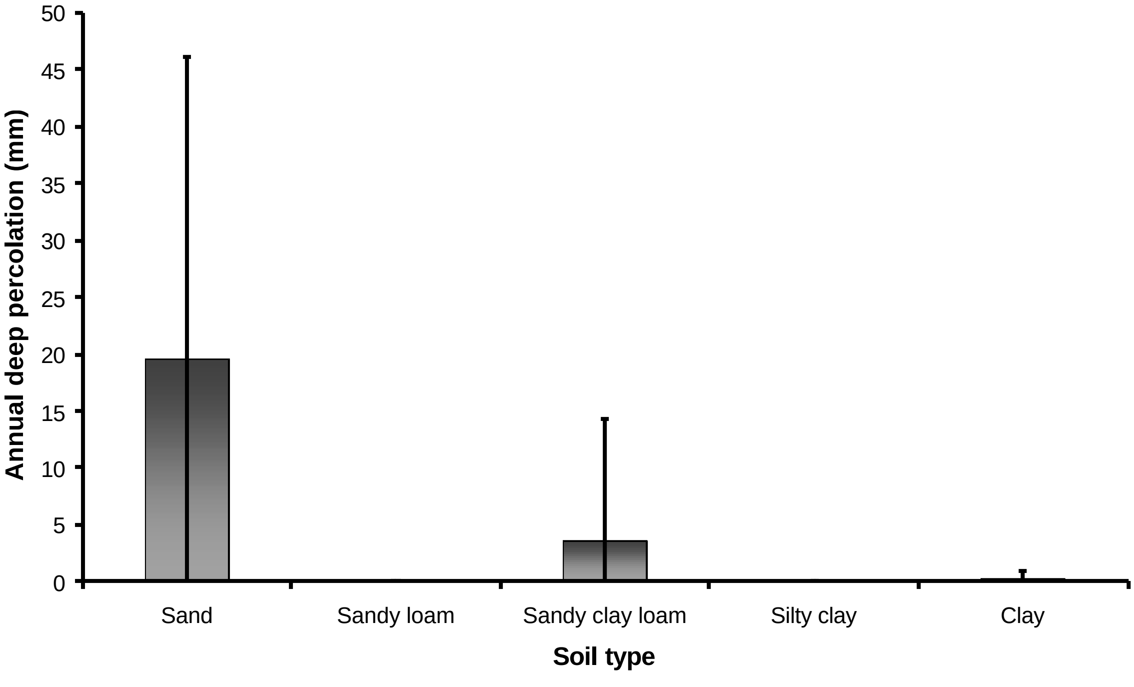

Figure 11. Effect of soil type on simulated annual deep percolation under willow SRC at Silsoe, Beds: 1970 – 1998. Error bars represent the 20% and 80% probabilities of exceedence.

For the parameter set used in this analysis there was little or no deep percolation below the root zone except for SRC grown on sand. There was also considerable year-to-year variability in annual deep percolation amount on sandy soils. In many years the soil did to wet back to field capacity during the winter and the early growth of the canopy could therefore be affected by drought during dry springs.

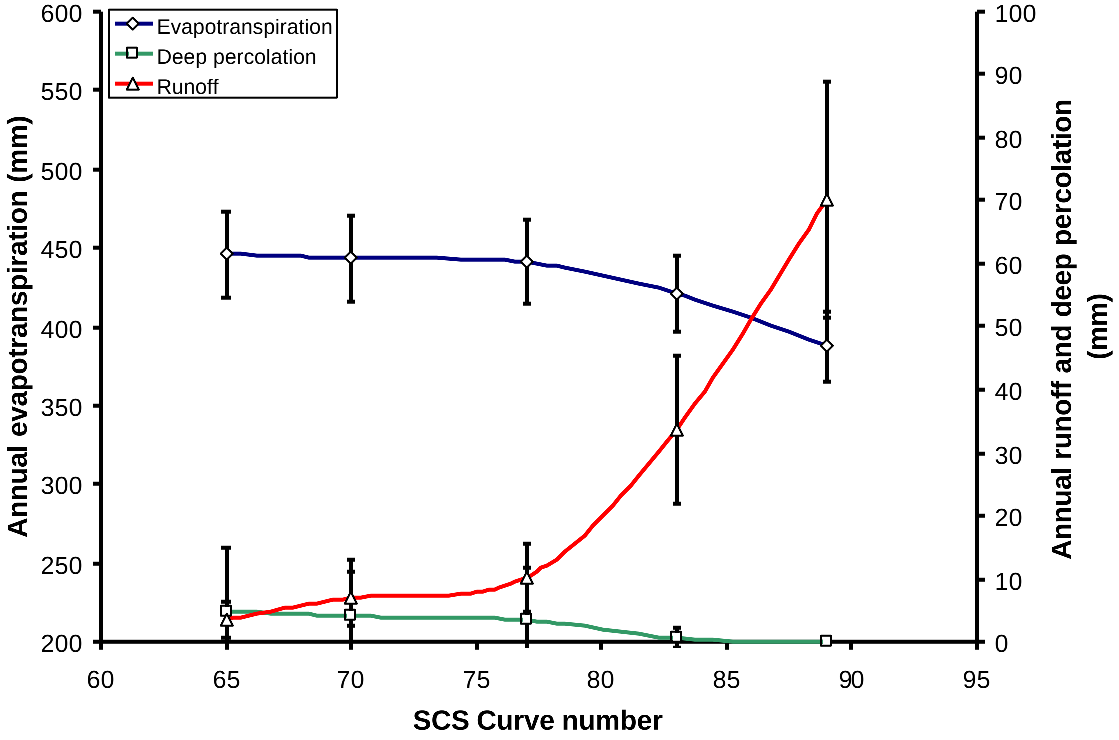

Figure 12. Effect of soil hydrologic condition on simulated annual evapotranspiration, runoff and deep percolation under willow SRC on sandy clay loam soil at Silsoe, Beds: 1970 – 1998. The error bars indicate the range within which 60% of values lie.

To investigate the sensitivity of the components of the water balance to infiltration the model was run for a range of SCS Curve Numbers between 65 and 89. For this soil type, the range covers deep litter and humus layers under woods to bare soil. Increasing infiltration increases deep percolation but also ETa. For curve numbers above 77 the effect was very marked indicating that the crop was increasingly water stressed during the growing season because insufficient water was infiltrating into the soil.

4.3.3 Canopy emergence

The date of canopy emergence can vary across the country with temperature and also with age and stage of the coppice cycle. This analysis assumes a range of emergence dates from mid-March to mid-May. In all scenarios the canopy was set to reach 20% cover after one month and full cover a month later. For all simulations leaf senescence began on 1 October and the crop was defoliated by 15 November.

The soil was assumed to be a sandy clay loam and the root depth 2.5 m representing a mature coppice crop on soil with no restrictions to root development.

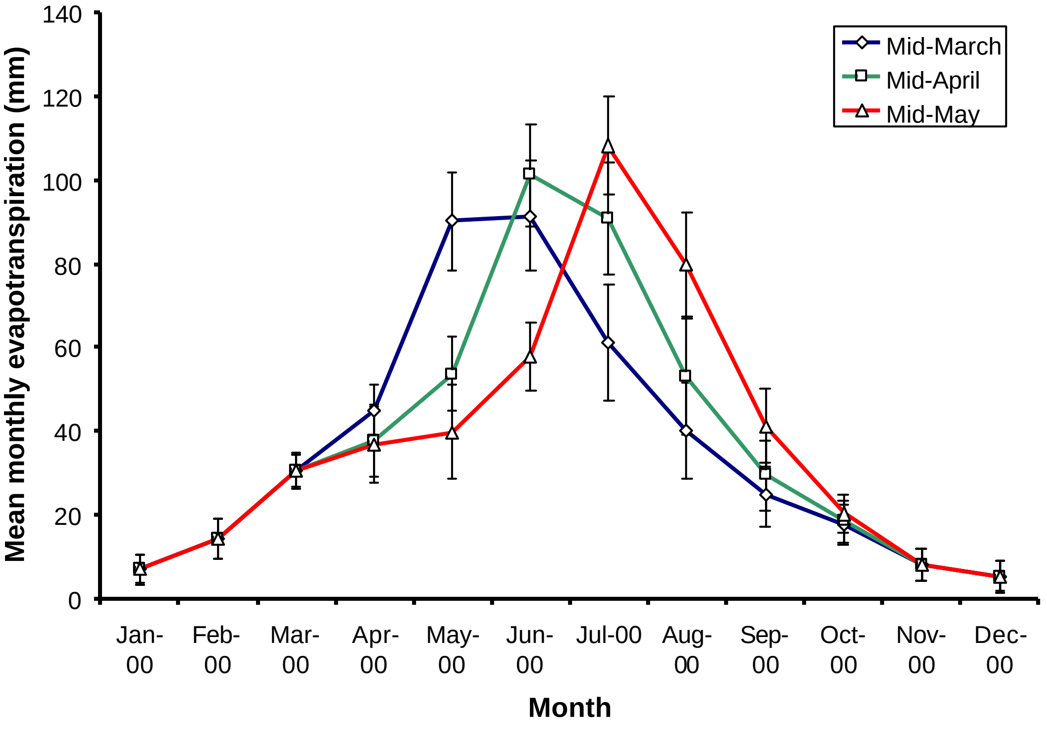

Figure 13. Mean effect of different canopy emergence dates on simulated actual evapotranspiration of Willow SRC at Silsoe, Beds, during 1970 - 1998. The error bars indicate the range within which the monthly values will lie in six years out of ten.

For all canopy emergence dates, the monthly ETa from October to March, when soil evaporation was the main component, was highly consistent as indicated by the small range in ETa for each month (Figure 13). When the canopy emerged, there was greater year-to-year variability in monthly ETa and there were clear differences in the seasonal pattern of ETa related to the different dates of canopy emergence.

The general pattern reflects the water limiting growth of coppice at Silsoe. When the canopy emerged in mid-March the crop used soil water faster than it was being replenished by rainfall in May. This meant that, by July, ETa was limited by water stress. Conversely, where the canopy emerged in May (as might be expected in the first year after cutback or harvest) there was sufficient soil water to sustain a high rate of evapotranspiration in July and August. In all three scenarios, even with a 2.5 m deep root system, there was only enough water for two months ETa at close to potential rates before the soil water storage was depleted.

Overall, this led to the maximum water use occurring in crops with late canopy development, primarily because they were less subject to water stress when there was maximum atmospheric demand in July and August (Figure 14).

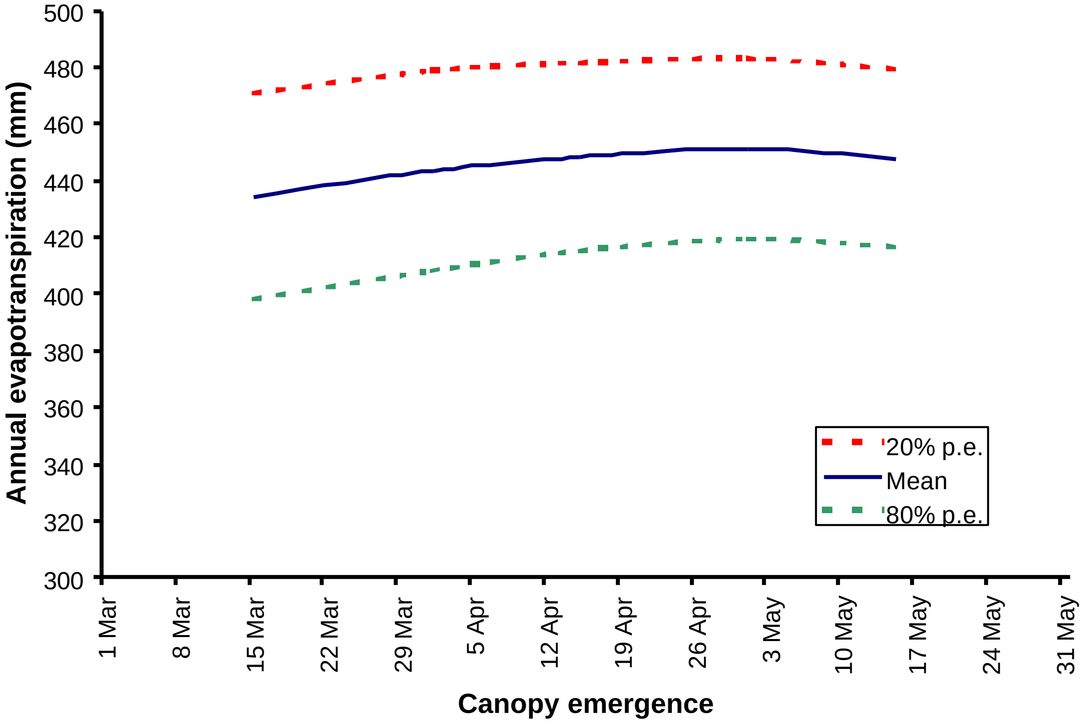

Figure 14. Effect of canopy emergence date on simulated annual actual evapotranspiration of willow SRC at Silsoe, Beds, showing the 20% and 80% probabilities of exceedence values.

