Modelling the influence of irrigation abstractions on Scotland's water resources

S.M. Dunn*, N. Chalmers*, M. Stalham, A. Lilly*, B. Crabtree* and L. Johnston***

* The Macaulay Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland, UK
(E-mail: *s.dunn@macaulay.ac.uk*)

** Agronomy Centre, Cambridge University Farm, Huntingdon Road, Cambridge, England, UK

Abstract Legislation to control abstraction of water in Scotland is limited and for purposes such as irrigation there are no restrictions in place over most of the country. This situation is set to change with implementation of the European Water Framework Directive. As a first step towards the development of appropriate policy for irrigation control there is a need to assess the current scale of irrigation practices in Scotland. This paper presents a modelling approach that has been used to quantify spatially the volume of water abstractions across the country for irrigation of potato crops under typical climatic conditions. A water balance model was developed to calculate soil moisture deficits and identify the potential need for irrigation. The results were then combined with spatial data on potato cropping and integrated to the sub-catchment scale to identify the river systems most at risk from over-abstraction. The results highlight that the areas that have greatest need for irrigation of potatoes are all concentrated in the central east-coast area of Scotland. The difference between irrigation demand in wet and dry years is very significant, although spatial patterns of the distribution are similar.

Keywords EU Water Framework Directive; irrigation; modeling; potatoes; water resources

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Introduction

Scotland is generally viewed as a nation with plentiful water resources, due to the large area of mountainous country with high rainfall and a comparatively small population to place demands on the resources. This view is reflected by relatively relaxed legislation controlling abstraction of water from surface and groundwater sources. Although specific statutes govern abstractions of water for specific purposes, such as public water supply, the right to abstract water from surface and groundwater is founded in common law (Wright, 1995). This means that a riparian owner is entitled to make use of water in a watercourse that flows through their land, and as a consequence the protection of watercourses from over-abstraction can be difficult to control.

In practice, Scotland's water resources are unevenly distributed and with the majority of the population resident in the central belt of the country, appropriate management of the water resources is essential. Furthermore, the more intensive agricultural areas of Scotland are predominantly located down the east coast, where the climate and soils are rather more favourable towards agricultural production. Irrigation of crops, primarily potatoes but also salad crops, grass and soft fruits, has taken place for many years in these areas. In recent years, the extent of irrigation practices has expanded in response to market forces (Weatherhead *et al*., 1997), because it is not only the yield but also the quality of finish of products that determines their market value. This can be strongly linked to water availability at key times during the development of the crop.

A form of legislation to control abstraction of water for irrigation has existed since the introduction of the Spray Irrigation (Scotland) Act 1964, subsequently replaced by the Natural Heritage (Scotland) Act 1991. However, because of the cumbersome nature of the application procedure involved with implementation of these Acts, control orders have only ever been issued to control irrigation abstractions in two catchments. These are the West Peffer Burn in East Lothian and the Ordie Burn in Perthshire. A recent analysis of the West Peffer Burn (Dunn *et al*., in press and Dunn *et al*., submitted) demonstrated the significance of abstractions for potato irrigation in terms of their impact on stream flows, despite the existence of the present control order.

In practice, therefore, watercourses in Scotland remain largely unprotected from over-abstraction. This situation is set to change under the requirements of the EU Water Framework Directive for member states to implement controls over the abstraction of fresh surface water and groundwater. This will necessitate the development of new policy and legislation in Scotland to control irrigation abstractions. As a first step towards development of appropriate policy, it is necessary to assess the current scale of irrigation in Scotland and to examine whether current practices are causing environmental problems.

In England and Wales, Knox *et al*. (1996) developed a procedure for mapping the spatial distribution of irrigation water requirements for maincrop potatoes, using a physiological approach. This enabled them to assess the potential volumetric requirements for irrigation water in different regions, for both current and future land use and irrigation practices. In this paper, the development of a similar approach for Scotland is described. Spatial estimates of soil moisture deficits are used to predict the extent of irrigation of potatoes, for a range of typical climatic conditions. The analysis focuses on potato irrigation as the single largest agricultural use of water in the UK, accounting for around 50% of the water usage in England and Wales (Stansfield, 1997). In Scotland this figure is likely to be higher, because of the greater importance of the potato crop. The significance of potato irrigation in terms of water resources is assessed by integration to a sub-catchment scale, where the potential impacts of the abstractions on different river systems can be examined.

