THE IMPACT OF RIVER FLOW RESTRICTIONS ON INSTRUMENTS TO CONTROL NONPOINT NITRATE POLLUTION

Ashar Aftab[γ], Nick Hanley, Athanasios Kampas and David Ogelthorpe

[γ] Corresponding Author: Department of Economics, University of Glasgow, Adam Smith Building, Glasgow G12 8RT, Scotland. Email: a.aftab@socsci.gla.ac.uk, Tel ++44 (0)141 3303397, Fax ++44 (0)141 330 4940.

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Abstract

An economic analysis of policies to control nonpoint source nitrate pollution in the presence of minimum river flow restrictions was undertaken. A non-linear bio-physical economic optimisation model of an intensively cultivated Scottish agricultural catchment was constructed. The presence of minimum river flow controls in the catchment was found to reduce nitrogen pollution. However, by themselves, river flow controls were found not to be a cost effective means to reduce diffuse pollution. River flow controls did not, for the most part, alter relative instrument ranking.

Institutional Affiliation

Ashar Aftab: Research Assistant, Department of Economics, University of Glasgow.
Nick Hanley: Professor of Environmental Economics, Department of Economics, University of Glasgow.
Athanasios Kampas: Lecturer Department of Agricultural Economics & Development, University of Athens.
David Ogelthorpe: Head of Natural Resource Economics Department, Scottish Agricultural College, Edinburgh.

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Introduction

The European Union's Water Framework directive (WFD) requires the integrated management of water resources at the catchment level throughout the EU from 2002 onwards. This implies that the environmental impacts of agriculture be integrated into catchment planning, both in terms of water quality and water quantity issues. The WFD sets a target of Good Ecological Status throughout Europe and implies the joint setting of river flow restrictions (water quantity) and ambient pollution standards (water quality). The Directive also requires responsible Agencies to prepare catchment management plans which achieve targets cost-effectively, the first time such a requirement has been imposed at the EU level, and calls on member states to investigate and promote the wider use of economic instruments.

In this paper, we develop a model which allows the estimation of the cost of improving water quality (measured by ambient nitrate levels) through a combination of on-farm management measures, economic incentives for fertiliser use, and through the restriction of irrigation water abstraction by farmers. Restriction of irrigation flows is carried out in a manner consistent with attaining minimum ecologically-acceptable flow levels in our case study river. Empirically, we a) investigate the impact of river flow restrictions on agricultural non-point nitrogen pollution control b) compare the relative efficiency of policies to control diffuse nitrogen pollution based on mean and wet weather conditions, and c) consider "mixed instrument" policies which may be more appealing to regulators.

The West Peffer catchment (Scotland) was used as a case study due to its combined problems of low flows due partly to irrigation abstractions, and high ambient nitrate levels, due mainly to farming activities. Diffuse pollution problems from nitrates, which can result in eutrophication and contamination of potable water supplies has been recognised and partially addressed in Scotland (Darcy, et al.; SEPA). Similarly there is evidence to support the need for further surface water extraction controls in intensively irrigated Scottish catchments due to the ecological consequences of low flows (Crabtree, et al.; Fox; Garrod and Willis).

Previous Work

There is an abundance of literature on the economics of nonpoint pollution control (Dosi and Tomasi; Shortle and Horan; Xepapadeas), and some investigation of the use of irrigation controls to control diffuse pollution (Booker and Young; Dinar and Letey; Helfand; Murillo, Karaj and Martinez; Stevens; Weinberg, Kling and Wilen). However, there is no study to our knowledge which empirically investigates the effect of imposing minimum river flow restrictions on the control of catchment nitrogen pollution.

