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Adjusting irrigation abstraction to minimise the impact on stream flow in the East of Scotland

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Abstract

Abstractions of surface and groundwater for irrigation in Scotland are currently subject to control in only two small catchments. Under the terms of the EU Water Framework Directive, it will be necessary to introduce new legislation to control abstractions elsewhere. To help in the development of appropriate policy for Scotland a study has been carried out to examine the significance of irrigation and the effectiveness of different types of control strategies in terms of the economics of potato cropping and stream hydrology in Scotland. This paper presents the findings of the hydrological study and highlights some of the spatial and temporal issues that need to be considered in the selection of control mechanisms, if they are to be successful in achieving objectives for environmental improvement.

The study was focussed on two catchments in the east of Scotland, the Tyne and West Peffer. The effectiveness of several different abstraction control strategies was examined to see how stream flows in the catchment would be modified by their implementation. The results of the study demonstrated that the West Peffer catchment in particular is significantly affected by irrigation abstractions. Control mechanisms based on allowable monthly abstraction volumes and flow-based abstraction bans would be of considerable help in restoring stream flows to their natural levels, but would modify the hydrological regime in slightly different ways. A spatial analysis of stream flows demonstrated that implementation of controls based on a single monitoring point may be ineffective at maintaining acceptable levels of flow throughout the catchment and that this may require a tighter control at the monitoring point.

Keywords: Modelling; Potatoes; Spatial; Streamflow; Temporal; Water

1. Introduction

Legislation controlling abstraction of water from surface and groundwater sources in Scotland has historically been relatively relaxed. Although specific statutes govern abstraction 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) describes the complex ownership of water that essentially means that a riparian landowner is entitled to make use of water in a watercourse that flows through their land. In order to meet the requirements of the European Water Framework Directive (2000/060/EC), new legislation must be introduced to control abstractions of this type. One of the primary forms of abstraction that is currently subject to only limited control in Scotland, and that will therefore be affected by this, is water drawn for irrigation. 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. Although irrigation abstractions occur in many catchments and there is the potential for flows in many small streams to be significantly reduced by the abstractions, in practice, control orders have only ever been issued to cover two small areas. This is primarily because of the cumbersome nature of the application procedure (Fox and Walker, 2002).

There are many different mechanisms by which abstractions may be controlled. Typical approaches used in other countries have included a simple licence system based on a maximum rate of abstraction combined with abstraction bans when flows fall to prescribed levels, such as the flow that is exceeded 95% of the time. In England and Wales, for

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example, an abstraction licence is issued that allows abstractors to take water within the limits of the conditions stated on the licence. These conditions will be determined for each individual situation. Adeloye and Low (1996) discusses the pros and cons of some approaches that might be introduced in Scotland, suggesting that all abstractions should be subject to licence and that sensitive watercourses which are highly prone to low-flow problems should be protected by refusing licences. Fox and Walker (2002) advocate a form of selective control similar to the current proposals for reform of abstraction control in England and Wales. This retains elements of their existing system, whilst at the same time introducing new features such as time limited licences and a system of Catchment Abstraction Management Strategies (CAMS). The objective of CAMS is to improve availability of information and to allow the balance between the needs of abstractors and those of the aquatic environment to be determined in consultation with the local community and interested parties (Environment Agency, 2001). Fox and Walker (2002) also point out that there is an opportunity for a future abstraction licensing system for Scotland to implement the latest thinking which would, for example, allow abstraction conditions to vary throughout the year. One relatively simple way of achieving this is to set monthly or seasonal abstraction allowances that are based on a fixed percentage of the mean flows for each month. Alternatively, there is a move in England and Wales towards increasing charges for abstraction beyond the current practice of cost-recovery. Charging schemes are already seasonally weighted to encourage abstractions when resources are plentiful and there is a suggestion that this weighting could be further enhanced (Department for Environment, Food and Rural Affairs, 2001).

In addition to the issue of temporal variability in consents, Knox et al. (2000) highlighted the need for location specific consents. They demonstrated the spatial and temporal variability in the value of irrigation water in a study of the potential financial impacts of restrictions on irrigation abstractions, in eastern England. Bonvoisin and Morre (1993) also illustrated the importance of spatial information in assessing discharge consents and abstraction licences, because of the importance of the stream size in determining its ability to withstand management pressures.

2. Situation

Irrigation in Scotland is carried out mainly for potato crops, and less commonly for salad crops, grass and soft fruits. It takes place in all parts of the country where potato production occurs, but is most significant in the east, in areas such as Angus, Perthshire, Fife and East Lothian. These areas have a drier climate than other parts, making water resources more scarce, and hence both the need for and impact of irrigation abstractions is exacerbated. The future demand for irrigation water is likely to increase, in common with the situation in England and Wales (Stansfield, 1997; Weatherhead and Knox, 2000), because of the relationship between irrigation and quality of finish of the potato crop, which affects its market value. Consequently, the environmental impacts of irrigation abstractions in Scotland, both now and in the future, may be of more significance than is generally realised.

The principle hydrological impact of irrigation abstractions in Scotland is a reduction in stream flows. The application for a control order on the West Peffer Burn in East Lothian (Lothians River Purification Board, 1973) highlighted the fact that as a result of irrigation abstractions there were occasions when flow in the burns was reduced almost to nil. Streams frequently act as carriers for sewage effluent and without adequate flows the water quality can be severely affected and result in accumulation of solid matter. In addition, where water supplies are limited there is a need for a form of control to ensure that available irrigation water is fairly distributed across the catchment and of an acceptable water quality throughout. Reductions in stream flows and poor water quality can also lead to ecological problems, such as a decrease in biodiversity and alteration of habitats. Many of the smaller streams in Scotland are spawning grounds for salmonid fish. These physical habitats can be damaged by reduced flows decreasing the wetted area of channel and leading to increased siltation.

New legislation for abstraction control is required in Scotland to satisfy the requirements of the EU Water Framework Directive. In order that the most appropriate policy is adopted to balance the requirements of agriculture for water with the environmental impacts of abstractions, an understanding of the impacts of irrigation abstractions on hydrology is required. To help in the development of such policy a study has been carried out to examine the significance of irrigation and the effectiveness of different types of control strategies in terms of the economics of potato cropping and stream hydrology in Scotland (Crabtree et al., 2002). In particular, the study aimed to evaluate the significance of spatial and temporal variability in the impacts of irrigation and to demonstrate that control mechanisms implemented at a catchment scale are unlikely to be successful in achieving objectives for environmental improvement across a whole catchment.

3. Case study catchments

The study was focussed on two catchments in East Lothian, the Tyne and the West Peffer, where potatoes are an important crop (Fig. 1). The West Peffer is one of the two catchments in Scotland where a control order for irrigation abstractions currently exists. The Ordnance Survey 50 m digital elevation model (DEM) was used to derive the boundaries of the two catchments and to generate a digital stream network.