Methods

Water balance model

A water balance model has been developed within a GIS to calculate weekly inputs and storages of water within the soil system, as well as drainage from the soil to ground and surface water systems. The model has been applied to the whole of Scotland using a grid resolution of 1 km^2. For each 1 km^2 grid cell, a weekly balance is calculated of the inputs and outputs to the soil system:

$$S_t - S_{t-1} + P_t - E_t - F_t$$

where S_t is the soil moisture storage (m) for week t, S_{t-1} is the soil moisture storage from the previous week, P_t is the precipitation input (m) for week t, ET_t is the evapotranspiration (m) for week t, F_t is the total flow out of the grid cell (m) for week t. The model uses weekly maps of precipitation and evapotranspiration as input data, as well as data on soil physical properties, such as field capacity and saturation capacity. Net precipitation enters the soil, where it is added to the existing soil storage. Flows out of each grid cell are partitioned into three different components, overland flow (*OF*), sub-surface flow (*SSF*) and groundwater flow (*GWF*), depending on the soil moisture conditions at each time-step. Three different states are considered:

(1) soil moisture storage < field capacity
(2) field capacity < soil moisture storage < saturation capacity
(3) soil moisture storage > saturation capacity

In situation (1) there is assumed to be no drainage from the soil column. In situation (2) there is both drainage to groundwater and sub-surface flow loss. In situation (3), the excess water beyond saturation capacity is assumed to constitute overland flow, and there is also drainage to groundwater and loss to sub-surface flow. The relative amounts of sub-surface flow and groundwater vary with the soil moisture, and also vary between different soils according to two calibration parameters.

For each week, the soil moisture deficit below field capacity, *SMD*, can be calculated as:

$$SMD_t = FC - S_t$$

where *FC* is the field capacity for the soil.

Data. The water balance model uses weekly maps of precipitation and evapotranspiration as inputs. Precipitation maps were derived by spatial interpolation of raingauge data, using a lognormal kriging method. Evapotranspiration rates were calculated using the Penman-Monteith method (Monteith, 1965) applied to standard measurements from meteorological stations. The evapotranspiration data were assigned spatially on the basis of the nearest meteorological station. This was deemed reasonable, as the spatial variability in evapotranspiration is low relative to differences in precipitation.

The model also requires values for field capacity and saturated capacity of soils. These values were derived from the Scottish Soils Database by pedotransfer. For each soil series, available water capacity was estimated from particle size data for each horizon down to a maximum depth of 1 m and using data published by MAFF (1988). Since many of the 1:250,000 scale soil map units comprise of a number of different soil series, a method was also required to estimate average soil properties by map unit. This was achieved by weighting values for the field capacity and saturated capacity for each soil series, by their relative frequency (and by their horizon thicknesses).

Irrigation potential

Once the soil moisture deficits have been calculated, the potential need for irrigation can be estimated. The decision rules that are applied for irrigation scheduling can be very complicated, and will vary as a function of factors such as planting date, potato variety, and soil type. For the purposes of this analysis a simplified set of rules was used to estimate optimal irrigation for a potato crop, assumed to be planted in the middle of April, as follows:

1. Allowable *SMD* at beginning of scab control period (27th May) is 13 mm
2. Allowable *SMD* increases linearly to 26 mm at end of scab control period (28th June)
3. Limiting *SMD* for yield increases linearly from 36 mm at end of scab control to 51 mm on 1st August
4. Limiting *SMD* maintained at 51 mm until end of season

These rules were incorporated within the water balance model by setting an allowable deficit on a weekly basis. The depths of irrigation applications necessary to satisfy the criteria were then calculated at each time-step. By summing the outputs of these calculations a map of the total annual irrigation potential across the country can be obtained.

Spatial sensitivity

In order to determine some measure of the significance of irrigation with respect to water resources, two further steps are necessary. First, spatial integration is required to calculate the average potential irrigation depth across a catchment. Each individual abstraction is unlikely to cause any environmental problems within a river system, but where multiple abstractions occur from the same system, problems are more likely to arise. In this context, the size of catchments can be very influential in determining its sensitivity. In general terms, the larger the catchment, the more likely that a significant proportion of it drains from the uplands where irrigation potential is low, and precipitation is high. The two catchments where abstraction control orders already exist are 37 km^2 and 45 km^2 and are indicative of the scale that might be considered appropriate for implementation of abstraction controls. Therefore, for this analysis, definitions of sub-catchments of the order of 30 km^2 in size were used as the spatial integrator.