Comparable work includes that of (Larson, Helfand and House) who found water to be the best input to regulate nonpoint source nitrogen pollution from lettuce production in California. Whereas Larson et al. varied irrigation water applications directly, this study examines the indirect effect of regulating river flows (hence irrigation water availability) on diffuse catchment pollution in a wetter Scottish climate. A study of cotton production in California (Stevens) determined the equivalence of taxing nitrogen and irrigation water under certain assumptions (nitrate emissions represented nitrogen leaching) but found their fiscal implications to differ. However, again no link was made with protecting minimum river flow requirements. Finally, a recent empirical study in Spain (Murillo, Karaj and Martinez) concludes that in terms of farmer costs, pricing irrigation water is the most expensive means to control nitrogen pollution . Again, however, no explicit link is made with maintaining minimum river flows.

We add to this literature by integrating minimum river flow restrictions directly into an economic optimisation model of land use, to enable targets for reducing nitrate concentrations in the river and minimum river flow rates to be achieved jointly. This is viewed as being important in the light of the WFD's requirement for integrated catchment management. We also consider the sensitivity of our results to variations in climate, which is of relevance given predictions for climate change due to enhanced global warming.

Modelling Methodology

Bio-physical simulation modelling can, to an extent, overcome the information asymmetry between the principal/regulator and agent/farmer and the regulatory inability to observe agricultural pollutant run-off (Weersink, et al.). Much policy analysis relies on the use of "second best" standards for environmental resources, set through the political process. Examples of such standards include the WFD general target of good ecological status, and more specific upper limits for nitrates in water of 50 mg N/l (or 11.3 mg nitrates/l) contained within the EU Nitrates Directive. A challenge facing regulators is to implement the WFD cost-effectively to catchment farming, given the need to meet specific minimum river flow requirements.

Our model simulates production activities in the 4,347 farmed hectares of the West Peffer catchment in East Lothian, Scotland as one economic decision maker whose objective is to maximise profits. It includes five major arable crops (winter wheat, spring barely, winter oilseed rape, main crop potatoes) besides livestock farming (dairy, suckler, intensive beef, sheep) and the associated grazing grass/silage production. Over laying G.I.S. mapping of the catchment boundary onto soil survey digitised maps yielded the three prevalent soil textures in the catchment (sandy, loamy, and silty) and their distribution. Spatial heterogeneity is therefore accounted for by the inclusion of different soil textures and multiple outputs (crops and livestock) which result in different production and nitrate leaching (Wu). A schematic diagram of the model is included as Appendix 2.

Crops were combined in two 4-5 year rotations, i.e. a) spring barley, winter wheat, spring barley followed by potatoes on predominantly sandy soils and, b) winter wheat, winter wheat, spring barley, followed by winter oilseed rape on loamy and silty soils. After consultation with the Agriculture Development and Advisory Service (ADAS), since estimating nitrate loss when leys are ploughed out is difficult and inaccurate (Lord) we assumed that all grass grown in the model is on permanent pastures (in fact, most grass in the catchment falls into this category). Catchment agronomic practices and parameters, crop rotations and the existing baseline scenario were deduced from the literature and catchment level farm survey[i] data. Transfer payment schemes and subsidy incentives for both livestock and arable cultivation were also included in the model (SOAEFD 1997a, b).

The farmer's decision on how much nitrogen to apply is based on crop production functions for each crop on the three soil types in the catchment, and the market price of the crops and production costs. The model was calibrated to the 1997/98 price level. Nitrogen crop growth functions for each crop/soil combination were estimated using ADAS data (Chambers and Johnson), while grazing and silage grass production was determined from Scottish Agricultural College data (SAC 1996; SAC 1997). Separate nitrogen potato production functions under different flow regimes and weather conditions were approximated from (Crabtree, et al.) and ADAS data.