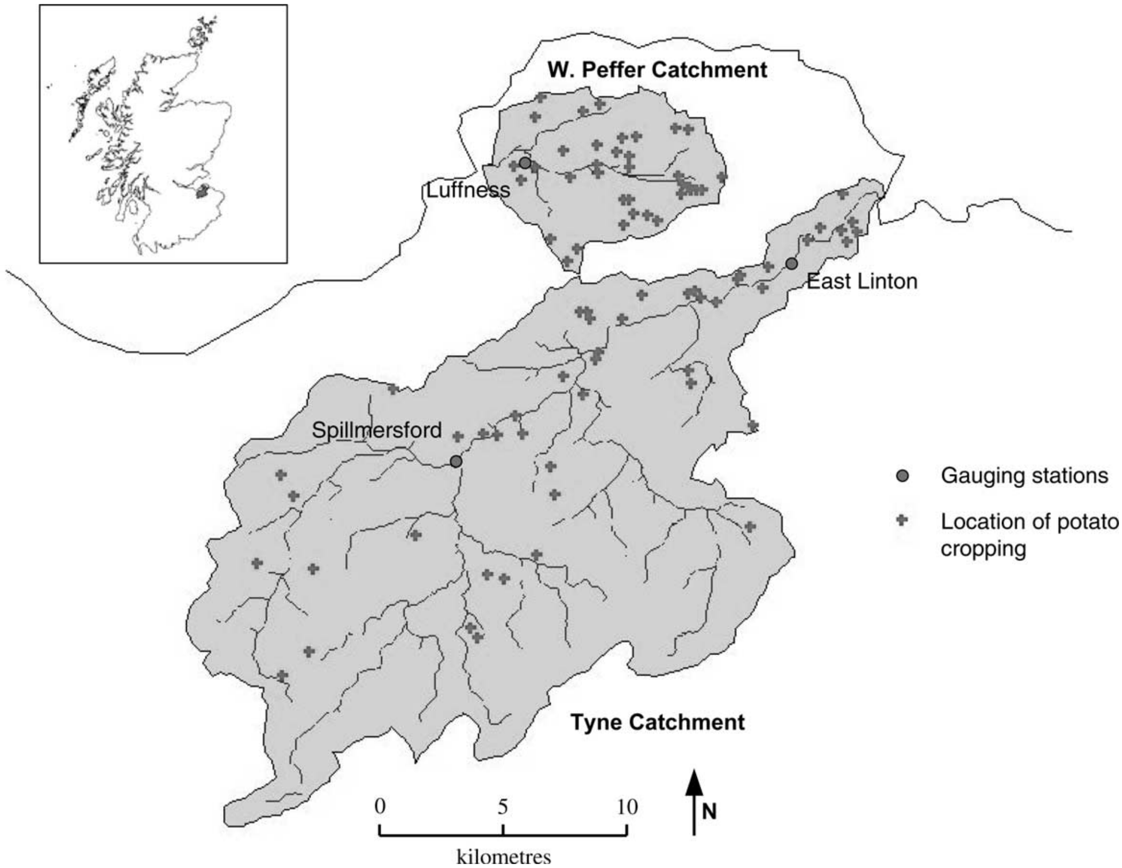

Fig. 1. Location of the case study catchments showing the stream network, locations of potato cropping and flow gauging stations.

The catchments were selected on the basis that they had a high proportion of agricultural land used for potatoes, and were perceived to be potentially vulnerable in terms of low flows in the rivers. The West Peffer is already subject to abstraction controls, whereas the Tyne is not. 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. Statistics on the area of agricultural land and potatoes given in Table 1 highlight the intensity of potato production in the West Peffer in particular. However, the distribution of potato production as shown by the IACS locations of potato fields (Fig. 1) also show parts of the lower Tyne catchment to be quite intensively used.

Topographically, the West Peffer catchment is a low-lying area with minimal relief. The West Peffer Burn flows east to west into the Firth of Forth, with stream flows gauged at Luffness. This point is upstream of the point of the main northern tributary in the catchment, and hence gauges an area of only 26 km^2, compared with the 46 km^2 of the whole catchment. The catchment has a mean annual rainfall of around 600 mm. When combined with potential evapotranspiration rates of around 500 mm per year, it is clear that there is little net runoff in the catchment, even without irrigation abstractions. Although controls have been placed on agricultural abstraction in the catchment for many years now, this has not prevented very low flows from occurring in the stream. Historical data supplied by the Scottish Environment Protection Agency (SEPA) for 1989-1998 show that for 10% of the time, the flow in the West Peffer is equivalent to less than 12 mm of runoff per year. This is a volume that might typically be used to irrigate the whole area in only a few days.

Table 1
Statistics describing agricultural land use in the Tyne and West Peffer catchments

Catchment	Total area (km^2)	Agricultural area (km^2)	Area of potato production (ha)	Potentially irrigated potato area (ha)
Tyne	329	227	631	300
West Peffer	46	37.9	484	380

The Tyne catchment covers a much larger area of 329 km^2 with the main river flowing from south-west to north-east and discharging into the North Sea to the north of Dunbar. Stream flows are monitored near the outlet at East Linton and also upstream at Spillmersford, encompassing an area of around 161 km^2 (Fig. 1). The catchment is more heterogeneous in its nature than the West Peffer. Whilst the lower parts of the system are very similar, the source of the Tyne lies in the Lammermuir Hills at an elevation of 527 m.

As a consequence, both the hydrology of the catchment and its land use are also more varied. Precipitation in the upper part of the catchment averages around 800 mm per year, generating much higher specific runoff rates. In this respect, flows from the upper part of the catchment are likely to be beneficial in maintaining acceptable levels of stream flow in the lower catchment, where irrigation abstractions for potato production are more likely to occur. By comparison with the figure of 12 mm for the West Peffer, there is an equivalent runoff of 60 mm per year that is exceeded for 90% of the time in the Tyne at East Linton.

The objective of the study was to determine the extent of irrigation abstractions for potato cropping in the Tyne and West Peffer catchments and thereafter to examine what the implications of abstraction controls would be. This paper focuses on the environmental aspects of the abstractions in terms of their impact on stream flows.