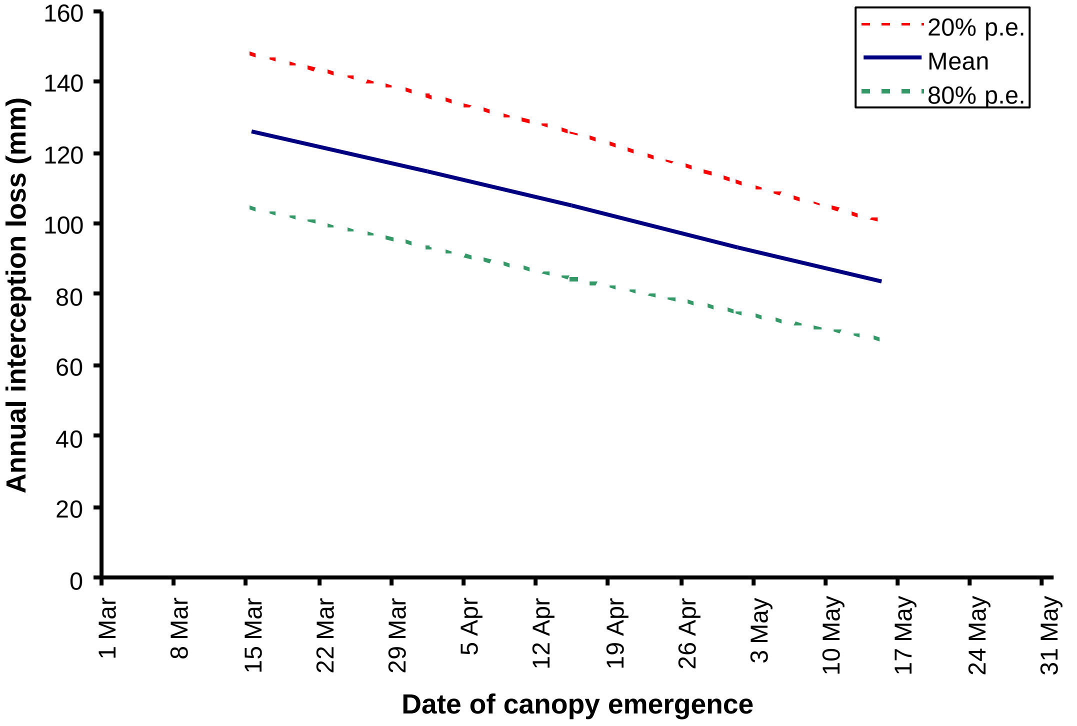

Figure 15. Effect of date of canopy emergence on simulated interception losses from willow SRC at Silsoe, Beds: 1970 – 1998.

The simulated interception losses decreased linearly with the decreasing canopy duration, as would be expected at a site where rainfall is fairly uniformly distributed through the year (Figure 15). The mean interception loss when the canopy emerged in mid-March was about

130 mm compared with only 90 mm when the canopy emerged in mid-May. The decreased canopy duration therefore means that the canopy would be wet on fewer occasions and net rainfall would be greater.

The effect of later canopy emergence on simulated deep percolation was, however, non-linear and increased almost exponentially with delayed canopy development (Figure 16). In the driest two years out of ten no deep percolation was predicted whenever the canopy emerged. By contrast, in the wettest two years in ten, deep percolation increased very rapidly with delayed canopy emergence.

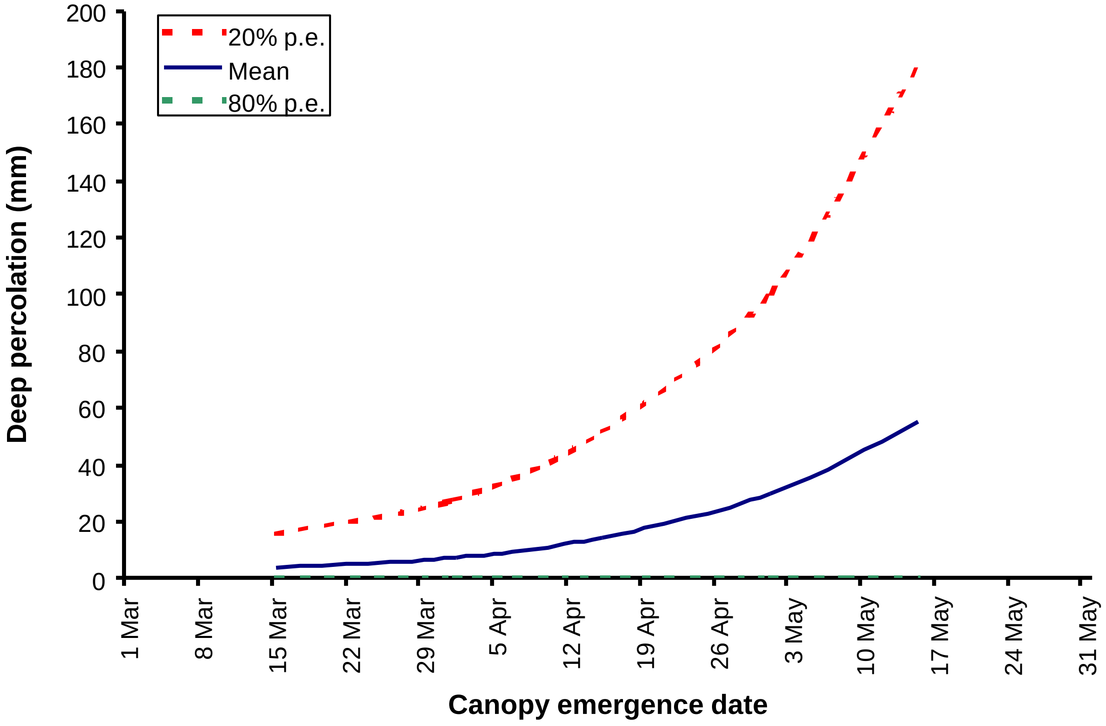

Figure 16. Effect of different canopy emergence dates on simulated deep percolation under willow SRC at Silsoe, Beds, showing the 20% and 80% probabilities of exceedence values.

The annual average deep percolation was not, however, normally distributed and a frequency distribution for different canopy development dates shows that with leaf emergence in mid-March, there was no predicted percolation below the root zone in 90% of years (Figure 17). If the canopy came into leaf in mid-May, for example in the year after coppicing or after a cold spring, then over 70% of years would have some deep percolation below the root zone and, in wet years, there would be relative large contributions to ground water recharge.

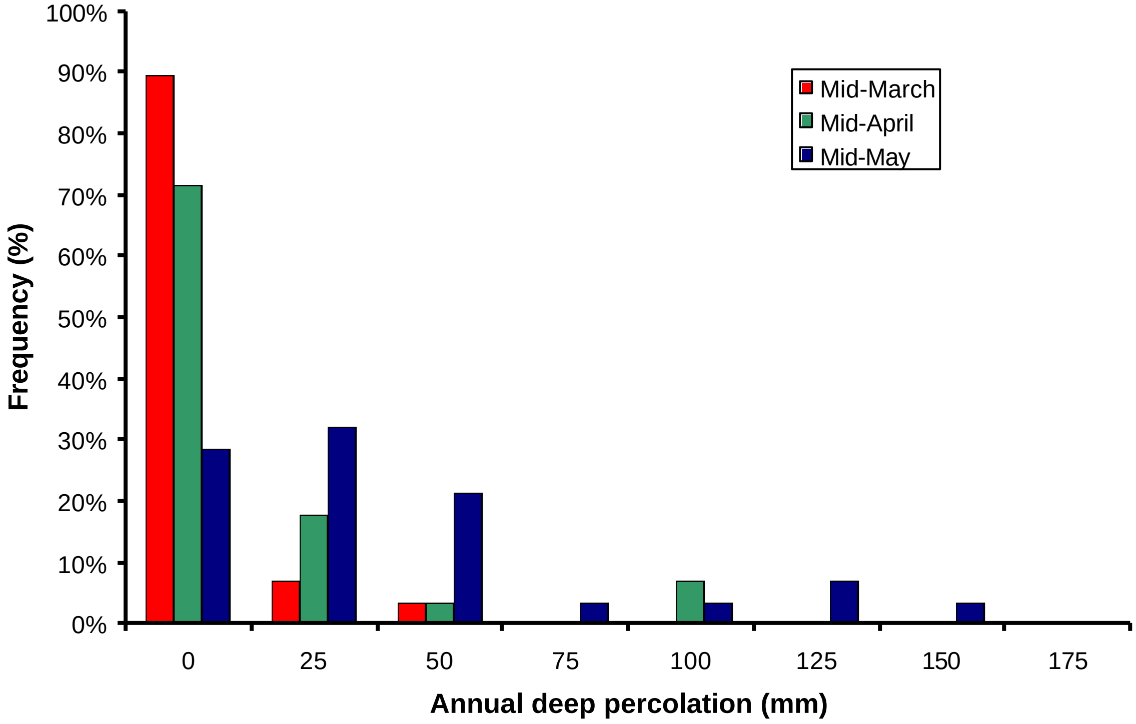

Figure 17. Frequency distribution of simulated annual deep percolation for three canopy emergence dates in willow SRC at Silsoe, Beds.

4.3.4 Interception losses

WaSim simulates canopy interception through two parameters: the canopy storage factor (where water retained on the leaves of the crop is assumed to evaporate); and the further proportion of rainfall that is assumed to evaporate from the canopy during rainfall. In order to simulate the effects of different levels of canopy interception the canopy storage was set at 0, 1 or 2 mm and the proportion of rainfall evaporated was varied between 0 and 10%.

The upper end of the simulation range (2 mm of canopy storage and 10% reduction in the remaining rainfall) results in a mean simulated interception loss of 20% of annual rainfall. This is close to the value recorded for poplar SRC by Hall *et al.* (1996) but less than the 31% observed in Sweden by Ettala (1988) when the foliage was wet on a large proportion of days with supplemental irrigation. The model was also run with no interception losses to simulate the scenario that all interception substituted for transpiration.

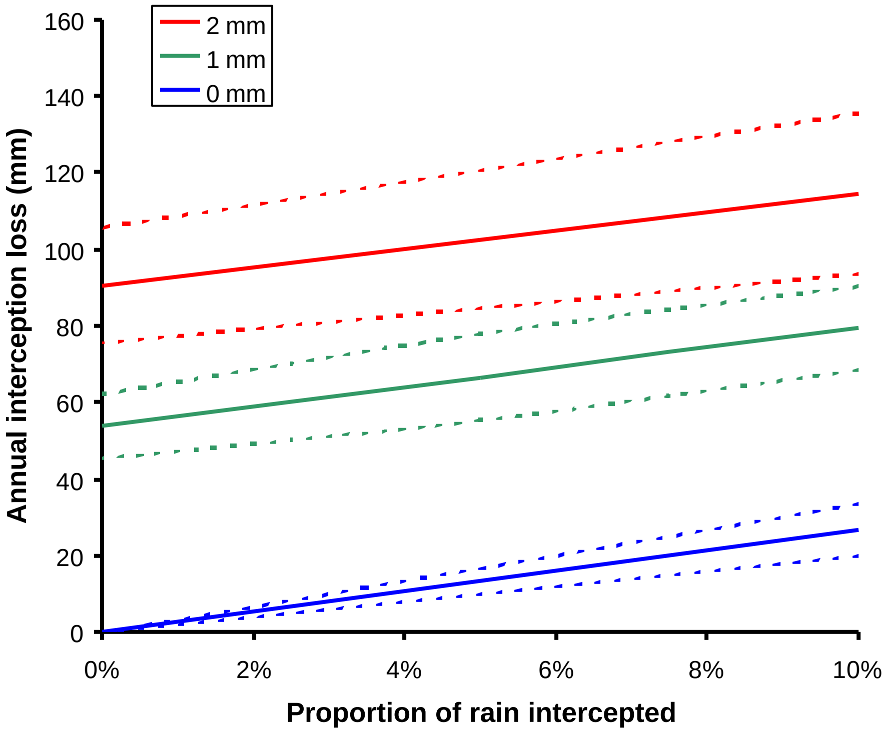

Figure 18. Effect of interception losses with 0, 1 and 2 mm canopy storage capacities on simulated annual interception losses from willow SRC at Silsoe, Beds: 1970 – 1998. The solid lines represent the mean annual response and the upper and lower dotted lines represent the 20 and 80% probabilities of exceedence respectively.