It was assumed that farmers follow the manure and slurry management guidelines outlined by Scottish Agricultural College (SAC 1992) and apply these products to grasslands only. Estimates of the nitrogen content of different farm animal wastes were approximated (SAC 1992). Depending on the most profitable land allocation to each crop/soil type and ensuing nitrogen application (including farm manure from livestock) the model uses leaching functions to estimate the weekly average leaching throughout the year based on the actual rainfall pattern of three ‘stylised’ years representing a dry, mean and wet year during the 1989-98 period. These leaching functions were obtained by regressing the results of numerous runs of the NITCAT model (Lord), for each crop/soil combination within a reasonable range of nitrogen fertiliser applications. The IRRIGUIDE model (Bailey and Spackman) was used to give crop-dependent weekly values of evapo-transpiration over winter; while elution was modelled using the SLIMMER algorithm (Anthony, Quinn and Lord). Grassland leaching was estimated using NCYCLE a model developed by the Institute of Grassland and Environment Research (INGER). Our model then assumes that the nitrogen leachate is transported via drains to the river instantaneously where it mixes with the river water. One model output is daily approximations of diffuse nitrogen pollution levels over a year.

Irrigation Controls and Crop Growth

Irrigation contributes both to potato yield and quality, and up to 65% of potato crop land is currently irrigated in East Lothian. The West Peffer catchment is extensively used for surface water extraction and is presently subject to abstraction controls (Fox). The need for controls arises from the damaging effects of uncontrolled surface water extraction on river ecology, wildlife populations, recreational use and amenity values during periods of low flow (Willis and Garrod). In practice, the rule operated by the regulator is to stop abstractions through licence suspension when river flow falls to the 95%ile (or minimum acceptable flow) at specific gauging points (Crabtree, et al.)[ii].

Hydrological modelling was employed to estimate the amount of water available for potato irrigation before river flows fell to the 90th, 95th and 98th percentile flow[iii], relative to a situation with no river flow restriction. The timing of this available water was inputted into a potato growth model developed by Cambridge University (Crabtree, et al.) to give potato crop quantity and quality[iv]. Besides the option of not irrigating potatoes at all, the modelling process allowed for two irrigation regimes termed *optimum* and *restricted*. Of the two, optimum irrigation resulted in the better quality potato crop with significantly less incidence of disease. Thus the potato and irrigation modelling yielded the total acreage of potato crops allowed under optimal and restricted irrigation for each river flow restriction under three different weather scenarios. These upper bounds on acreage acted as constraints in the economic model reflecting the scarcity of irrigation water due to the desire to maintain minimum acceptable river flows.

Economic Modelling of Policy Options

A non-linear model was written using the General Algebraic Modelling System (GAMS) (Brooke, et al.) and solved using the CONOPT II solver (Stolbjerg-Drud)[v] . Appendix 1 gives a brief mathematical formulation of the model. Overall the model's baseline allocation was very similar to the reported land use data, with the percentage deviation between reported data and baseline being -6.37% for arable, -4.63% for grassland and -1.64% for setaside land[vi]. The policy options we simulated included a) nitrogen input and emission taxation, b) nitrogen input quotas c) managerial restrictions on stocking density and the area of setaside, and d) various combinations or "mixed instrument" packages combining economic incentives with managerial restrictions.

Impact of river flow requirements on policy outcomes under current climatic conditions

The impact of a catchment fertiliser tax was simulated by running the model iteratively with increasing nitrogen costs under 4 different minimum river flow targets, based on mean weather conditions over 1989-98. Figure 1 shows the percentage increase in the price of nitrogen required to reduce the number of weeks in the year which exceed the standard under 4 different river flow standards, where the 90th percentile is the strictest target. It is evident that with irrigation restrictions in place the required increase in nitrogen taxation is less than without any river flow controls. The more stringent the surface water extraction control, the lower the optimal N tax. In other words there is complimentary interaction between N taxes and river flow maintenance. Secondly, as the regulator tightens the requirement to meet the water *quality* standard, the difference in taxation required with and without the river flow restrictions increases. Regarding irrigated cropping, by restricting irrigation through river flow controls, the regulatory authority lowers the profit per hectare, prompting a shift in land allocation from optimal to restricted irrigation, which then reduces the incentive to apply as much nitrogen to the potato acreage.