The second piece of information that is required is the actual locations and areas of potato cropping. Information on potato production in Scotland was available from the June Census, the British Potato Council (BPC) census and from IACS (Integrated Administration and Control System) returns. The IACS returns are incomplete, because potatoes are not a supported crop under the area payments scheme, but they are of value in providing a precise geographical reference for locations of potato fields. Areas of potato cropping from the IACS data were associated with their geographical reference and then weighted to give the correct total area according to the June Census. To account for the actual distribution of the cropping, the point information was buffered out and apportioned to neighbouring grid cells. Although physiological conditions may indicate that irrigation of potatoes is required, there are a number of reasons why the crop may not be irrigated in practice. This includes factors such as the availability of irrigation equipment, type of crop (seed potatoes are rarely irrigated) and access to water sources. Detailed data are not available to define whether or not potatoes are irrigated. However, a strong regional trend in the nature of potato cropping activities means that average figures by county, from the British Potato Council 1999 data set, can be used to estimate the percentage of the total potato cropping areas that are actually irrigated. These percentages range from 12% in Aberdeenshire to 63% in East Lothian.

In order to simplify the calculations of spatial sensitivity, the analysis was carried out only for those parts of the country where potato cropping accounted for more than 1% of the land use. In other areas, the sensitivity to potato irrigation could be assumed to be low. Figure 1 shows the percentage of potato cropping as defined by data from the June Census, by parish, together with the sub-catchment definitions used in the analysis.

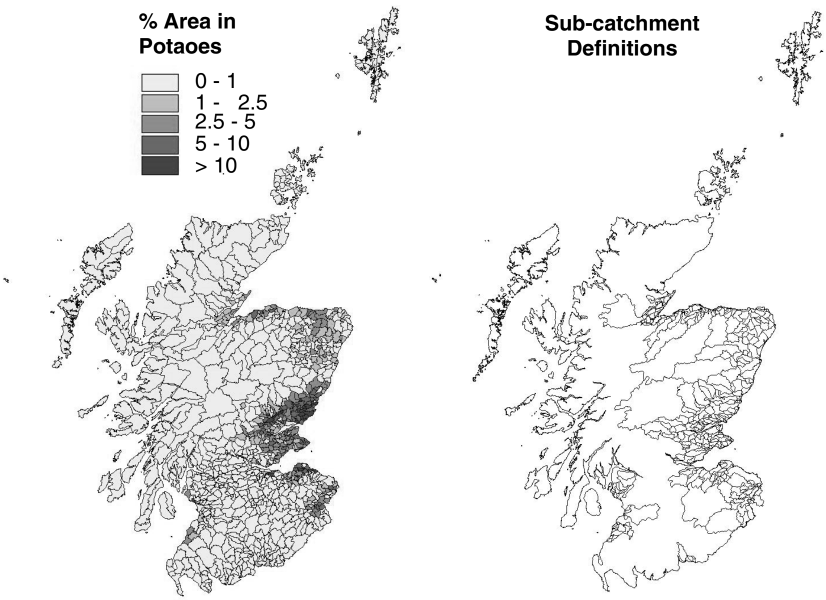

Figure 1 Distribution of potato cropping in Scotland and definition of sub-catchment boundaries for all areas where area under potato >1%

Results and discussion

The water balance model was applied using meteorological data from 1989, 1992 and 1998. 1989 was generally a dry year across the whole of Scotland, whilst 1992 could be considered average and 1998 had a particularly wet summer. Total annual precipitation across the country varied from 358–3,854 mm in 1989, 597–4,020 mm in 1992 and 614–3,958 mm in 1998. These years should effectively cover the typical range of climatic conditions and hence give an indication of typical irrigation requirements and impacts.

Soil moisture deficit and irrigation potential

Figure 2 shows a map of the calculated soil moisture deficits at the end of May, prior to any irrigation applications, for the three years. At this stage, in order to bring the allowable SMD back to 13 mm, an irrigation depth of up to 75 mm would have been necessary in some areas in 1989, whilst in 1992 and 1998 there would only have been a need for a maximum of 25 mm irrigation.

Figure 3 shows a map of the total irrigation potential summed over the whole growing season, for each year. As would be expected, the need for irrigation is much greater in the east of the country where precipitation is relatively low. For the dry summer of 1989, the irrigation potential exceeded 200 mm in parts of Angus, Fife and East Lothian. In 1992, the highest values were around 140 mm. However, in 1998, there was nowhere a need for more than 50 mm of irrigation over the whole season.

The total irrigation potential was then linked with the data on locations of potato cropping and integrated across sub-catchment areas, to give an estimate of the actual irrigation depth averaged across each sub-catchment. The results from this analysis are shown in Figure 4 for the areas where potato cropping > 1% of land use. The sub-catchments with the highest calculated irrigation depths are: the West Peffer Burn and lower reaches of the Tyne in East Lothian; two small coastal sub-catchments in Fife; two sub-catchments of the River Isla in Perthshire and a coastal sub-catchment in Angus. The difference in irrigation between dry and wet years is very significant. Since the availability of water resources will follow the reverse pattern, the potential impact of abstractions in dry years is doubly emphasized. Although the analysis has taken into account regional estimates of the percentage of potato areas that are irrigated, these figures are still based on optimal irrigation to satisfy physiological requirements. For other reasons, the actual depths of irrigation applied may be lower than this, for example due to equipment constraints or scheduling errors (Weatherhead *et al.*, 2000).