The size of the canopy will determine the amount of water that can be stored. For many crops the storage capacity is in the range 1 to 2 mm but when they are decoupled from the atmosphere then intercepted water may substitute for transpiration. The effect of increasing the storage capacity of the canopy is large, equivalent to about 6% of mean annual rainfall at this site (Figure 18). In addition the variability in annual interception increases with the larger storage capacity.

The effect that interception has on evapotranspiration is less marked with a reduction in rain throughfall of 10% resulting in only a 3 to 4 % reduction in ETa (Figure 19). With no interception, ETa was predicted to be 520 mm annum^{-1}.

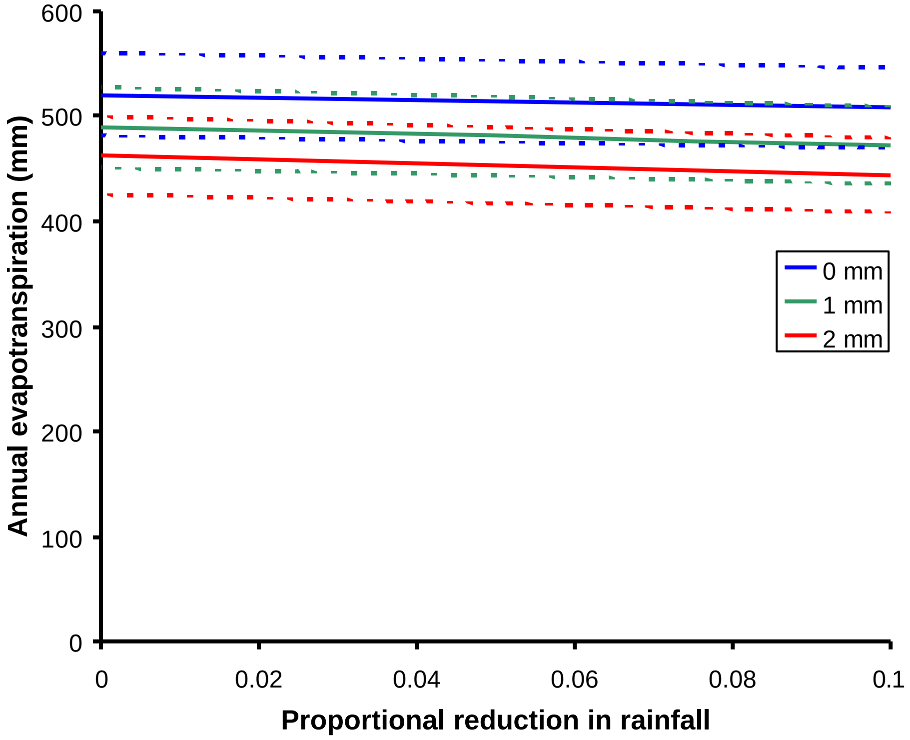

Figure 19. Effect of interception losses with 0, 1 and 2 mm canopy storage capacities on simulated annual evapotranspiration from willow SRC at Silsoe, Beds: 1970 – 1998. The solid lines represent the mean annual response and the upper and lower dotted lines represent the 20 and 80% probabilities of exceedence respectively.

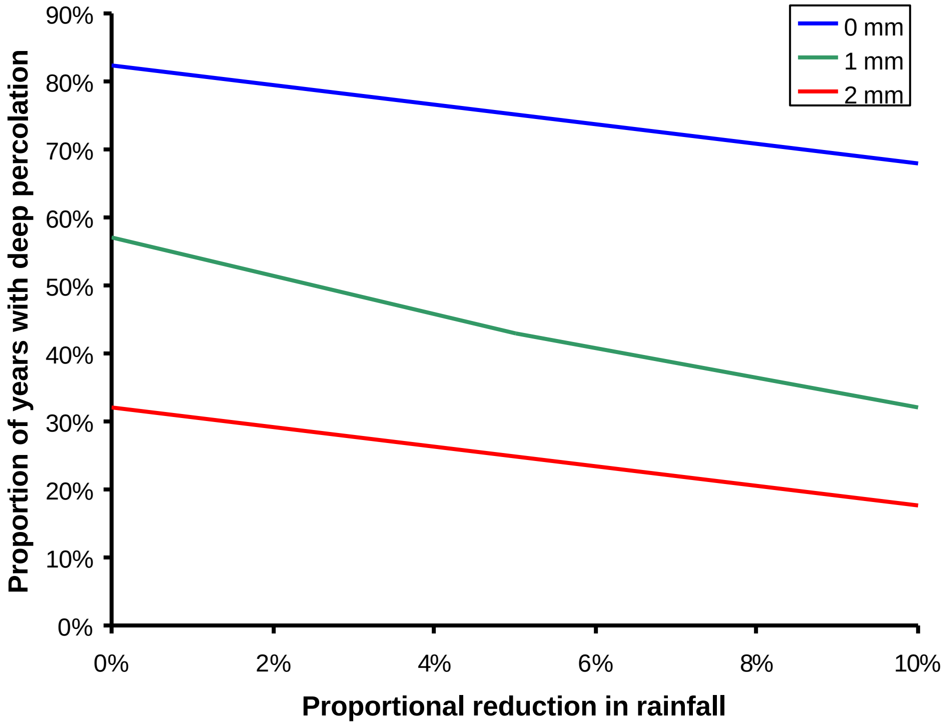

Figure 20. Effect of interception losses with 0, 1 and 2 mm canopy storage capacities on simulated deep percolation under willow SRC at Silsoe, Beds: 1970 – 1998.

Increasing interception losses has a large effect on deep percolation in particular (Figure 20). There is a large reduction in the predicted number of years in which deep percolation occurred reflecting the close balance between ETa by energy crops and rainfall in this agroclimatic area.

4.3.5 Crop coefficient (Kc)

Varying the crop coefficient, relating crop evapotranspiration (ETa) to reference evapotranspiration (ET_0), changes the rate at which the crop is predicted to use water. Running WaSim with a range of crop coefficients from 0.8 to 1.5 allowed the annual ETa and the other components of the hydrological balance to be predicted.

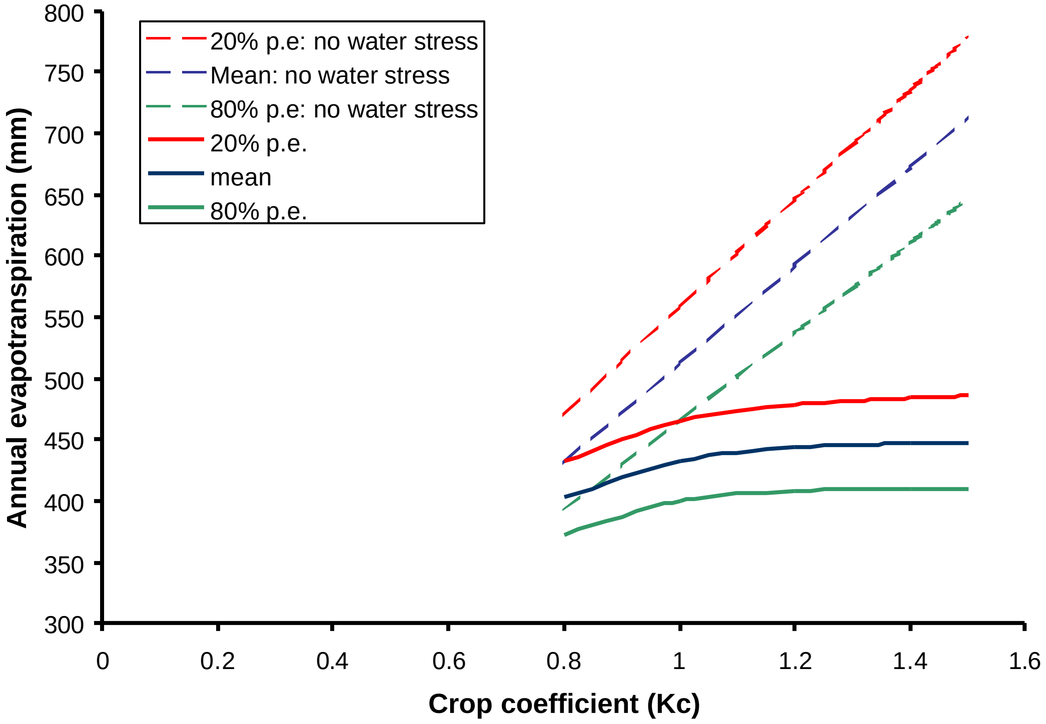

Figure 21. Effect of crop coefficient on simulated actual evapotranspiration (ETa) from willow SRC at Silsoe, Beds with and without water stress. The dashed lines show the simulated ETa when there is no water stress.

At Silsoe, water stress has a very marked affect on the simulated ETa even with low crop coefficients (Figure 21). The mean annual ETa only increases by 5% to about 490 mm annum^{-1} with a 50% increase in Kc from 1.0 to 1.5. With no water stress, the simulated ETa increases linearly reaching over 700 mm annum^{-1} for a well coupled crop (Kc 1.5). This series of simulations also clearly illustrates the likely effect of drought on dry matter production. At a Kc of 1.2 for a large area of coppice, predominantly decoupled from the atmosphere, the unstressed crop was predicted to transpire 150 mm more than the crop relying solely on rainfall. Thus, at least in the drier areas of the country, the growth of energy crops that are not able to access ground water will be water limited even when the root depth is 2.5 m.

Table 2. Effect of crop coefficient (Kc) on the proportion of years with deep percolation and the annual total in those years: Silsoe, Beds 1971 – 1998.

Kc	Proportion of years	Annual mean (mm)
0.8	82%	50.8
1.0	43%	31.4
1.2	18%	23.6
1.4	7%	25.3

The effect on deep percolation is very marked as increasing Kc not only reduces the number of years in which there is any drainage below the root zone but also reduces the mean amount in those years (Table 2). Thus the likelihood of groundwater recharge in any year beneath a rainfed coppice crop with a Kc of 1.4 is less than 1 in 10. At low Kc values, the amount of deep percolation in wet years is substantial and exceeded 100 mm in almost 20% of years (Figure 22).

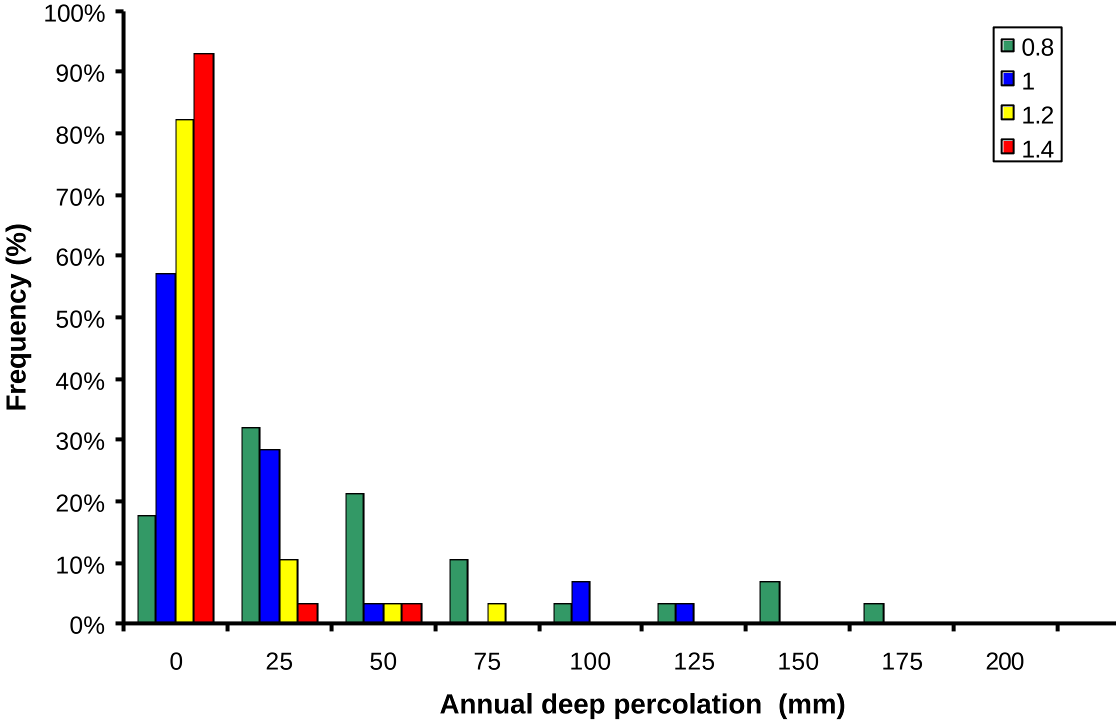

Figure 22. Effect of crop coefficient (Kc) on simulated annual deep percolation under willow SRC at Silsoe, Beds during 1971- 1998.