Four other measures to reduce diffuse nitrogen pollution were considered. These were stocking density reduction (figure 2), a setaside[vii] restriction (figure 3), a catchment wide input quota (figure 4) and emission taxation (figure 5). The results are consistent with those for input taxation i.e. the maintenance of river flow controls reduces the need to impose as strict a policy to control diffuse nitrogen pollution when compared to the absence of any irrigation limits. Under all regulatory regimes the distinction between the presence and absence of a river flow restriction is clear with the exception of stocking density reduction, where the difference is marginal.

However, the ranking amongst the four river flow restrictions is not consistent. Irrespective of the pollution control policy, one would expect the tightest river flow restriction (90th percentile) to result in the most diffuse pollution control followed by 95th and then 98th percentile river flow restriction. The results are not entirely consistent in this regard due to certain rotational and livestock restrictions in the model. It seems that within the feasible region there are land, nitrogen and crop/soil allocations under the 95th and 98th percentile river flow restrictions which result in marginally less diffuse pollution than under the 90th percentile restriction. This is not an error; rather it highlights the non-linearities in the bio-physical economic model.

Varying climatic conditions

Predictions from UK CIP (2002) indicate that Scotland's climate will become wetter due to enhanced global warming over the period to 2050. The same policy simulations were therefore carried out under the 'wet' year weather scenario. Here, the difference in diffuse nitrogen pollution between any of the three river flow restriction and the absence of any flow restriction was insignificant (figure 6). It is plausible that irrespective of the river flow regime and irrigation type (optimal, restricted or un-irrigated), leaching rates are fairly similar due to the high volume of sub-soil drainage. Thus when rainfall is plentiful irrigation controls will not affect nitrogen input levels or the acreage of land irrigated. Therefore in terms of diffuse nitrogen pollution control in a wetter climate, the presence of river flow restrictions has a much lower impact on the shadow price of pollution control. However, note that the required nitrogen tax rate is higher under wet weather conditions than under mean conditions (figure 6), since more rainfall translates into higher leaching rates.

Targeting of controls

The question remains as to whether under existing weather conditions it is more cost effective to control diffuse pollution in the catchment with irrigation controls or through conventional instruments targeting the polluting input i.e. nitrogen. Suppose the regulatory objective was to ensure that the ambient nitrate standard of 50 mg/l was not violated more than 8 weeks of the year. In the absence of a river flow control this requires an input tax of 266% of the product price, whereas under a 95th percentile river flow control the required input tax was 233% (for a market price of £0.42 pre kg). Under taxation, the resource cost (due to loss of profit) under no river flow control amounts to £24,140 whereas the resource cost with the lower tax rate required with river flow controls is £901,954. This is because flow controls mean the farmer can no longer grow as much highly-profitable potatoes. A policy which uses taxes to control nitrate pollution alone (i.e. disregarding river flow requirements) is much cheaper than one using a combination of lower taxes and river flow controls. But note that this addresses the problem purely from the viewpoint of nitrate pollution control, ignoring low flow problems.

As a means to control diffuse pollution, river flow controls alone are not an efficient mechanism. The reduction in pollution in the presence of river flow controls was modest when compared to the reduced crop profitability. Whether this can be said of other irrigated crops depends on the crop's input demand function for irrigation water, climate, and nitrogen leaching functions. It must also be noted that this analysis does not consider the transaction/implementation costs of imposing and monitoring percentile bans on river flow which may be higher than those of enforcing input taxation. Finally, due to the inclusion of existing agricultural support payments, losses in farm incomes as calculated by our model overstate the net social costs of alternative policies.

Conclusions

This study researched the efficient joint management of two agricultural externalities, i.e. diffuse nitrogen pollution in rivers and low river flows due to surface water extraction for irrigation. Overall we found that the presence of river flow restrictions contributed towards pollution mitigation and thus should be considered in the design of nitrogen control policies. However, as a means to control diffuse nitrogen pollution imposing river flow controls by themselves were not in themselves cost effective.

Furthermore, minimum river flow restrictions did not influence optimal instrument level under wetter weather conditions.