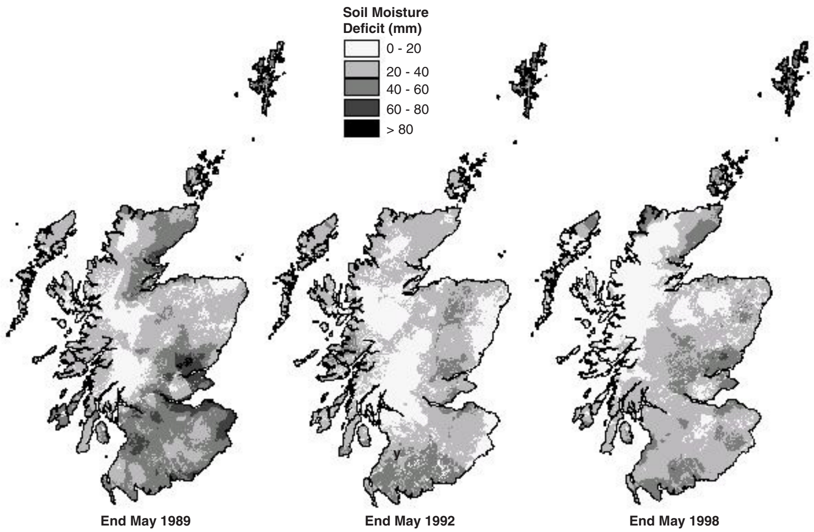

Figure 2 Calculated soil moisture deficits at the end of May, prior to any irrigation applications