The effect on runoff is not so marked and increasing Kc from 0.8 to 1.4 only decreases the annual runoff by about 1 mm (Figure 23). This reflects the low runoff expected from a well-structured soil beneath an established coppice crop where most water will infiltrate rapidly. In crops that suffer no water stress there may be marginally more runoff as the soil will tend to be wetter and hence rainfall may exceed the infiltration capacity of the soil more quickly.

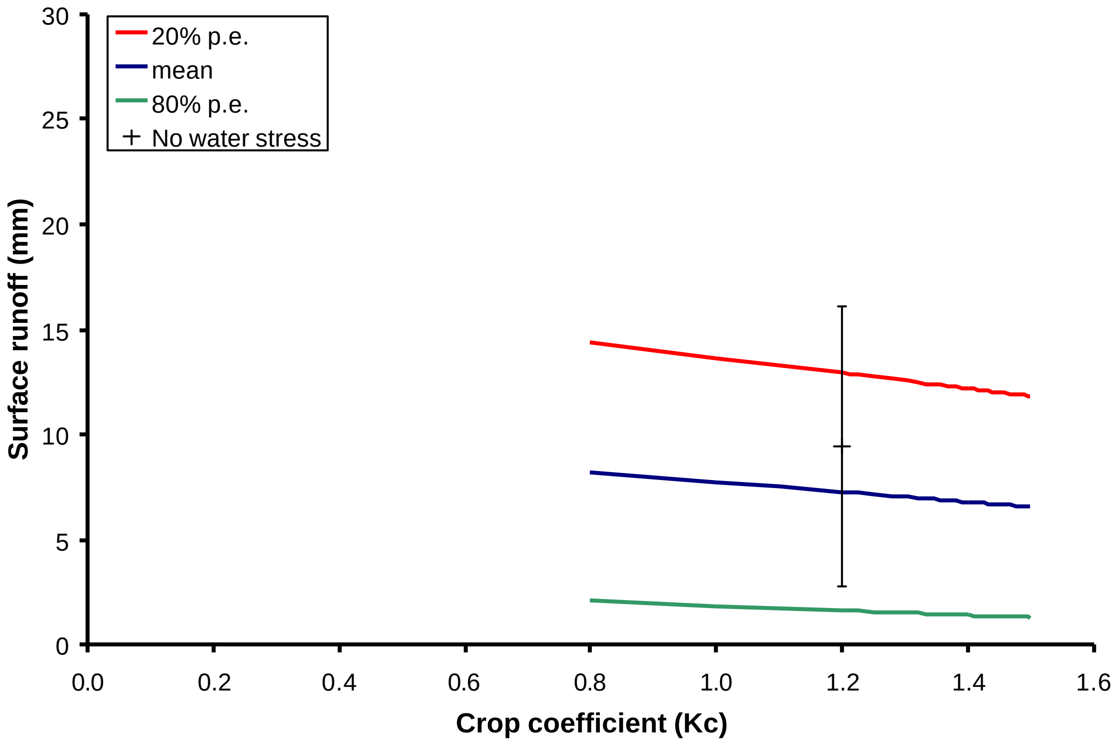

Figure 23. Effect of Kc on simulated surface runoff on a sandy clay loam growing willow SRC at Silsoe, Beds: 1970-1999. The error bars show the range of surface runoff in six years out of ten for this soil when there is no water stress.

4.3.6 Readily available water

The proportion of the available water capacity of the soil that is accessible to the crop without any reduction in transpiration is known as the readily available water. This depends on the crop type as well as on soil type and structure and on the evaporative demand from the atmosphere. A crop with an extensive root system, growing under moderate evaporative demand in a soil with good structure might be able to extract 70% of the available water before suffering water stress.

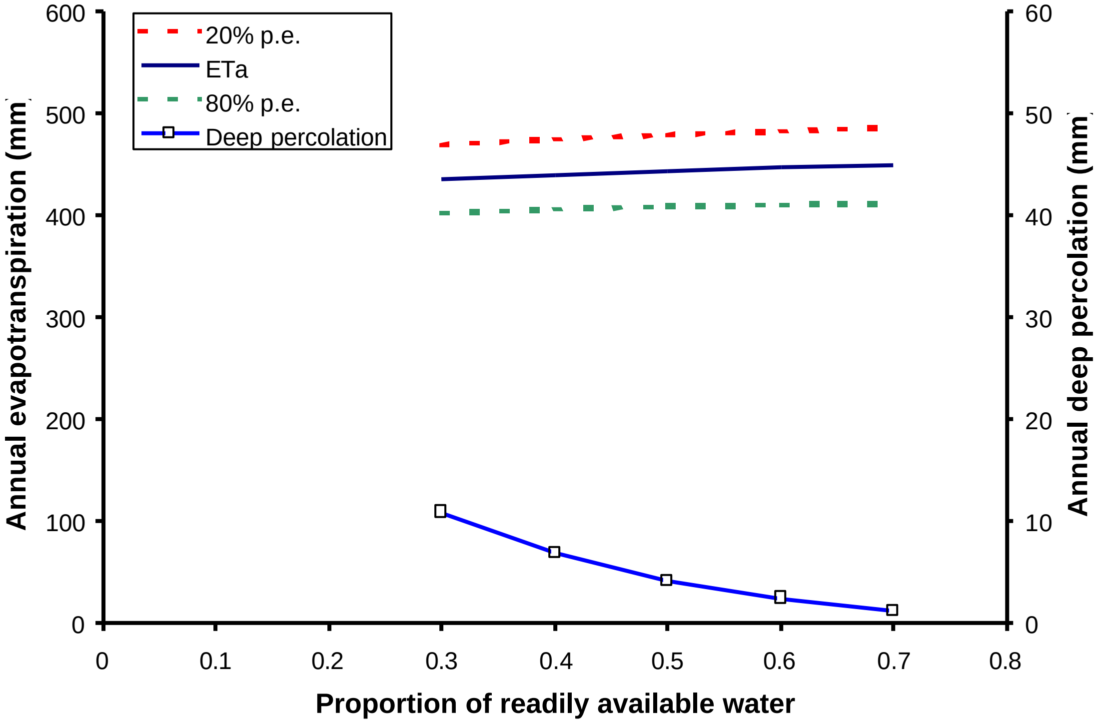

Figure 24. The effect of changes in readily available soil water on simulated annual evapotranspiration and deep percolation from willow SRC grown on a sandy clay loam at Silsoe: 1971 – 1998.

As the proportion of available soil water that is easily extracted by the crop increases from 30% up to 70% simulated mean ETa increase by less than 3% from 435 to 448 mm (Figure 24). Any change in utilisation of soil water, however, has a large proportional effect on deep percolation, and, over the range of readily available water used in these simulations, there is a predicted reduction in the number of years with active recharge from about 38% to 7% (Table 3).

Table 3. The effect of the proportion of the available water capacity easily available to plants (readily available water) on the proportion of years with deep percolation and on the mean amount in those years.

Readily available water	Proportion of years with deep percolation	Annual mean in years with percolation (mm)
30%	38%	28
40%	21%	32
50%	17%	23
60%	10%	23
70%	7%	18

4.3.7 Root depth

Another factor that is critical in determining the amount of water that is readily available to the crop is the effective root depth. The evidence from Section 3.7 suggests that, when there are no constraints to development, the effective root depth of Miscanthus and coppice may well be as deep as 2 and 3 m respectively. Where there are shallow soils or physical barriers to root penetration then the root depth may be much shallower.

Simulating willow SRC water use using a range of root depths from 0.5 to 3.0 m suggests that there would be a steady increase in actual evapotranspiration (ETa) with increasing root depth until about 2.5 m. Thereafter, further increases had relatively little further effect on ETa (Figure 25).

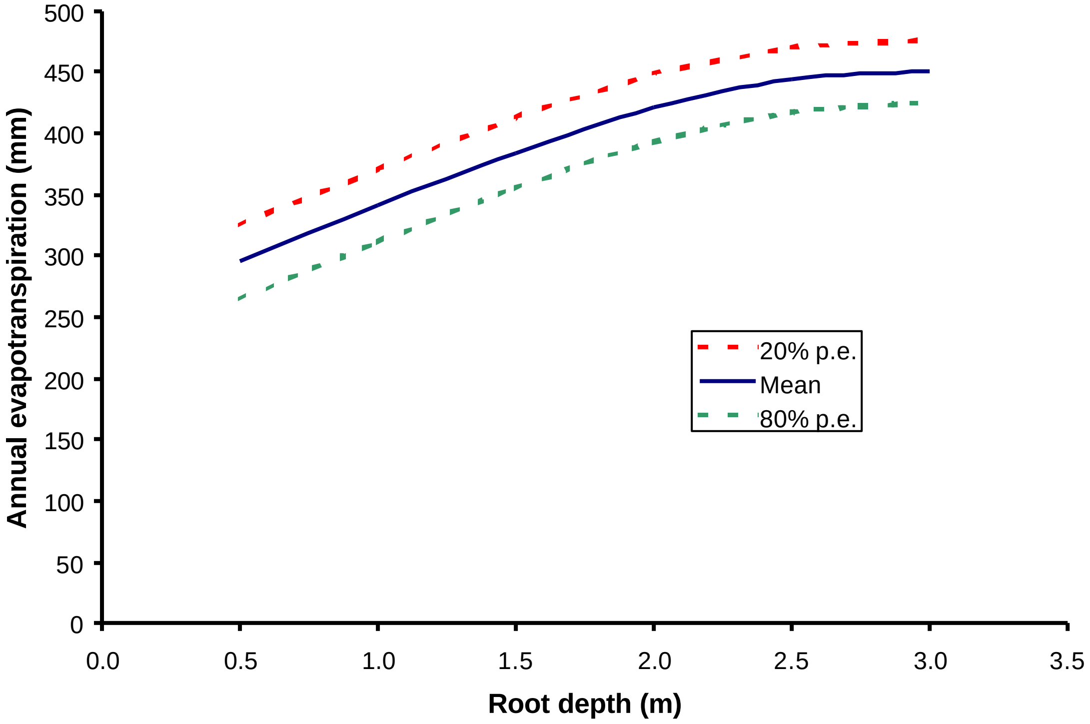

Figure 25. The effect of root depth on simulated annual evapotranspiration by willow SRC at Silsoe, Beds, showing the 20% and 80% probabilities of exceedence values.

As with other factors that increase the predicted ETa of the energy crop, root depth had a direct effect on deep percolation (Figure 26). As the root depth increases from 0.5 to 2.0 m the predicted mean annual deep percolation decreased from almost 150 to less than 30 mm.