4. Modelling methodology

The study involved the use of a spatial hydrological modelling approach to simulate flows in the catchments under natural hydrological conditions, where current land use (predominantly agricultural) is assumed but no abstractions take place. The modelling was then used to simulate flows for different scenarios of irrigation management, which were derived from data pertaining to potato cropping in the area. The flow predictions provided input data to a potato growth model to identify the availability of water for surface abstraction at different times. The output from the potato growth model subsequently provided feedback to the hydrological analysis by establishing optimal irrigation scheduling under those conditions. Although historical measurements of stream flow were available for the case study catchments, these data reflect the managed system whereas it is the capacity of the system excluding existing abstractions that needs to be analysed in relation to irrigation demand. Hydrological analysis was also necessary to examine how different scenarios of irrigation control would modify the hydrological regime, and hence how effective they would be in achieving environmental improvements, in terms of stream flows. Modelling of the stream flows using a spatially distributed rainfall-runoff model had the added advantage that the impact of irrigation abstractions on stream flows could be spatially analysed. This allowed the effectiveness of the control instruments to be assessed across the whole catchment, rather than just at a single point on the watercourse. The model could also be used as an investigative tool to examine different climatic and irrigation scenarios.

The DIY model (Dunn et al., 1998) was used as the basic tool to derive the naturalised flows. The term ‘natural’ is used throughout this paper to refer to the existing agricultural land use system, but without any irrigation abstractions. The model uses a GIS approach to spatially categorise a catchment into $50 \times 50\ m^2$ cells, on the basis of a range of physical properties. These properties typically include rainfall, elevation, hill-slope, distance to stream and soil type. For each characteristic category, a hill-slope routing model is used to calculate a time-series signature of the flow, which that category contributes to the stream. The flows from each category are combined and weighted by their relative numbers to determine the catchment stream flow. This means that stream flows can be estimated for any location within the catchment, by determining the contributing areas to the stream at each point. Although the Tyne and West Peffer catchments are hydrologically disconnected, the structure of the DIY model meant that it would be possible to analyse both catchments in conjunction, whilst still calculating flows for the catchments independently.

The version of the DIY model used for this study included developments to several sub-modules, which have been applied to the generic framework described in Dunn et al. (1998). Fig. 2 illustrates the structure of the model used and model parameters are summarised in Table 2 together with a description of their function. In other studies the model has been applied within a Monte-Carlo framework to run multiple simulations that will identify a suite of acceptable parameter sets. This acknowledges the influence of parameter uncertainty and equifinality of predictions derived from different parameter sets, as observed by authors such as Freer et al. (1996). However, in the context of this application, the internal processes of the model functioning were perceived to be relatively insignificant, because the only objective function of interest was the end prediction of total stream flow, and the model was not required to predict the effect of changes in any physical characteristics. Therefore, it was deemed acceptable to base the analysis on a single calibrated set of parameters.

One of the aims of the study was to evaluate the manner in which typical irrigation abstractions affect stream flows, not just over the catchment as a whole, but also at any specific location in the stream network. In addition, the effectiveness of flow-based criteria for controlling abstractions was to be examined. A spatial mapping of potential irrigation abstractions was therefore derived, to link to the spatial predictions of natural stream flows. From the potato crop model different time-series scenarios of irrigation abstraction were derived to correspond to a range of potential policies that might be used to control surface water abstraction on the basis of flows at a particular point in the system. Although the IACS returns are incomplete, because potatoes are not a supported crop under the area payments scheme, 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 uniformly to give the correct total area according to the June Census. Data from 1999 were used to generate a typical spatial

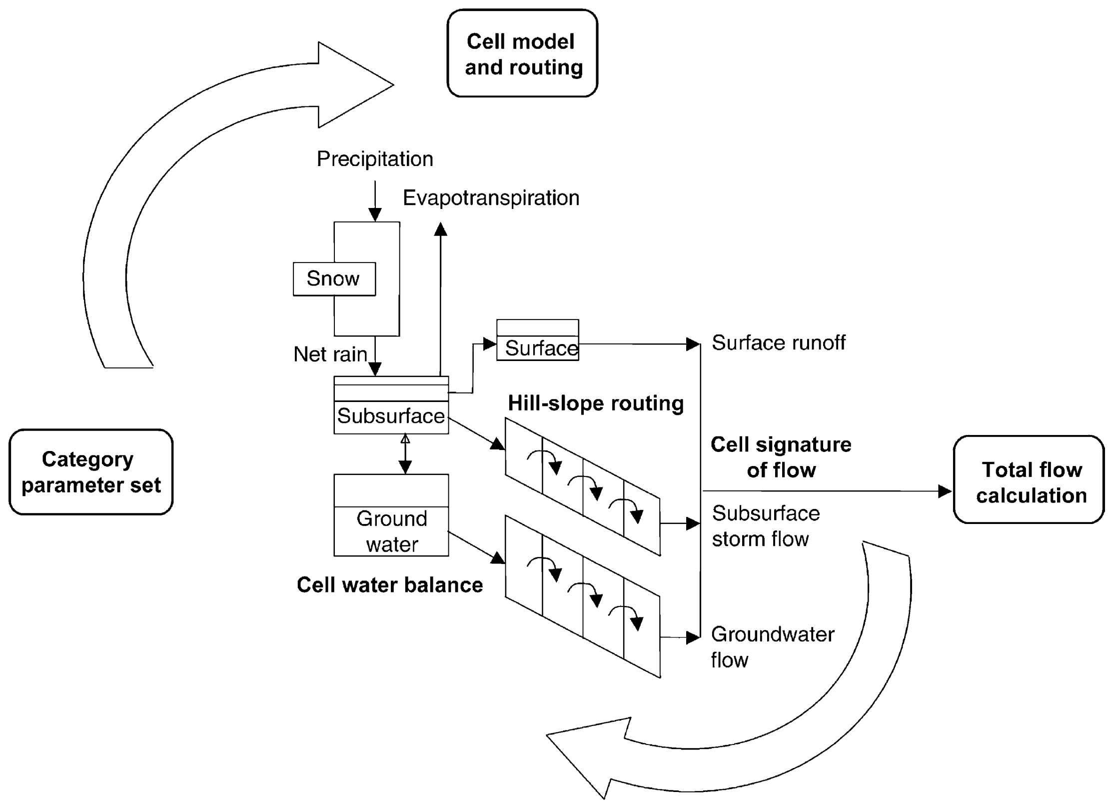

Fig. 2. Schematic of the DIY model used for rainfall-runoff modeling.

Table 2
DIY model parameters

Parameter	Variable	Function
Active zone conductivity	KACT	Control rate of sub-surface flow
Threshold storage	THMAX	Soil moisture level at which surface runoff response is initiated
Total soil porosity	PORE	Define relationship between soil storage and head
Fast response distance	FASTD	Define density of fast drainage network for surface runoff
Groundwater recharge fraction	RCHGF	Control recharge rate to groundwater
Groundwater conductivity	KGW	Control rate of groundwater flow
Slope to stream	SLOPE	Define hydraulic gradient for hill-slope model
Flow path distance to stream	DIST	Define hill-slope routing distance for each cell
Up-slope contributing area	UPAR	Control soil storage through balance between up-slope inflow and down-slope outflow
Snow accumulation and melt parameters	TS, TM, K, FG, FT	Partition precipitation between rainfall and snow and determine snowmelt rates

mapping of potato cropping. It was assumed that abstractions for irrigation were from surface water and that they would take place from the nearest location on the stream network to the geographical reference of the potato field. This made it possible to spatially combine irrigation abstractions with the predictions of natural flow from the DIY model, using GIS analysis. The resulting model maps the net flow across the entire catchment stream network, and hence highlights areas where the irrigation abstractions are of a level that is liable to cause environmental damage.