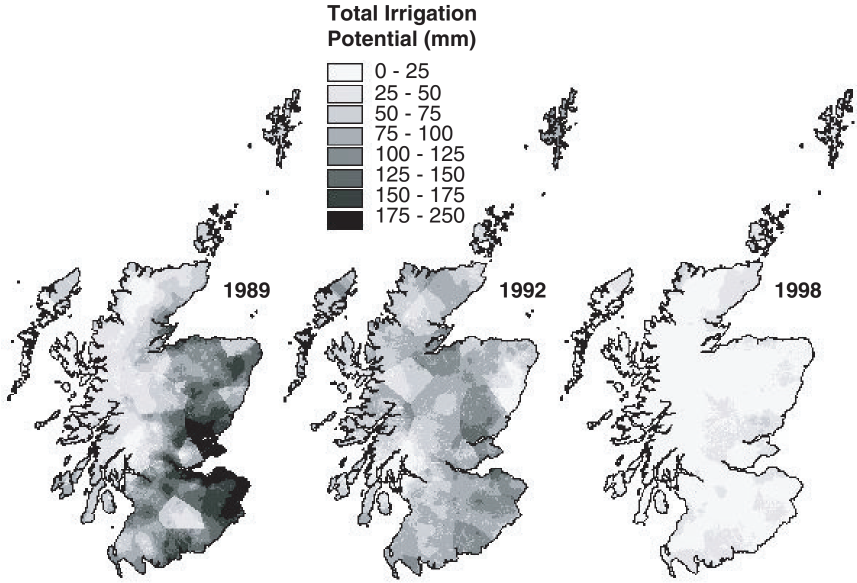

Figure 3 Total irrigation potential for a potato crop in three different years

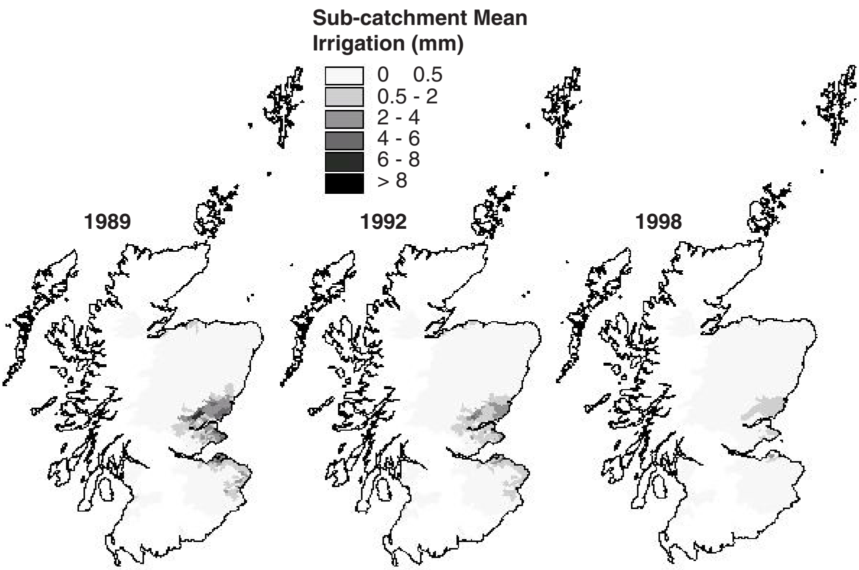

Figure 4 Calculated actual irrigation abstractions for potato crop, averaged across sub-catchment areas

Another factor that is important to consider in quantifying the significance of the abstractions is the water balances for the sub-catchments. Using the outputs of the flow calculations from the water balance model, the annual sub-catchment runoffs were estimated, and hence the irrigation could be expressed as a fraction of the total annual natural water balance. This analysis proved even more revealing in terms of differentiating between different parts of the country. Table 1 summarises the calculated irrigation percentages for all sub-catchments where the values exceeded 10% in 1989. In catchments such as the West Peffer Burn the difference between precipitation and evapotranspiration in dry years, such as 1989, is very small and hence the natural runoff is extremely low. It should not be a surprise that in these cases the demand for irrigation abstractions can become a significant proportion of the net runoff. However, with only a slightly higher margin between

Table 1 Summary of sub-catchments where calculated irrigation abstractions expressed as a percentage of sub-catchment runoff exceeded 10% in 1989

Sub-catchment	Irrigation/ 1989	Runoff (%) 1992	(Runoff depth in mm) 1998
W Peffer Burn (S), E Lothian	87 (19)	10 (109)	2 (86)
W Peffer Burn (N), E Lothian	20 (23)	3 (111)	0.5 (134)
Lower Tyne, E Lothian	38 (24)	4 (141)	0.7 (219)
Back Burn (Tyne trib.), E. Lothian	18 (23)	2 (130)	0.3 (186)
Fife coastal, Crail	13 (67)	3 (163)	0.4 (399)
Angus coastal, S of Lunan Bay	13 (43)	2 (128)	0.4 (386)
Lower Whiteadder, Borders	11 (33)	0.9 (178)	0.06 (417)
Whiteadder trib., Borders	10 (34)	0.8 (194)	0.04 (447)

precipitation and evapotranspiration, such as that observed in 1992, the abstraction requirements become much less significant.

These results serve to give an overview of the relative sensitivity of different parts of the country to abstractions for irrigation of potato crops. However, analysis of annual totals gives little indication of the actual impacts of abstractions on water resources throughout the year. A more detailed modelling study of the Tyne and West Peffer catchments (Dunn *et al.*, in press, Dunn *et al.*, submitted), demonstrated that irrigation abstractions would have a negligible impact on flow in the main stem of the River Tyne. However, stream flows in summer in the West Peffer Burn were found to be inadequate to meet the demand for irrigation and could result in drying out of the stream in any year, regardless of the weather. This has been observed in practice. One of the main reasons for the discrepancy in impact between the two catchments is that the Tyne is a larger catchment where flows in the lower reaches, where most abstractions occur, are sustained by runoff from the upper parts of the catchment. Clearly, this spatial element is an important factor in determining the potential impact of abstractions on water resources. Similar issues have previously been highlighted by Bonvoisin and Moore (1993), in relation to the assessment of discharge consents and abstraction licences. A more detailed study of each individual catchment is necessary to ascertain whether or not abstractions will have a significant impact in practice.

Conclusions

The volumes of water abstracted for irrigation of potatoes in Scotland vary significantly from year to year, depending on weather conditions. In dry years, irrigation volumes may be quite high and there is the potential for some streams to suffer environmental damage as a consequence of over-abstraction. However, the areas involved are relatively small. The highest levels of abstraction are concentrated in the east of the country, in Angus, Perth, Fife and East Lothian. The catchment that has the highest apparent sensitivity to irrigation abstractions is the West Peffer Burn in E Lothian. This is one of the two areas in Scotland that is currently subject to a control order for irrigation. The West Peffer Burn is particularly sensitive because it has a low effective runoff depth, combined with a high intensity of potato cropping, and is a small stream that does not receive any runoff draining from the hills. In most cases detrimental impacts are likely to be quite localized and identifiable only by detailed catchment studies. Such factors will need to be taken into consideration if policy implemented in response to the EU Water Framework Directive is to be effective in achieving its aims.

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