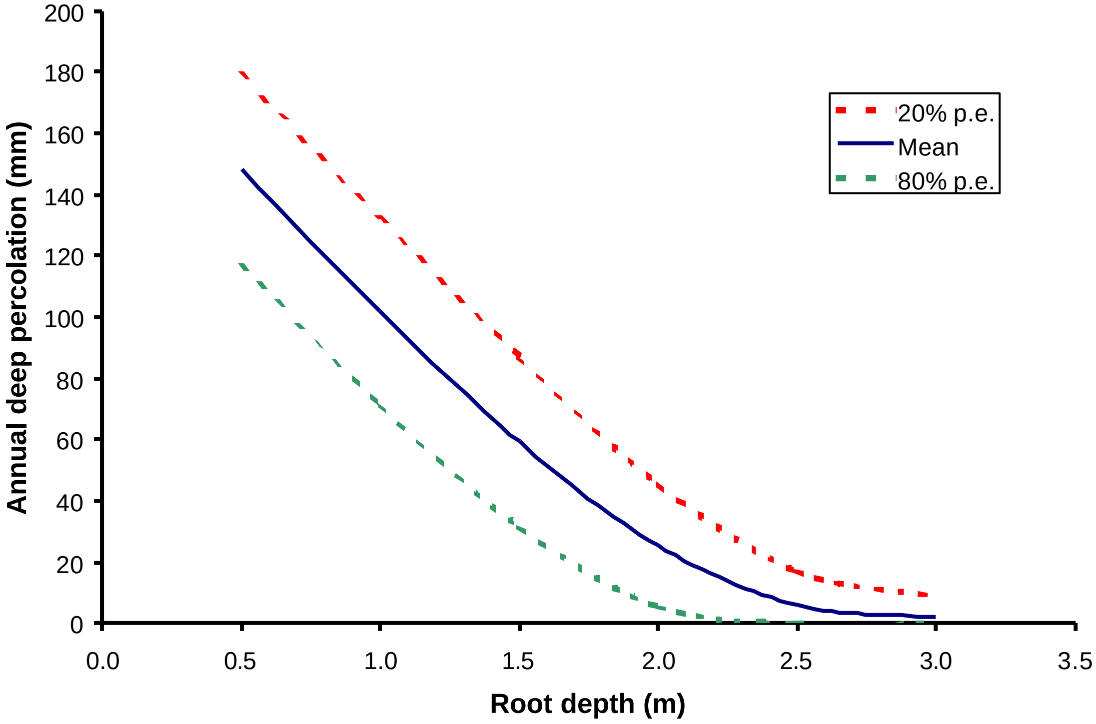

Figure 26. Effect of root depth on simulated annual deep percolation under willow SRC at Silsoe, Beds, showing the 20% and 80% probabilities of exceedence values.

There was virtually no deep percolation predicted once the root depth reached 3 m. The reason for this large effect is that, in dry areas such as Silsoe, the crop is dependent on stored water for much of its water requirements. By the end of the season, the soil will be dry to the limit of the roots and soil moisture will therefore have to be replenished before any deep percolation takes place. When roots are shallow, the root zone may be close to permanent wilting point by the end of the summer but will require much less rainfall during winter to return the whole profile to field capacity so that subsequent rainfall contributes to deep percolation and aquifer recharge.

4.4 CONCLUSIONS

Using a water balance model to investigate the sensitivity of hydrologically effective rainfall to different crop parameters has highlighted that, in the drier eastern parts of England, energy crops can have a large impact on the amount of runoff and deep percolation. In well maintained energy crops grown on all but the heaviest clays, the amount of surface runoff is likely to be small and the major contribution to stream flow would be through deep percolation to aquifers.

The key determinants of the amount of deep percolation appear to be interception losses and root depth though later canopy emergence (for instance in the first year after coppicing) is also likely to increase the amount of deep percolation. Interestingly, for simulations of deep-rooted coppice at Silsoe, increasing the crop coefficient (Kc) had a proportionately small effect on evapotranspiration above a Kc of 1 but had a proportionately large effect on deep percolation as it is already marginal. A similar response was shown when the proportion of soil water that is easily extracted by the plant was varied. In both cases, the relatively small effect on ETa reflects the fact that water limits production in this climate.

When the model was run with no limit to water availability, mean annual ETa was about 150 mm more and exhibited greater year-to-year variability. In other words, in water limiting conditions, energy crops appear to make use of all the water infiltrating into the soil over the growing season. This highlights a conundrum in that any reduction in ETa resulting from shallow soils and late or reduced canopy development will threaten the attainment of commercially viable yields but is likely to mean that there is some recharge to aquifers.

Overall, site-to-site variations could have large effects on the total water use of energy crops and therefore the amount of hydrologically effective rainfall. When determining the likely large scale effects, mean data can be used but for any site-specific work a more accurate prediction, taking into account local site factors, will be required.

The next section of the report compares simulated water use and hydrologically effective rainfall for energy crops, winter wheat and permanent grass for three agroclimatic areas where NFFO power stations are already operating or are likely to be sited.

5 COMPARISON OF ENERGY CROPS WITH ANNUAL CROPS AND GRASS

5.1 INTRODUCTION

The impact of energy crops on the hydrology of an area must be judged in relation to the crop or land use that they replace. In most cases, the proposed expansion of energy crops within England will replace arable crops, such as wheat, in East Anglia or permanent grassland in wetter areas. This section of the report provides comparative simulations to predict the likely extent of the impact for three areas where energy crops are being grown or are likely to be grown as a result of the NFFO obligations.

All these areas, for which rainfall and potential transpiration data are summarised in Table 4, have a greater rainfall but very similar potential transpiration indicating that the absolute amount of hydrologically effective rainfall will be greater than at Silsoe. For Selby and Diss, where long-term meteorological data were not readily available within the time frame of the project, daily rainfall ant ET$_0$ data from Silsoe were multiplied by the appropriate percentage to give the correct long-term averages. In higher rainfall areas, there will be more rainy days as well as a higher mean daily rainfall so this procedure will lead to some errors particularly in terms of interception losses. Within the scope of this project, however, the results will indicate the relative rankings of the sites and hydrological components of the water balance.

Table 4. Mean monthly rainfall and potential evapotranspiration (Eo) for four agro-climatic areas in England: 1941 – 70 (Smith, 1976).

	Area 28: Bedford - Cambridge		Area 12: Ripon - Selby		Area 24: Diss - Norwich		Area 30: Gloucester - Swindon - Bath	
Month	Rain (mm)	Eo (mm)	Rain (mm)	Eo (mm)	Rain (mm)	Eo (mm)	Rain (mm)	Eo (mm)
Jan	48	1	58	3	55	1	69	3
Feb	38	10	47	10	45	10	53	11
Mar	38	33	39	30	40	32	51	32
Apr	37	57	42	53	40	57	53	55
May	44	83	50	77	46	85	65	80
Jun	47	94	47	87	49	95	57	93
Jul	56	94	58	86	55	95	66	93
Aug	60	76	75	69	66	78	78	75
Sep	49	48	56	43	52	50	67	46
Oct	49	22	51	22	54	22	65	20
Nov	58	5	68	5	66	5	78	5
Dec	50	0	52	1	55	0	74	1
Total	574	523	643	486	623	530	776	514
Proportion of Area 28 total:			**112%**	**93%**	**109%**	**101%**	**135%**	**98%**

5.2 SIMULATIONS

5.2.1 Model parameterisation

The simulations were run using the same parameters for all cases. In practice the canopy duration in Yorkshire may be less than that in Suffolk or Wiltshire but errors associated with the assumption of uniform canopy development and senescence are likely to be small compared to the overall uncertainties involved in this type of model.

Table 5. Dates assumed for canopy development stages for comparative simulations of water use and hydrologically effective rainfall[8].

Stage	Cover	Wheat	Permanent grass	Miscanthus	Willow SRC
Planting date	0%	15 Sep			
Emergence	0%	25 Sep		15 Apr	1 Apr
20% cover	20%	1 Dec		25 May	25 Apr
100% cover	100%	1 Feb	1 Jan	25 Aug	1 Jun
Mature	100%	15 Jul	31 Dec	25 Sep	25 Sep
Leaf fall/harvest	0%	15 Aug		11 Nov	15 Nov

Winter wheat and permanent grass both have canopy durations longer than either of the energy crops but they have smaller crop coefficients since they are relative short crops (Table 6). In grass and wheat, the lack of coupling with the atmosphere means that evaporation of water intercepted by the canopy substitutes for transpiration and is therefore ignored for these scenarios.

Table 6. Crop parameters used for comparative simulations of water use and hydrologically effective rainfall.

Parameter	Winter wheat	Permanent grass	Miscanthus	Willow SRC
Crop coefficient	1.1	1.0	1.2	1.2
Interception loss[9]	0	0	0.9(p -	0.9(p -
SCS runoff curve	83	74	70	70
Root depth (m)	0.8	0.7	2.0	2.5
Readily available water	0.5	0.5	0.5	0.5

The US Soil Conservation Service runoff curve numbers used are appropriate for row crops, grassland and woodland with a good litter and humus layer. Root depths are the maximum effective root depths with no physical impediments to growth. The proportion of soil water that is readily available assumes a good rooting density within the profile.

5.3 RESULTS AND DISCUSSION

5.3.1 Water balance

Running the WaSim model for the selected sites revealed clear differences in water use between the crops and between sites. These differences had important consequences for the hydrologically effective rainfall components: rainfall and deep percolation (Figure 27). The results for Diss are not presented as they are similar to those from Silsoe.

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[8] Dates for *Miscanthus* summarised from data provided by Bullard (pers. comm., 2000).

[9] Interception losses calculated as the greater of 2 mm and the daily rainfall (p) and 90% of the incident rainfall thereafter.

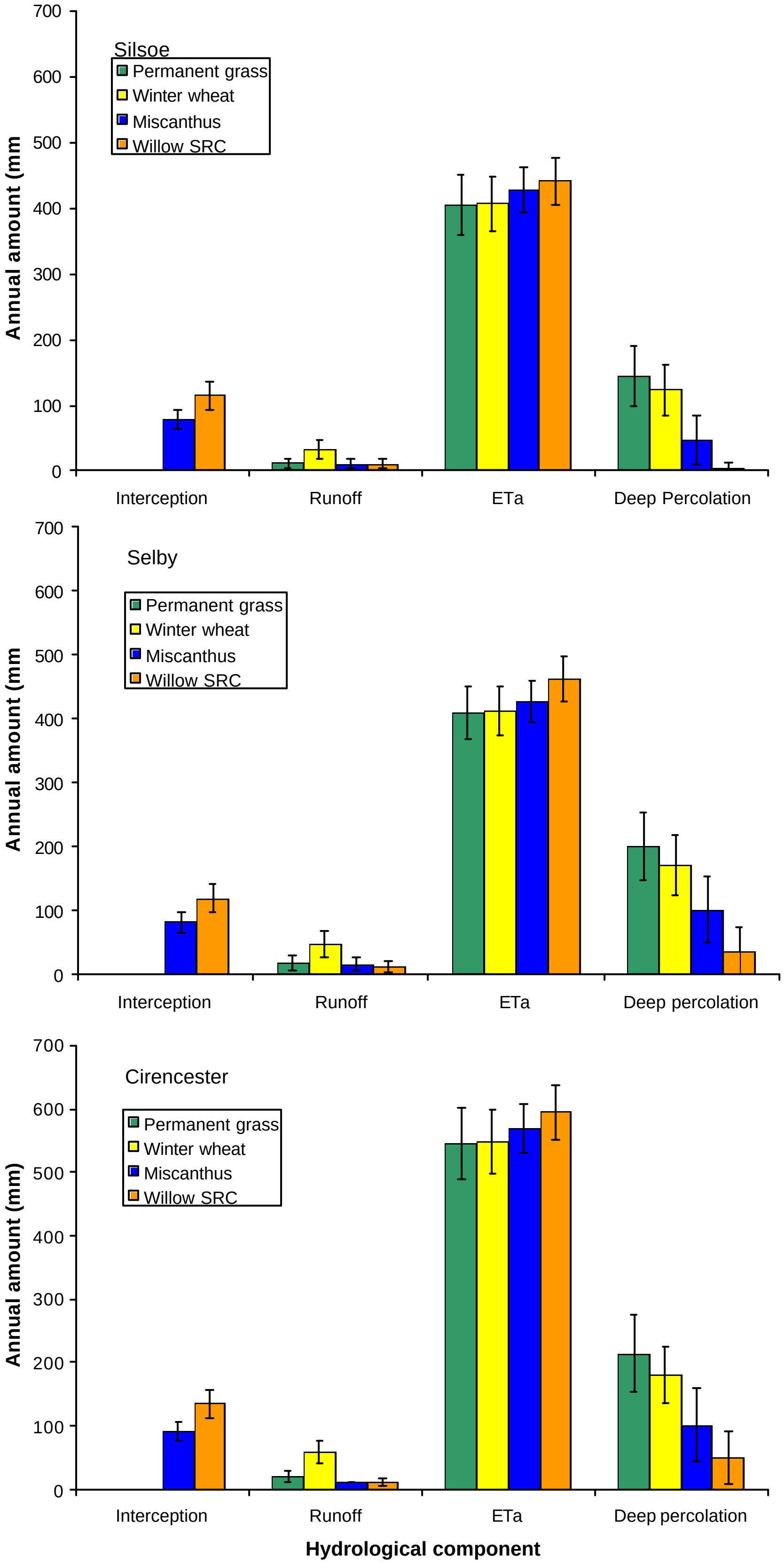

Figure 27. Comparison of simulated interception, annual runoff, evapotranspiration and deep percolation for permanent grass, winter wheat, Miscanthus and willow SRC grown on sandy clay loam soil at Silsoe, Beds (1970 – 1999), Selby, Yorks (1970 – 1999) and at Cirencester, Wilts (1983 – 1999).