5. Model application

5.1. DIY simulation of natural flows

The DIY model was applied together with the potato growth model and irrigation scheduling to a 10-year period of meteorological data covering 1989–1998. Spatial categorisation for the DIY model was derived from maps of elevation, flow-length to stream, hill-slope and up-slope contributing area, as illustrated in Fig. 3. Evapotranspiration calculations were based on a typical arable land cover. Soils were assumed to be homogeneous for the purposes of the hydrological analysis.

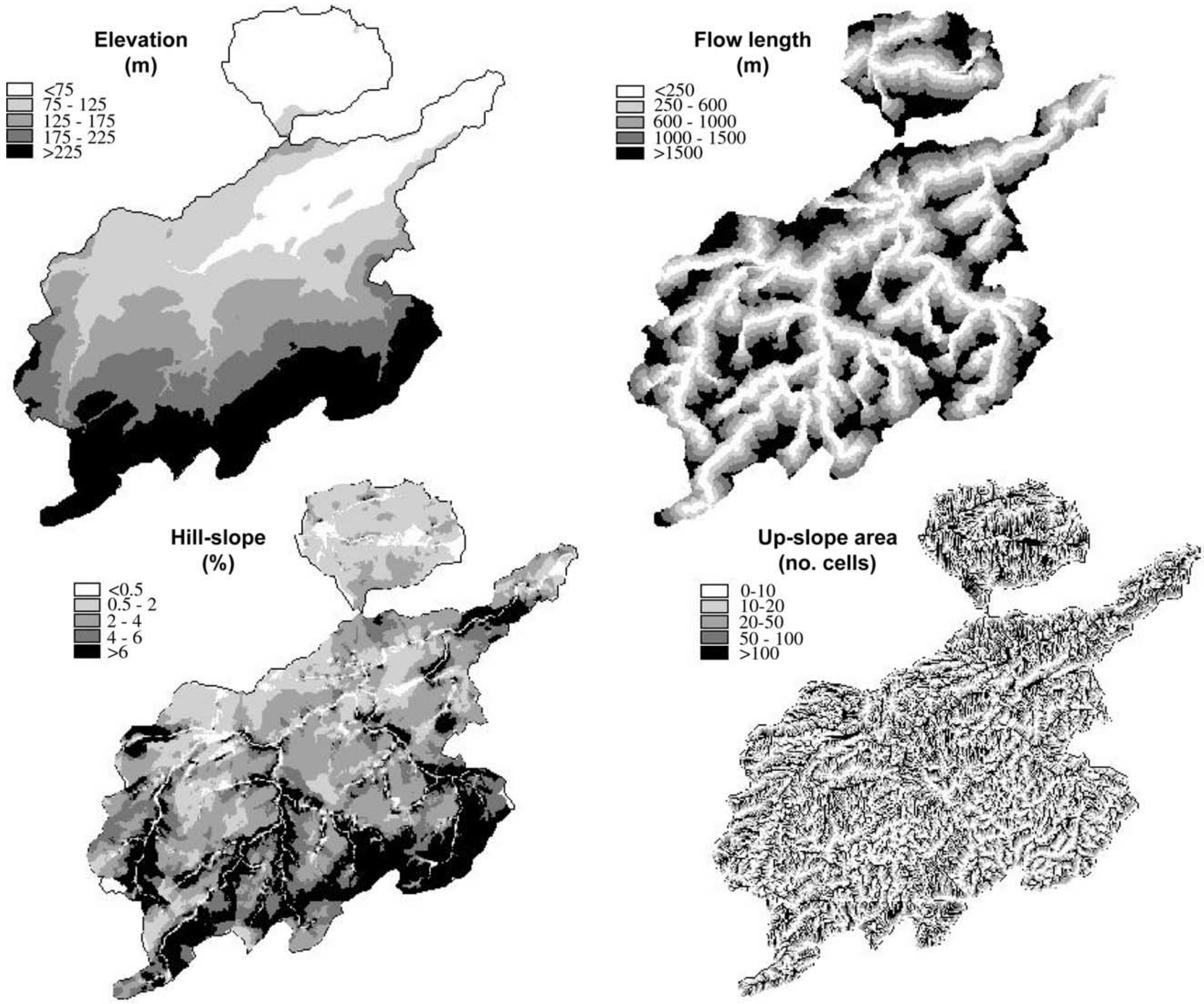

Fig. 3. Maps of elevation, flow-length to stream, hill-slope and up-slope contributing area, used to derive DIY model categories.

5.2. Simulation of irrigation scenarios

The potato growth and quality model developed at Cambridge University Farm (Stalham and Allen, 2003, and Stalham et al., 2003) enabled the relationships between irrigation amounts and potato yield and quality to be modelled. This means that irrigation scheduling for optimum quality could be predicted using information about variations in catchment flow and further used to quantify the effect of any water restrictions on grower returns, as a result of reduced quality or yield.

For any scenario, the potato growth model outputs dates and amounts of applications, based on an assumption that irrigation applications are made in a single day. In practice, across the catchment, even if all farmers are irrigating optimally, the irrigation applications will be spread over a number of days, due to limitations imposed by equipment availability, time to irrigate etc. The time-series of irrigation were therefore smoothed such that abstractions from the streams occur over 3 or 4 days either side of the optimal date.

In addition to optimal irrigation, a further range of irrigation scenarios was studied based on different flow criterion for restricting abstractions. These included:

1. a ban on abstraction when flows fall below the level of the 98%ile natural flow
2. a ban on abstraction when flows fall below the level of the 95%ile natural flow
3. a ban on abstraction when flows fall below the level of the 90%ile natural flow
4. a maximum allowed abstraction of 10% of the mean monthly available flow volume
5. a maximum allowed abstraction of 20% of the mean monthly available flow volume.

Having been provided with input data defining the volume of available water for abstraction to satisfy the flow-criterion, the potato growth model was used to determine the area of potato cropping that could be optimally irrigated, and the time-scheduling for that irrigation. These data were passed back to the hydrological model to calculate time-series of managed flows under each scenario.

The abstraction control scenarios should theoretically be self-fulfilling in terms of their impact on stream flows, maintaining the flow at the monitoring point at a minimum prescribed level. Nevertheless, there are several issues that need to be examined in relation to their effectiveness, including:

1. How the natural flow statistics are modified by abstractions up to this level
2. The impact of abstractions that occur when flows are just above the limiting level
3. The spatial effectiveness of the abstraction controls.

6. Results

6.1. DIY simulation of natural flows

Naturalised mean daily flows were simulated from an input of daily precipitation and evapotranspiration, with parameter values calibrated using stream flows at Spillmersford measured during 1989 and 1998. The effects of irrigation abstractions above Spillmersford will be very small relative to the total flow, as the majority of potato cropping occurs lower in the Tyne catchment. No other forms of management of the river system were considered likely to have a significant impact on stream flows.

The predicted natural flows for points in the catchment corresponding to each of the three gauging stations were compared with measured managed flows over the full 10-year period. Nash and Sutcliffe efficiencies (Nash and Sutcliffe, 1970) for the full simulations were good, with values of 0.83, 0.85 and 0.88 for Spillmersford, East Linton and Luffness, respectively, despite the influence of abstractions on the measured flows.

A closer examination of the summer low flows, illustrated in Fig. 4, can be used to elicit information about the actual effects of irrigation abstractions. For Spillmersford, it was anticipated that the effects of irrigation abstractions would be minimal. This time-series can therefore be used to quantify the potential error in the model predictions of low flows. The timing of the predicted summer recession follows the measured flows closely, but there is a tendency for the model to slightly over-predict the summer flows. There are many reasons why this may be the case including; limitations in the representation of groundwater processes, the assumption of homogeneity in soil hydrological processes, or feedback effects of soil moisture on actual evapotranspiration rates. Bearing these apparent errors in mind, examination of the low flows at East Linton suggests that irrigation abstractions also have a limited impact on flows in the main stem of the river at this point, with the natural flow predictions only slightly higher than measured flows. The same cannot be said about the low flows for Luffness, where there is a very large discrepancy between the modelled natural flow and measured data. The model predictions suggest the presence of a natural baseflow that does not fall below 0.03 $m^3 s^{-1}$, whereas in practice during most summers flows have been reduced to, or very close to, zero. Again, the shape of the early recession for the modelled flows suggests that the model may be slightly over-predicting low flows, but certainly not to the extent that the measured data would suggest. The fairly close match between predictions and measurements, for the wet summer of 1998, when irrigation abstractions will have been minimal, confirms this to be the case. Clearly, for other years, summer abstractions have an important influence on flows in the main stem of the West Peffer Burn.

6.2. Impact of optimal irrigation abstractions on stream flows

Fig. 5 shows predictions of the stream flows at the three gauging points for the scenario where optimal irrigation practice is adopted, assuming 100% of the abstractions are from surface water. The maximum rates of irrigation abstraction work out at around 0.10, 0.04 and 0.11 $m^3 s^{-1}$ for East Linton, Spillmersford and Luffness, respectively. The effect of this has negligible impact on stream flows at East Linton and Spillmersford, even during the driest periods. However, stream flows at Luffness are inadequate to meet this demand and will cause the stream to dry out, as is observed in practice.

Although the irrigation abstractions have negligible impact on flows in the main stem of the Tyne, this does not mean that the impacts of abstraction are negligible across the full catchment. The spatial analysis carried out with the DIY model demonstrates that several of the tributaries of the Tyne may be adversely affected by abstractions, as a consequence of a high rate of abstraction from a small stream. Fig. 6 shows an example output from the model, for a particular day during the dry summer of 1989. In several places the irrigation abstraction amounts to greater than 75% of the available flow.

6.3. Effectiveness of abstraction control scenarios

Simulations for the five scenarios to define abstraction control criterion were also carried out for the period from 1989 to 1998. Table 3 summarises the flow duration statistics for the West Peffer at Luffness for each of the scenarios and compares them with the calculated natural flow statistics as well as those of the measured flows.

The results show that all of the instruments significantly improve the levels of low flows over the historic measurements. The natural flows exceeded 60% of the time are largely unaffected by the abstractions. The scenarios still