In many studies on crop water use, data are presented on the seasonal water use of crops but in this report we present the annual values since the balance between rainfall and evaporation out of season will be important in determining the hydrologically effective rainfall.

Table 7. Simulated mean annual evapotranspiration for four crops at three sites.

	Annual evapotranspiration (mm)			
Site	Permanent grass	Winter wheat	Miscanthus	Willow SRC
Silsoe	405	407	429	441
Selby	410	411	427	462
Cirencester	545	547	569	594

Predicted mean annual evapotranspiration (ETa) at Silsoe ranged from about 400 to almost 600 mm across the range of crops and sites (Table 7). The evapotranspiration at Cirencester was predicted to be considerably greater than at either Silsoe or Selby. This could either be because the greater annual rainfall at Cirencester allowed the potential evapotranspiration to be met. The large predicted ETa for grass and wheat suggests, however, that the reference evapotranspiration (ET_0) is also very high. Smith (1976) report that annual open water evaporation at Cirencester was about 510 mm annum^{-1} during the period 1941 – 1970 so the data obtained from the BACS website may overestimate ET_0.

Further examination of the raw data reveal that the recorded wind speed for this site averaged 5 m s^{-1}. If these data are correct then the daily ET_0 will peak at 8 or 9 mm d^{-1} on dry, sunny days in mid summer and energy crops that were not suffering from water stress could then be expected to transpire 10 – 11 mm d^{-1}; similar to results reported by Hall *et al.* (1998) for poplar SRC in the same region of the country. The simulations have therefore not been rerun with other data but further investigations would need to use a wider range of data sources to corroborate the results reported here.

The evapotranspiration at all sites was limited to a certain extent by water stress during the summer months. This limitation was greatest at the driest site (Silsoe) and resulted in an average reduction in ETa of about 150 mm annum^{-1} (see page 30). This amount was predicted to increase linearly to 260 mm annum^{-1} where the energy crop was grown in small blocks or strips and was able to use extra advective energy from the environment for transpiration (Figure 21).

Table 8. Simulated mean annual hydrologically effective rainfall for four crops at three sites.

	Hydrologically effective rainfall (mm)			
Site	Permanent grass	Winter wheat	Miscanthus	Willow SRC
Silsoe	156	157	58	14
Selby	220	219	119	50
Cirencester	234	240	114	61

It is difficult to compare the predicted annual hydrologically effective rainfall with actual runoff as there are few catchments in England with truly natural flows and the effect of abstractions and discharges is difficult to quantify. However, a broad verification of the method can be obtained from an analysis of the runoff data from the Flit catchment near Silsoe.

The catchment is predominantly rural with a mixture of grassland and arable land uses, in addition to some small areas of woodland. The mean annual runoff depth is 245 mm, of which approximately 100 mm/year is estimated to come from sewage works discharges and springs (bringing groundwater from outside the surface catchment). Therefore the estimated average annual hydrologically effective rainfall would be 145 mm, which compares favourably with the estimates of about 150 - 160 mm for permanent grass and winter wheat calculated by the WaSim model (Table 8).

The discussion on the effects of crops and sites on hydrologically effective rainfall in this section refers to crops grown on soils where there is no restriction to rooting and no access to groundwater. In these circumstances, the simulated hydrologically effective rainfall, the sum of surface runoff and deep percolation, was considerably reduced at all three sites by growing energy crops (Table 8). The scale of the reduction was less for Miscanthus (100 to 120 mm annum^{-1}) than for willow SRC (140 up to 180 mm annum^{-1}) at Silsoe and Cirencester respectively. The difference between the two energy crops relates primarily to the shorter canopy duration and shallower rooting in Miscanthus.

5.3.2 Scaling up to catchment level

In absolute terms, the consequences of the reduction in hydrologically effective rainfall beneath these crops may be much more serious in the drier areas of the country since there may be no deep percolation in up to eight years in ten. The implications of this prediction need to be evaluated at a range of scales from national to local catchment to determine the importance of the impact.

If the mean reduction in hydrologically effective rainfall is assumed to be about 150 mm then the magnitude of the national plan to plant 100,000 ha of energy crops is large[10]. The mean annual reduction in total water resource replenishment will therefore be 1.5 x 10^8 m^3, equivalent to a river with a constant flow of about 4.8 m^3 s^{-1}. This represents just over 0.2% of the total freshwater resource for the United Kingdom of about 7.1 x 10^{10} m^3 (Anon, 1998). In terms of the annual freshwater withdrawals of 1.2 x 10^9 m^3, the proportion increases to about 12% - a considerable proportion of the national figure.

Table 9. Comparison of potential water abstraction by energy crops in relation to total water abstractions for irrigation for all crops and potatoes in the Anglian Region during 1995. Data for all crops and potatoes from Knox *et al.* (2000).

Crop	Average irrigation depth (mm)	Area irrigated (ha)	%	Volume abstracted (Mm^3)	%
All crops	102	81,000	100%	82,289	100%
Potatoes	148	26,730	33%	39,499	48%
Energy crop (restricted)	150	2,500	3%	3,750	5%
Energy crop (unrestricted)	250	2,500	3%	6,250	8%

At a regional level the potential reduction in HER resulting from changes in landuse from arable to energy crops can be compared with current levels of abstraction for irrigation. For example, in the Anglian Region, a comparatively small area of 2500 ha could result in an average reduction in recharge and runoff equivalent to between 5 and 8% of the total irrigation volume (Table 9).

The areas where energy crops are grown will, however, be concentrated around power stations. The maximum financially viable distance to transport energy biomass at present appears to be about 40 km. The total land area within a circle centred on a power station is therefore about 500,000 ha of which say 2500 ha might be required to be planted with energy crops to supply the annual fuel requirements. The mean reduction in hydrologically effective rainfall within

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[10] 150 mm is equivalent to 1500 m^3 ha^{-1}.

this area would be about 0.5%. For comparison, in six years out of ten, the hydrologically effective rainfall under wheat may vary within a range of 28% of the mean annual amount. At this scale the change is therefore unlikely to be detectable. Johnson (1998) suggested that afforestation of about 25% of the catchment was necessary before reductions in base flow became apparent and this is unlikely in large catchments.

At a sub-catchment scale, within the maximum transport distance to the power station, there may be considerable clumping in where the energy crops are grown, with a preference for areas closest to the station where transport costs are cheapest. At this level, the presence of several hundred hectares of energy crops in a sensitive catchment may have much more noticeable effects. For instance, large areas of energy crops grown in the floodplain upstream of wetland habitats may have a detectable effect on baseflow during the summer months and hence the sustainability of the ecosystem. The effects at sub-catchment level therefore need careful consideration since they are likely to vary considerably from site to site depending on soil and water table characteristics.

Under some circumstances the reduction in HER may be regarded as beneficial rather than a negative impact. For example, in areas prone to flooding, the presence of large areas of energy crops with substantial soil water storage capability at the beginning of winter and with good infiltration rates could allow 100 – 150 mm more water to be stored in soils before deep percolation and increased surface runoff occurred. Once again this would be a local rather than large scale effect as the energy crops would have no effect on floods arising from heavy rainfall elsewhere in the catchment.

5.4 CONCLUSIONS

The modelling exercise reported here confirms the reductions in hydrologically effective rainfall (HER) predicted by Hall *et al.* (1996). The results of our simulations also suggest that Miscanthus may reduce HER by less than willow SRC with the greatest difference between the two energy crops in the wetter areas of the country.

Reductions in energy crop root depth could increase HER until the root depth is less than 1 m when the annual evapotranspiration from energy crops would be quite similar to that of winter wheat. Any reductions in ETa, however, may have direct consequences for biomass production. This issue is discussed in Chapter 6.

The scale of the predicted reduction in HER means that there could be potentially large impacts on hydrology where large areas of energy crops are grown within a small catchment. At larger scales the area of energy crops proposed is unlikely to have a noticeable effect on river flows since the proportion of the total catchment affected by the change in landuse is small. These findings do need confirmation and a methodology for scaling up is proposed in the Chapter 7.

6 BIOMASS PRODUCTION

6.1 POTENTIAL BIOMASS PRODUCTION

A detailed review of biomass production by energy crops is outside the scope of this report. The implications of the results of the water use modelling exercise on the potential yields are, however, significant and we include this Chapter in order to highlight the key issues.

Total leaf area and leaf area development are important variables in determining biomass production, through their effect on light interception. In the UK, temperature and hence the duration of the growing season are closely related to altitude and latitude. For example, a difference of over 60% in biomass production was predicted for the same poplar variety growing in Edinburgh and in Bristol (Cannell *et al*., 1987). This disparity was due to the difference in growing season duration between the two locations. More recently, Ceulemans (1999) showed that the field performance of poplar clones was linked to the time of bud set and bud break, with the duration of the growing season closely linked to climatic conditions.

Yields of 20 tonnes ha^{-1} annum^{-1} of oven dry biomass (odt) have been found in research plots for poplar, and of up to 17 odt ha^{-1} annum^{-1} for certain willow varieties in the Forestry Commission site-yield trials (Armstrong, 1999). However, these production levels occur only on the best sites, and poor nutrient or water availability is likely to reduce these values significantly. In Bedfordshire, severe water stress reduced biomass production in young poplars by up to 74 % (Souch and Stephens, 1998), and the willow variety Q683 produced 27% less biomass on a dry sandy soil compared to a clay soil in a higher rainfall area (pers comm. C. Souch).

Annual above-ground biomass production in established Miscanthus grown in Europe ranges between 25 – 35 odt ha^{-1} annum^{-1} (Ercoli *et al*., 1999; Himken *et al*., 1997; Venendaal *et al*., 1997), although this figure often includes leaves which were not harvested, so the harvested dry weight was 30% less than this (Himken *et al*., 1997). In the UK, yields in excess of 20 odt ha^{-1} annum^{-1} are achievable where water stress is not limiting (Bullard and Kilpatrick, 1997).

6.2 EFFECTS OF WATER STRESS

The commercial reality is that, in many areas, biomass production from willow coppice is about 7 – 10 odt ha^{-1}. There are many reasons for the gap between actual and potential biomass production ranging from poor conditions or plant material at planting through to competition for resources. Even in a well-managed crop, however, drought is likely to reduce biomass production substantially in the drier eastern areas of the country.

The biomass water ratio, often less correctly referred to as the water use efficiency, of a crop describes the relationship between the sum of transpiration, evaporation and interception and the above-ground biomass production (Beale *et al*., 1999). Crops that are able to produce more biomass per unit of water have a higher biomass water ratio.

The humidity of the atmosphere has a large effect on the amount of water used without affecting the uptake of CO_2 by the canopy. At high saturation deficits (low humidity, high temperature), the evaporative demand is high and the biomass water ratio tends to decrease. Increasingly therefore, this ratio is normalised by multiplying by the saturation deficit to give a value that is independent of weather conditions. In willow and poplar the biomass water ratio is about 5 g kg^{-1} (Lindroth and Båth, 1999; Souch and Stephens, 1998) and, in northern Europe where the mean saturation deficit is about 1.0 kPa, the normalised water biomass ratio will be similar. For example, in six years out of ten at Silsoe, the predicted 90 – 210 mm reduction in evapotranspiration due to water stress (Figure 28) could result in a reduction in annual willow above-ground biomass production of 4.5 – 10.5 t ha^{-1}.

Miscanthus has a larger biomass water ratio, which in eastern England is about 9 – 10 g kPa kg^{-1} (Beale *et al.*, 1999). This should mean that, in the same environment, Miscanthus would produce almost twice as much biomass per unit of water as willow SRC. The main complicating factor is that in the UK, Miscanthus is close to the northern limit of its range and the growing season duration is limited by temperature. Water stress will also have a greater total effect on biomass production of Miscanthus than on willow. Overall, in the warmer drier regions of England however, Miscanthus may be preferable to willow SRC in terms of its better biomass water ratio, as it should use less water during the year and produce more biomass.

Irrigation of energy crops is highly unlikely and would not be financially viable since the irrigation costs four to five times the value of the increase in biomass. Growing these crops in the riparian areas, where their roots can abstract water from the capillary fringe above the water table, would allow them to achieve their potential yield but their water use in these circumstances would be 100 – 200 mm greater than the same crops grown in an upland area.