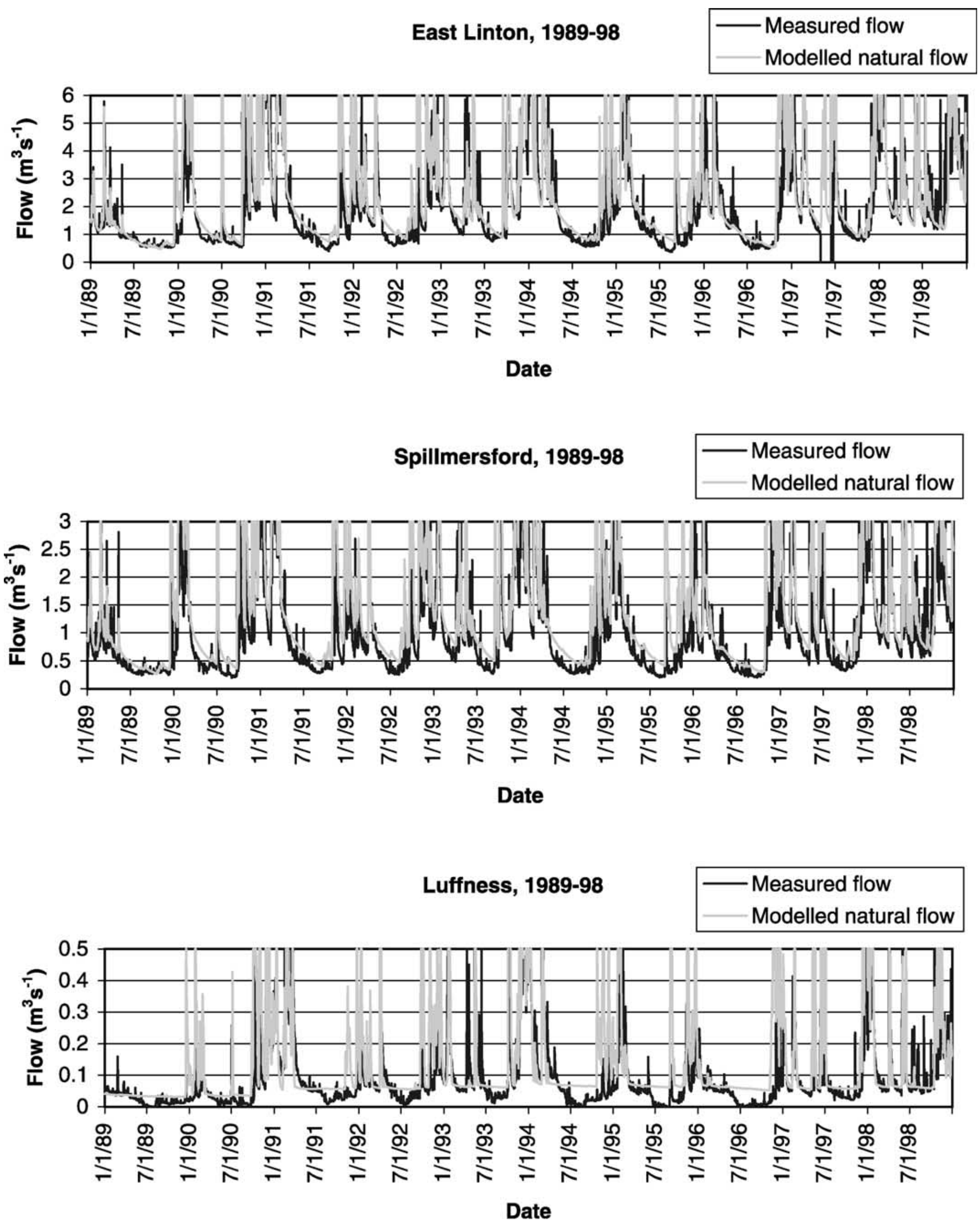

Fig. 4. Predictions of natural flow compared with measured managed flows for low flow periods at East Linton, Spillmersford and Luffness.

show a significant reduction in the levels of the low flows when compared to the predictions of natural flow, but this is inevitable. An abstraction allowance based on 10% of the mean monthly flow volume results in a flow regime that is closer to the natural flow of the river than any of the percentile based instruments, apart from at the very driest times. However, an allowance based on 20% of the mean monthly flow volume is ineffective at controlling abstractions during dry periods.

The duration over which stream flows are affected by the irrigation abstractions is quite significant and is summarised in Table 4 for each of the scenarios when applied to the West Peffer. Even with a ban on abstractions imposed at the 90%ile flow level, flows fall below the 98%ile level for 10% of the time. The reason for the limited success of the flow bans is that potential levels of abstraction are such that, even when there is no ban in place just above the 90%ile level, the demand for irrigation in the West Peffer could exceed the available water within the system. Although the instruments would minimise the amount of time that streams are dried out, they would not prevent the situation from arising. A ban would have to be introduced at an unrealistically high level for this to be achieved.

The instruments based on allowable monthly abstraction volumes are more successful in terms of the period of time that the instruments fail to achieve particular flows.

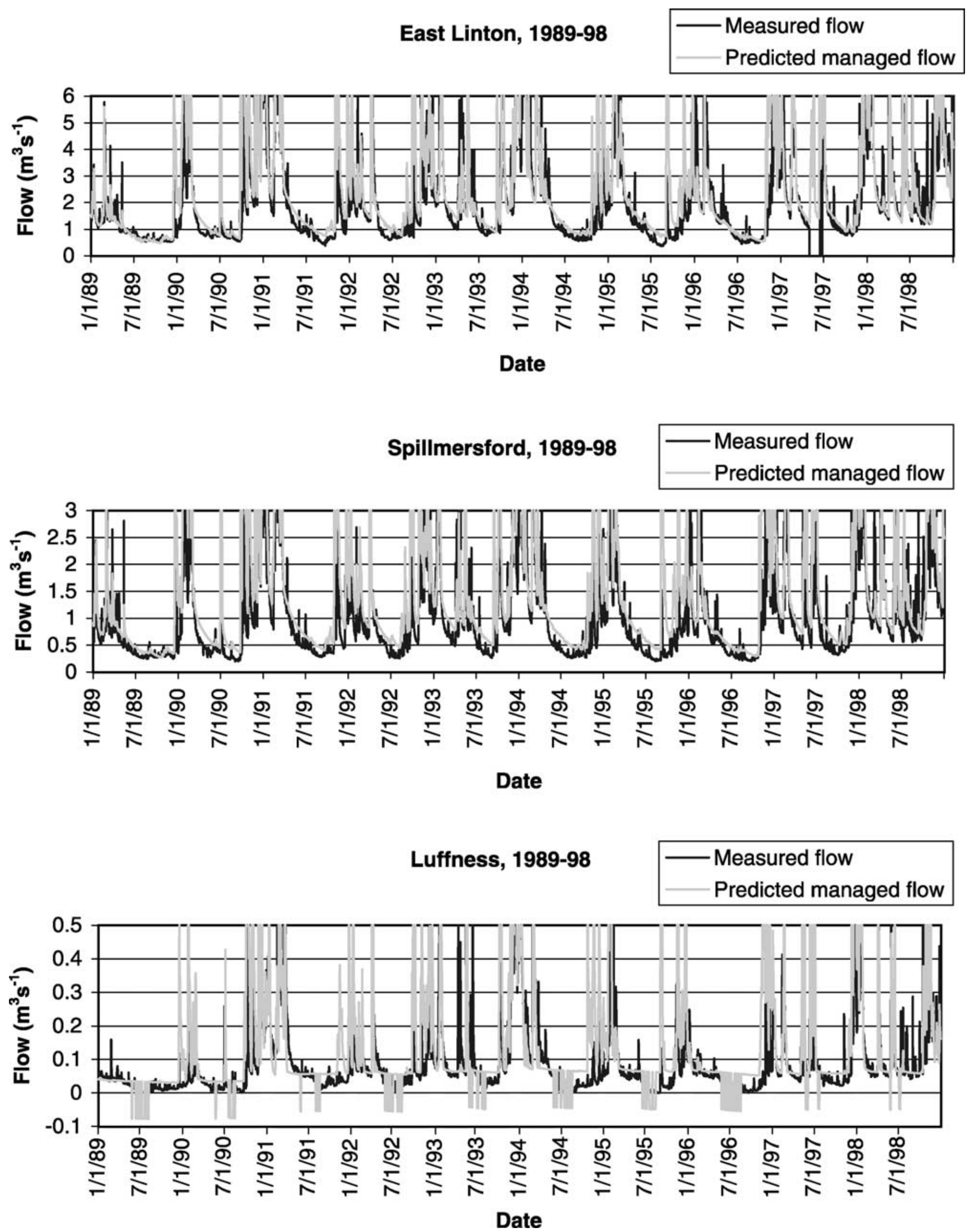

Fig. 5. Predictions of stream flow at East Linton, Spillmersford and Luffness, under an optimal irrigation scenario.

The allowance based on 10% fails the 98%ile flow for only 5% of the time and the allowance based on 20% fails the same level of flow for 9% of the time. However, from the flow duration statistics in Table 3 it is clear that when the instruments based on allowable monthly abstractions fail, that the severity of the failure will be greater.

Potato growers are likely to respond to abstraction controls by optimally irrigating a smaller area of their crops, with the remaining area irrigated as the availability of water permits. Table 5 summarises the average area of land in the West Peffer catchment that can be optimally irrigated (to maximise financial output) for the 10 years from 1989 to 1998, for each of the control instruments. In this respect, it is clear that the mean monthly flow allowances are much more satisfactory than the controls based on threshold flow percentiles. This is particularly the case in very dry years. In 1989, for example, only 3 ha of land could have been optimally irrigated with a 95%ile abstraction ban, because natural stream flows were lower than this level for a large part of the summer. By contrast, the control based on 10% mean monthly flow volume would have enabled 89 ha to be optimally irrigated. However, the advantage of the controls based on monthly flow allowances, in terms of area, must be offset against the fact that the total depth of irrigation that could be applied under the optimal scenario was considerably smaller than that which could be applied using the threshold flow percentile controls. This would result in a poorer quality crop with respect to common scab.

The instruments that have been studied are all based on monitoring of stream flows at one particular point in

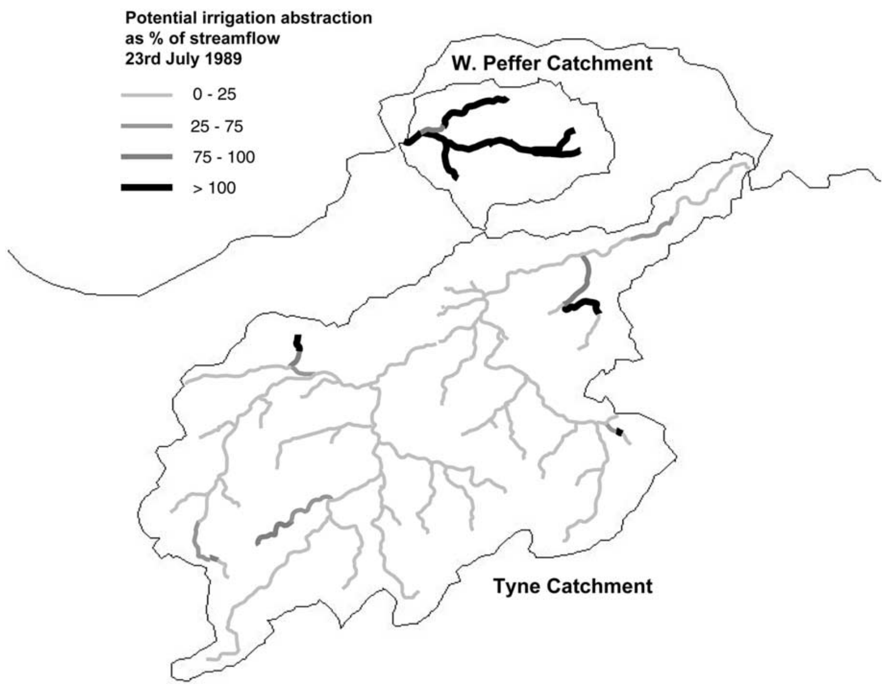

Fig. 6. Spatial predictions of managed flow across the Tyne and West Peffer under an optimal irrigation scenario, for 1 day, during the summer of 1989.

a catchment. Even if the control mechanism operates satisfactorily at this point, there is a danger that it may not be effective in controlling flows in other parts of the catchment. To examine this issue, the effect of a 2.5 mm/day irrigation abstraction on flows across the Tyne and West Peffer has been calculated, for an example day when flows at Luffness and East Linton are at their 90%ile level. The results of this, illustrated in Fig. 7, shows a map very similar to that calculated for the optimal irrigation scenario, shown in Fig. 6. For the Tyne, flows in most of the catchment are greater than 75% of the natural flow. However, there are several small tributaries where flows are significantly reduced to less than 50% of their natural level. For the West Peffer, flows throughout the catchment are grossly affected by the abstraction, and the main southern tributary does not have the capacity to meet the demand. A scenario of this type could be envisaged as a realistic reaction to an abstraction ban threat, causing a panic response.

7. Discussion

The case study analysis of abstraction for potato irrigation in the Tyne and West Peffer catchments has demonstrated the potential impact of irrigation activities on stream flows in certain parts of Scotland. The catchments were chosen for the case study as they were believed to be at risk in terms of over-abstraction, and as such represent the more extreme situation, rather than a general picture of irrigation impacts in Scotland.

The study confirmed that optimal irrigation of potato crops in the West Peffer catchment has a very significant impact on stream flows during the summer, and can very easily cause the streams to dry out. Indeed, the apparent impact of irrigation abstractions on stream flows is considerably higher than that reported by Hiscock et al. (2001) for three rivers in Norfolk, in one of the driest parts of England. However, in most parts of the Tyne catchment

Table 3
Flow duration statistics for flow controlled abstraction scenarios, compared with both predicted natural and historical measured flow statistics

% Time flow exceeded	Natural flow $m^3 s^{-1}$	Predicted flows at Luffness (West Peffer) for different scenarios ($m^3\ s^{-1}$)					Measured flow $m^3 s^{-1}$
		98%ile Ban scenario	95%ile Ban scenario	90%ile Ban scenario	10% Month volume	20% Month volume	
60	0.062	0.060	0.060	0.060	0.061	0.061	0.043
80	0.056	0.036	0.037	0.036	0.042	0.040	0.020
90	0.036	0.030	0.032	0.032	0.035	0.033	0.010
95	0.034	0.023	0.026	0.028	0.032	0.016	0.004
98	0.032	0.008	0.012	0.015	0.012	0.000	0.002

Table 4
Duration of failure to achieve flow thresholds for flow controlled abstraction scenarios

Natural flow %ile	Percentage of time scenario fails flow threshold				
	98%ile Ban scenario	95%ile Ban scenario	90%ile Ban scenario	10% Monthly volume	20% Monthly volume
90	20	20	20	13	16
95	16	15	15	8	12
98	14	11	10	5	9

Table 5
Area of land in the West Peffer that can be optimally irrigated for each abstraction scenario

Period	Area of optimal irrigation (ha)				
	98%ile Ban scenario	95%ile Ban scenario	90%ile Ban scenario	10% Monthly volume	20% Monthly volume
1989–98 average	113	103	95	133	266
1989	13	3	0	89	178

stream flows are high enough to buffer the impact of irrigation abstractions, despite quite intensive potato cropping in the lower catchment. The severity of the impact in the West Peffer catchment is notable particularly because the magnitude of the individual abstractions is quite small. Yet, the combined effect of the individual abstractions is large, because the stream is small, has a low specific runoff and a high proportion of the land is used for potatoes. Factors of this type need to be taken into consideration in establishing legislation for abstraction control, where it is likely that a lower limit may be set on the magnitude of abstractions that require licensing (Scottish Executive, 2001).