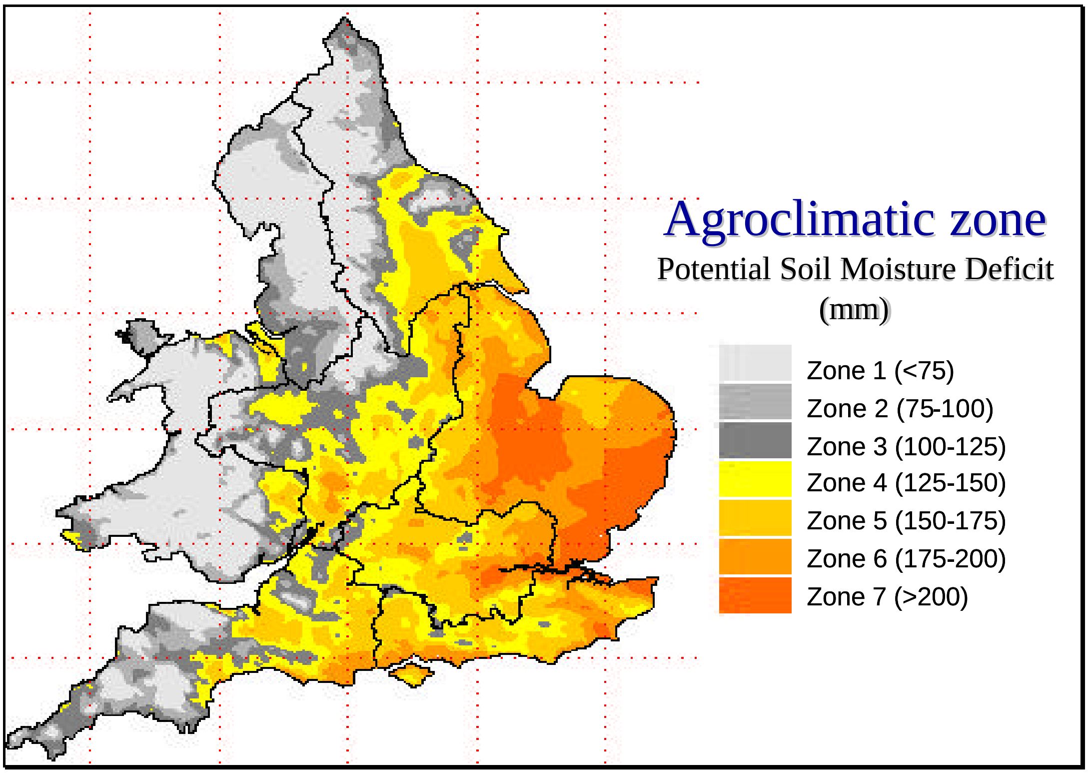


Figure 28. Map of England and Wales showing the agroclimatic zones defined as mean annual potential soil moisture deficit under permanent grassland (Knox and Weatherhead, 2000).

6.3 CONCLUSIONS

The aim of the energy crop industry is to maximise profit by achieving large yields of biomass. The corollary of this aim is that the crops will use large quantities of water with the consequent implications for hydrologically effective rainfall.

In drier areas, where the total water use is less, the biomass production will also be reduced which could jeopardise the financial viability of the crop. The choice between willow SRC and Miscanthus could be important in these regions as Miscanthus has a potentially greater biomass water ratio.

7 UP-SCALING SITE SPECIFIC MODELLING TO THE CATCHMENT LEVEL

7.1 INTRODUCTION

So far, this study has considered the relative importance of the various components of the water balance and the implications of different growing conditions on energy crop water use. The analysis, conducted for a specific site, confirms that high water use by such energy crops could result in reduced surface runoff and deep percolation, leading to a reduction in both aquifer recharge and stream flows. Extrapolating these findings to a catchment level could clearly have major environmental and water resource implications in certain catchments in the drier parts of the country. Other recent studies (e.g. Finch, 2000) support this view, and confirm that changes in land use from arable to woodland can have major impacts on annual runoff and soil drainage with implications for catchment water resources.

Although the water requirements of energy crops grown at specific sites are well documented, the potential environmental and water resource impacts at a catchment level, particularly in response to changes in the pattern of land use, has not received much attention. In this context, the role of the Environment Agency (EA) should be recognised, particularly with respect to their duty in managing water resources and balancing the water requirements of all users with that of the environment. The establishment of areas of energy crops in catchments where water resources are already fully committed could place greater pressure on both the environment and also on the EA in terms of managing and allocating water resources. This situation would be most pronounced in the drier regions of the country, in the driest years, and in the summer months when water resources are severely constrained within many catchments.

In this section a methodology is proposed to evaluate, at catchment level, the likely spatial impacts that such changes in land use from arable crops or permanent grassland to energy crops may have on local water resources and hydrology. A methodology is required that takes into account local spatial variations in climate, soil type, the pattern of land-use, the characteristics of energy crop production and the existing demands on water resources. In this context, a GIS approach is particularly well suited.

7.2 METHODOLOGY

In preceding chapters, a methodology has been described to evaluate the impacts of SRC on hydrology. The methodology was applied to a specific site, rather than at the catchment scale. However, previous research studies conducted for both MAFF and the EA (Knox *et al*., 2000; Weatherhead *et al*., 1997) have enabled various spatial analysis techniques that integrate water balance models with spatial information within a GIS framework to be developed for use in quantifying water demands for agricultural crops at the catchment level (Knox and Weatherhead, 1999).

A similar approach here, it is felt, could readily be adopted and applied to quantify the volumetric water requirements and hydrological impacts of energy crops at the catchment level. The most immediate need for this methodology could be in specific catchments in the drier eastern regions of the country where water resources are already severely constrained and where the establishment of energy crop systems could therefore have the greatest impact on hydrology and water resources. If appropriate, the proposed research findings could also feed directly into the CAMS process for these catchments.

In summary, a three-stage methodology, working at catchment level, is proposed involving the:

1. collation, pre-processing and analysis of relevant spatial information using a GIS;

2. application of a water balance model to estimate the volumetric demand for water from energy crops; and
3. combination of spatial information and energy crop water demand data to estimate the impacts on catchment hydrology and water resources.

A brief summary of the methodology is given below.

7.2.1 Collation, pre-processing and analysis of spatial information

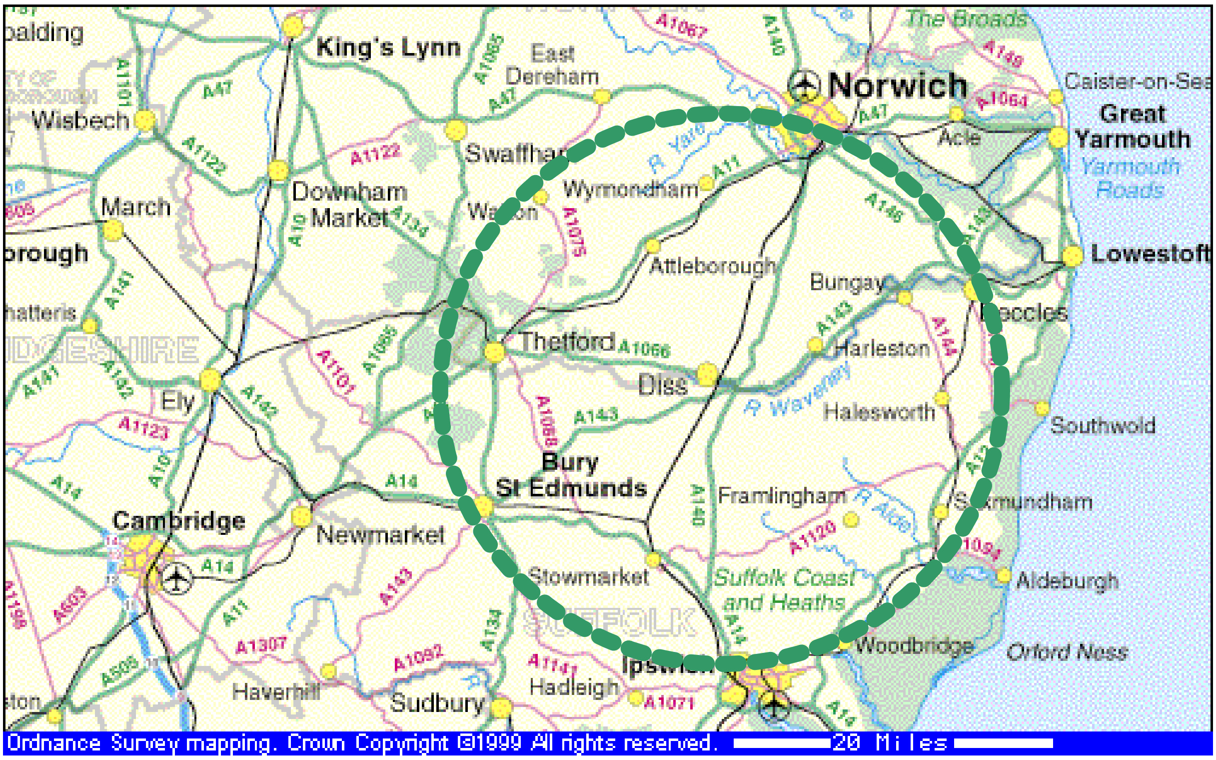
For each catchment, information on a range of spatial factors could be collated, pre-processed and integrated within a GIS. This would include the:

- location of the proposed power station (point data);
- hydrological boundaries of the sub catchments (vector data);
- composition of land use, by crop category (raster data);
- local variability in soils, classified according to water holding capacity (raster data);
- local climate information relating to rainfall and ET for each catchment (point data); and the
- network of major and minor roads connecting the power station to the surrounding catchments (vector data).

Data requirements

Most problems associated with the application of GIS relate to the quality, quantity and availability of spatial data. All the above datasets are currently available in digital format, at varying resolutions and in differing formats, and have been used in numerous water resource studies (e.g. Knox *et al*., 1996; Mathieson *et al*., 2000).

Using the GIS, a series of digital ‘layers’ would be developed. The study area would be defined by the location of the proposed power station in relation to the maximum distance that SRC biomass would be transported. A buffer analysis using the GIS could be used to define the maximum distance along all the arterial roads along which the biomass would be transported into the power station. A limit (of say 40 km) would define the maximum extent of the study area (Pegg, 1999).



Ordnance Survey mapping. Crown Copyright ©1999 All rights reserved. 20 Miles

Figure 29. Map of Suffolk and Norfolk showing the potential catchment area included within a 40 km radius (●●●) around the proposed renewable energy power station at Eye.

These boundaries would also define the catchments and proportions of each catchment that lie within the economically viable transport radius. For each catchment, spatial information of the composition of land use (by crop category), soils (water holding characteristics) and climate (rainfall and ET) would be prepared. The derivation of each of these datasets is briefly described below:

Land use

Two alternative sources of information on land use in England and Wales are currently available namely: computerised agricultural statistics or remote sensed satellite imagery.

Each year MAFF conduct an Agricultural and Horticultural Cropping Census, which collects information on over 150 items of agricultural activity on farms in England and Wales. For selected years and crop categories Edinburgh University have computerised these censuses. The gridded datasets list the crop area (ha), geo-referenced to the OS National Grid, at various resolutions (2, 5, 10, 50, and 100 km) for direct import into a GIS. The datasets have provided an excellent source of information on both the spatial and temporal changes in distribution of crop production across England and Wales.

The US Landsat series of satellites provided the first commercially available information on agricultural land use in UK. Since 1972, rapid advances in sensor and processing technologies, combined with the launch of other European satellites, such as ERS-1 and SPOT, have offered an alternative cost-effective source of data on agricultural land use. For example, the Land Cover Map of Great Britain developed by the Institute of Terrestrial Ecology (ITE), records 25 target cover types including the semi-natural, cultivated and urban landscapes, recording the dominant component for each 25 m cell of the OS National Grid. A number of Very High Resolution (VHR) satellites have also been launched (e.g. SPOT 4/5, Quickbird, and Orbview-3), which all offer much improved spatial resolutions (<1 – 5 m) compared to current systems such as Landsat TM and SPOT (20-30 m) (Plumb *et al.*, 1997).

Previous studies for MAFF and the EA have relied on the MAFF agricultural statistics, computerised by Edinburgh University Data Library. For crop demand modelling at the catchment level, these have proved sufficient in terms of cost, spatial accuracy and resolution. However, the costs of remote sensed data are falling, and future catchment based studies to quantify the impacts of energy crops on water resources should not necessarily discount the feasibility of using high resolution data derived from satellite imagery.

Working from a land use dataset, for each catchment, a table summarising the composition of all the main categories of land use could be produced. The cropped areas of specified land uses (e.g. low value or marginal lands) suitable for conversion to energy crops could be determined. A table summarising the potential cropped area for energy crops, by catchment could be produced.

Soils

A similar GIS overlay procedure could be applied to identify the spatial distribution of soil types, by catchment. For this, digital spatial information from LandIS, a national Land Information System (LandIS), developed by Soil Survey and Land Research Centre (SSLRC) would be appropriate. LandIS contains various soil and agroclimate information, as well as other environmental datasets, all geo-referenced to the OS National Grid. The principal soil database appropriate for use in this type of study would be the National Soil Map. This represents a digital image of the 1:250 000 scale soil map, available at 100 m (16 million pixels), 1 km (170 000 pixels) or 5 km (6456 pixels) resolutions. The 100 m dataset records one map unit code (an association of soils) for each unique easting and northing, whereas the 1 km and 5 km datasets record only the dominant soil association in each grid square. This directly influences the accuracy of the data. At 5 km resolution, the dominant unit may occupy less than 50% of the grid square, as there may be more than 5 map units occurring within a 5 km by 5 km grid map square. The 5 km resolution data are therefore suitable for national and regional summaries, the 1 km data for regional and catchment studies, and the 100 m data appropriate down to farm level (Hallett *et al*., 1996).

For this study, the basic soils data could be reclassified to map the spatial changes in water holding capacity (AWC). For example, previous studies (Knox *et al*., 1997) have reclassified and mapped the 1 km resolution National Soil Map into 3 AWC classes, namely low, medium and high. From this, a table summarising the proportion of each soil AWC class, by catchment, could be produced.

Using the GIS, a correlation between these derived land use and soils datasets could be completed. A table summarising the proportion of each crop category overlying each soil AWC class could be developed. This data would provide information on the water holding characteristics of each soil underlying the area of land potentially suitable for energy crop establishment.

Climate

Within the selected study area, the spatial variability in climate and its impact on energy crop water use will need to be considered. For this various sources of local climate data (rainfall and ET) are available, including long-term national or site-specific agroclimatic datasets (rainfall, evapotranspiration and soil moisture) or aggregated datasets (MORECS) available from the Met. Office. Spatially aggregated datasets are also available from other sources including LandIS, which contains an agroclimatic database comprising a 5 km resolution point dataset recording 15 climatic parameters, including information on rainfall, temperature, field capacity, and potential soil moisture deficit. Other land and environmental spatial databases are available from the British Geological Survey (BGS) and Institute of Terrestrial Ecology (ITE) and for specific climatic parameters from the Environment Agency.

Collectively, these processed land use, soil and climatic databases, at catchment level, will provide the input datasets required for defining the scenarios under which the energy crop water balance modelling would be completed in Stage 2.

7.2.2 Water balance modelling

In Chapter 4, we used a one-dimensional water balance model to predict energy crop water use. This allowed the sensitivity of the main components to variations in inputs and land use to be identified. The same model and approaches are suggested here, but rather than modelling for a single site, the combination of climate/soil type permutations found to exist within each catchment would be modelled.

For each soil/climate permutation, the water balance model would be run over the length of available climate records, ideally spanning a sequence of wet and dry years. The procedure would be repeated for each catchment. Levels of water use in an average and statistically defined dry year would be determined.

The water balance model would need to be run for both sets of land use within each catchment i.e. under the current pattern of land use, and following conversion to energy crops. This would enable the net difference in recharge between the two land use patterns to be estimated.

A sensitivity analysis similar to that conducted in this review would be undertaken to identify the range and impact of specific variables within the water balance, again for both sets of land use.

7.2.3 Combining spatial information and energy crop water demand data

The GIS analyses in Section 7.2.1 identified the potential cropped areas of energy crops that could be grown in each catchment, assuming specific crop types would not change (e.g. high value crops and permanent crops such as orchards). By combining the results from the energy crop water balance modelling with information on potential energy crop areas, the potential volumetric water demand by energy crops in each catchment could be estimated. An analysis of the temporal variation in demand could also be undertaken to identify periods during the year when the maximum impact on water resources would be expected.

Estimates of the likely total volumetric water use by energy crops, combined with other output data from the water balance modelling would provide estimates of the impact that energy cropping might have on hydrologically effective rainfall and aquifer recharge, within each catchment. This change in aquifer recharge within each catchment due to the presence of energy crops could simplistically be considered as an additional abstraction, rather than trying to model the actual impacts on hydrological flows, which would require a complex hydrological modelling approach incorporating all inputs and outputs in the system.

Information from the Environment Agency aquifer levels, water resource commitments and abstractions from the environment (e.g. for spray irrigation) could be combined with the modelled data to provide a broad assessment of the hydrological impact that energy cropping in each catchment might have on local hydrology and water resources.

A sensitivity analysis of the changes in the areas of energy crops could be undertaken to evaluate the impact of future changes in land use on catchment water resources. Similarly, the impacts energy crops on water resources under scenarios of climate change could also be modelled, using recently published climate change factors predicted by the UK Climate Impacts Programme (Hulme and Jenkins, 1998).

7.3 CONCLUSIONS

The combination of GIS spatial analysis techniques combined with a water balance model has been shown to work well for conceptually simple mathematical models for use in catchment based water demand assessments. Although this approach lacks flexibility and speed when compared to a fully integrated GIS model with embedded code, this approach is preferable for methodologies where external models require regular updating and modification (e.g. WaSim). The GIS is therefore at the core of the system, but with linkages to various databases and an external model. This approach, known as a data bridge approach, is commonly used to pass spatial data from a GIS to a model, then convert the results back to further analyse and display the data within the GIS (Knox *et al*., 2000).

The methodology described above builds on approaches that are integrated into existing water resource planning systems. In the past, the EA have concentrated solely on the abstraction of water through physical interventions such as water diversion or pumping. The increasing realisation of the interdependence of natural and managed landscape features, however, and the potential impacts of anthropogenic changes to land use on the sustainability of those systems means that the effects of large scale changes towards crops using more water will increasingly be considered in the same light as those crops using extra water through irrigation.

The challenge facing the energy crop industry and the EA is to develop objective ways of assessing the magnitude and significance of impacts at the catchment scale and using this information to allow better informed decision making at a local level.

8 CONCLUSIONS AND RESEARCH RECOMMENDATIONS

8.1 CONCLUSIONS

Our review of the existing literature and our preliminary modelling exercise support the view that energy crops can, in many circumstances, use substantially more water than the arable crops they are likely to replace.

The impacts of this enhanced water use of energy crops on hydrologically effective rainfall (HER) at a single point in the landscape will differ in magnitude and significance depending on a range of factors. The key factors appear to be:

1. The connection between transpiration and atmospheric humidity. Small, linear blocks of coppice will be the most affected – the “clothesline” effect.
    a. The importance of interception losses in reducing hydrologically effective rainfall will depend on the size and orientation of blocks of energy crops.
    b. Relatively warm dry air from other areas can substantially increase transpiration by energy crops with little or no benefit in terms of increased dry matter production.
2. The effective root depth of the energy crop.
    a. The ability of energy crops to dry the soil out to a depth of 2 – 3 m means that winter rainfall takes longer to fill the soil profile to a point where aquifer recharge can occur.
    b. Where roots are prevented from penetrating below the normal root depth of arable crops, however, the hydrologically effective rainfall will be similar under arable and energy crops.
    c. The importance of root depth will depend on the critical feature of the catchment. In wetter areas, increasing the ability of the soil to store water could have important benefits in delaying or preventing floods.
3. Access by roots to groundwater during the growing season.
    a. Where energy crops are able to extract water from the water table, transpiration can be very substantially greater than from the same crop with no access. Energy crops grown in riparian areas, especially in drier areas of England, will therefore tend to have much greater hydrological effects than those grown outside the floodplain.

Comparing the water use of winter wheat, permanent grass, Miscanthus and willow SRC with no restrictions to growth at three sites in different agroclimatic zones in England suggests that both energy crops consistently used more water than the crops they might replace. HER from Miscanthus was predicted to be greater than from willow SRC as the canopy duration is likely to be shorter leading to lower interception losses and the root depth is less, resulting in a smaller soil volume to rewet before deep percolation occurs.

The reduction in HER as a result of replacing wheat and grass with energy crops was 100 – 120 mm for Miscanthus and 140 – 180 mm for willow. This represents a reduction of 50 – 60% for Miscanthus and 75 – 90% for willow with the greatest proportional reductions in the drier areas. These simulations suggest that Miscanthus may be a more appropriate energy crop from a hydrological stand point than willow SRC in drier regions where the effects on HER are greatest.

The implications of these reductions at national level is that the establishment of 100,000 ha of energy crops would result in a reduction of the total freshwater resource of about 1.5 x 10^8 m^3 $annum^{-1}$, equivalent to 0.2% of the national freshwater resource or 1.2% of annual freshwater abstractions.

Around individual power stations the 40 km maximum radius for energy crop delivery defines a catchment of about 500,000 ha. The 2500 ha required to provide fuel for the power station would result in a reduction in HER of about 0.5% within this area. Considerable year-to-year variations in the HER exist beneath arable crops due to variations in annual rainfall. For winter wheat, the HER in six years out of ten was within 28% of the mean value so the reduction due to energy crops would be difficult to detect.

At a sub-catchment scale, however, the proportion of the catchment covered by energy crops might be greater and thus detectable reductions in aquifer recharge and stream flow might occur.

Biomass production is intimately related to water use in crops and this study indicates that, in the drier eastern areas of England, water stress is likely to reduce biomass production below the climatically determined potential in many years. An indicative figure is that, in six years out of ten, drought could reduce aboveground annual biomass production in willow SRC by 4.5 – 10.5 t ha^{-1}.

The literature review and the sensitivity analysis highlight the potential variability in water use and impact on HER due to site factors. This means that a spatial approach to upscaling is necessary. We suggest that upscaling to catchment level can be achieved by using a GIS based approach to relate the one dimensional water balance model to a spatial database of soils and climate data. This approach has been used successfully for MAFF and the Environment Agency to predict the water requirements of irrigated crops and would be applicable for energy crops as well. Changes to landuse within individual catchments and sub-catchments could be investigated to identify the likely impacts for different combinations of soils, land use and climate.

8.2 RECOMMENDATIONS

One of the key objectives of this study was to identify areas where further research may help to clarify issues of concern or lessen the impacts of energy crops on hydrology. This final section of the report outlines topic areas that should be prioritised. These can be categorised as either basic research, aimed at changing the performance of the crop, or applied studies designed to mitigate against the likely hydrological impacts of growing energy crops.

8.2.1 Increased biomass water ratio

The production of large quantities of harvestable biomass by energy crops is associated with high water use. Where the quantity of water used is of concern then one approach that should be considered is to breed varieties with improved biomass water ratios. The two benefits accruing from success would be:

1 greater biomass production in water limited areas; and

2 reduced water use in wetter areas.

8.2.2 Field scale studies on factors affecting hydrologically effective rainfall

One area of uncertainty highlighted by this review is the importance of the degree of coupling between the canopy of energy crops and the atmosphere. There are indications that energy crops grown in large blocks are effectively decoupled for most of the growing season in which case rainfall intercepted by the canopy could be considered to be substituting for evapotranspiration from the soil. The effect of advection on ETa from blocks of energy crops of different sizes is also an important factor to which there is currently no adequate answer.

These issues are best studied on commercial scale plantations by monitoring all aspects of the water balance. Comparison with the water balance of energy crops grown in small plots would help to clarify the relative importance of advection and interception losses.

8.2.3 Energy crop biomass production models

Although outside the terms of reference for this review, the need to be able to predict the likely biomass production for individual sites is important since site factors can have large effects on the growth and development of crops. These mechanistic process-based models would be able to refine the analysis undertaken here in terms of feedback effects such as that of drought on canopy duration. Clearly, the models should have the components of hydrologically effective rainfall as key outputs.

8.2.4 A GIS approach for evaluating potential sites

This report and the simplified water balance approach taken to simulate the water use of energy crops has confirmed the assertion that they use considerably more water than annual crops or permanent grass. The implications of this finding at different scales within the landscape are not clear. Using a GIS approach to scaling up such as the one described above will allow a first step towards understanding of the interactions between land use and hydrologically effective rainfall. Where serious impacts are predicted then a more detailed approach involving catchment specific hydrological models may be appropriate.

9 ACKNOWLEDGEMENTS

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