Clearly, the major problem associated with abstractions for irrigation is that the water is required at times when stream flows are at their lowest. In this respect, direct surface abstraction will have the greatest impact on flows. It was assumed in this analysis that all abstractions were from surface water, but in practice a survey of potato growers in the West Peffer showed that most had either a storage reservoir or borehole to supplement the supply from the river. However, no reservoirs or boreholes were reported in the Tyne. The use of storage reservoirs in particular could be seen as a good solution to the irrigation problem, enabling abstractions to be made during the winter and spring when stream flows are higher. From the growers perspective this would also seem to be advantageous, as it would ensure that water was actually available at the times when it is needed, removing some of the uncertainty caused by unknown future weather.

The cost implications of installing storage reservoirs are discussed by Crabtree et al. (2002) in relation to the benefits of increasing the availability of irrigation water. The hydrological benefits in terms of improvements to the levels of summer flows, would be directly related to

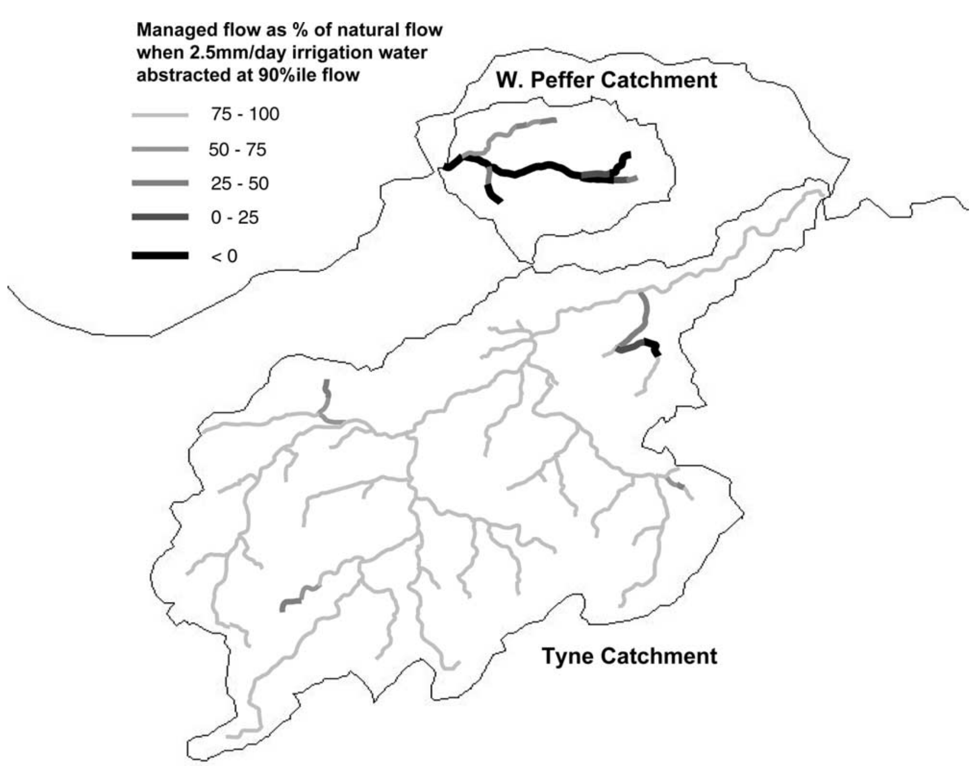

Fig. 7. Effect of a 2.5 mm/day irrigation abstraction on flows across the Tyne and West Peffer, when natural flow is at its 90%ile level at East Linton and Luffness.

the additional storage volume available and hence controlled by economics. Additional use of storage reservoirs is likely to come about indirectly through implementation of abstraction controls rather than through direct legislation. The move towards increased use of seasonal charging as proposed for England and Wales (DEFRA, 2001) would clearly help to encourage such practice.

Decreases in the demand for irrigation water could also be achieved through more efficient water use, for example by employing trickle irrigation methods in place of spray irrigation, or by the use of short-term weather forecasts in irrigation scheduling, as illustrated by Gowing and Ejieji (2000). The preferential use of groundwater over surface water abstraction may also be less disruptive to stream flows as it smooths the effect of the abstraction over time. However, the EU Water Framework Directive will also require controls on the use of both impounding reservoirs and abstractions from groundwater.

The study of the different flow-based control mechanisms raised the interesting issue of whether it is more damaging to the stream system to have quite low flows that will be held at that level for a long duration, or to have more severe low flows for a shorter duration. The theoretical control mechanism based on licensed monthly abstraction volumes generated a hydrological regime that is maintained very close to the natural system, except at times of greatest drought, when it becomes ineffective. By contrast, the mechanism based on a flow percentile threshold resulted in more frequent small reductions in flow. The answer as to which mechanism is more appropriate will depend on the nature of the ecological and water quality problems that are associated with the low flows. However, understanding of the link between hydrological processes and ecological quality is still limited (Gilvear et al., 2002). Smakhtin (2001) reviews many of the techniques that are now being used for environmental flow assessment. Clearly, there is a need for assessments of this type to be undertaken in conjunction with policy selection for abstraction controls and it is clear that in different circumstances different solutions may be more appropriate.

The spatial analysis of the irrigation impacts highlighted the problem of using a point measurement of flow as the criterion for triggering an irrigation ban. Due to the heterogeneity of abstraction activities and the different sizes of streams from which they occur, the level at which the ban is triggered may be inadequate to prevent smaller tributaries from being dried out. This effect was observed in the analysis of the Tyne catchment as well as the West Peffer. In practice, to achieve maintenance of flows at, say, the 95%ile across all of the catchment, it is probably necessary to set a level of the 90%ile flow as the criterion at a downstream point. The scale of implementation of any abstraction controls needs to be carefully considered as does the suggestion that only abstractions of greater than a critical threshold would be subject to control (Scottish Executive, 2001). Temporal aspects are also important when it comes to practical implementation of controls. The regulatory authority will need to give growers warning about probable imposition of an abstraction ban, when flows drop close to the limit. The response to this will inevitably be an immediate increase in abstractions, thus exacerbating the situation.

8. Conclusions

Despite the fact that as a nation Scotland has plentiful water resources, there are areas of the country where streams are presently under threat from over-abstraction. Under the terms of the EU Water Framework Directive it will be necessary to introduce new legislation in Scotland to control abstractions from surface and groundwaters. This study has highlighted the importance of considering spatial and temporal variability in flows and abstractions, if the controls that are introduced by the new legislation are to be effective in achieving environmental improvement. In particular, different mechanisms for abstraction control will modify stream flows in different ways. The relative importance of duration and severity of low flows, in terms of ecological impact of the agricultural system, must be determined for the most appropriate mechanisms for abstraction control to be selected. Irrigation impacts should also be assessed spatially to ensure that controls, based on flow measurement at a specific point, will be effective throughout the catchment.

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