These results are hopefully of policy relevance in the context of legal requirements for integrated water catchment management under the EU water framework directive. However, more work needs to be done here: for example, to investigate whether these results are consistent across catchments of different size, differing dependences on irrigation and different land use patterns. Groundwater resources are also impacted by nitrate pollution and abstraction, yet were not included in our framework. Finally, a direct incorporation of uncertainty over future weather patterns could be attempted, rather than relying on the sensitivity analysis we report here.

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Appendix 1: A Concise Mathematical Representation of the Model

Regulatory objective

$$\textit{Minimise} \quad \Pi^{\varpi\kappa} - \sum_c \sum_s \left(p_c Q_{cs} - w^n n_{cs} l_{cs}\right) + \sum_i \sum_j h_{ij}^{\varpi\kappa} \rho_j + \sum_b a_b p_b$$

$$- w^n \left(\sum_i \eta_i^{\varpi\kappa} \lambda_i^{\varpi\kappa} - \sum_t \sum_s \mu_{ts} g l_{ts} \right) - C \qquad \text{(EQ 1)}$$

Subject to:

Secondary Expenses:

$$C = \sum_c \sum_j L_c \upsilon_{c\tau} - \sum_b \sum_m a_b f_{bm} - \sum_t \sum_u G_t z_{tu} - \sum_i \sum_x \lambda_i^{\varpi\kappa} q_{ix}^{\varpi\kappa} \qquad \text{(EQ 2)}$$

Crop production: $y_{cs} = \gamma_{cs}^0 + \gamma_{cs}^1 \left(\gamma_{cs}^2\right)^{n_{cs}} + \gamma_{cs}^3 n_{cs}$ (EQ 3)

Total output: $Q_{cs} = y_{cs} l_{cs}$ (EQ 4)

Grass production: $g_{ts} = \beta_{ts}^0 + \beta_{ts}^1 + \left(\beta_{ts}^2\right)^{\mu_{ts}} + \left(\beta_{ts}^3\right)\mu_{ts}$ (EQ 5)

Grass requirement constraint: $\sum_b a_b G_{tb} = \sum_s (g_{ts} g l_{ts})$ (EQ 6)

Livestock N (kg/ha): $\sigma = \dfrac{\sum_b a_b \Lambda_b}{\sum_t \sum_s g l_{ts}}$ (EQ 7)

Total grassland N (kg/ha)*:* $\mu_{ts} = \sigma + o_{ts}$ (EQ 8)

Total grassland Nitrogen use: $\sum_t \sum_s \mu_{ts} g l_{ts}$ (EQ 9)

Livestock stocking density rate: $d = \dfrac{\sum_b a_b}{\sum_t \sum_s g l_{ts}}$ (EQ 10)

Stocking density constraint: $d \le \hat{d}$ (EQ 11)

Potato Production: $\varphi_i^{\varpi\kappa} = \varepsilon_{0i}^{\varpi\kappa} + \varepsilon_{1i}^{\varpi\kappa} + \left(\varepsilon_{2i}^{\varpi\kappa}\right)^{\eta_i^{\varpi\kappa}} + \varepsilon_{3i}^{\varpi\kappa} \eta_i^{\varpi\kappa}$ (EQ 12)

Potato Quality/ Irrigation: $h_{ij}^{\varpi\kappa} = H(\varphi_i^{\varpi\kappa}, \lambda_i^{\varpi\kappa})$ (EQ 13)

Potato irrigation constraints: $\lambda_i \le \hat{\lambda}_i^{\varpi\kappa}$ (EQ 14)

Bounds on land allocation : $G_t = \sum_s gl_{ts} \leq \hat{G}_t$, $L_c = \sum_s l_{cs} \leq \hat{L}_c$ (EQ 15)

Land use constraints: $\sum_t gl_{ts} + \sum_c l_{cs} + u \sum_i \lambda_i^{\varpi\kappa} \leq T_s$ (EQ 16)

Crop Rotational Constraints: $\sum_t l_{ts} r_{ts} + \sum_c l_{cs} r_{cs} + \psi \sum_i \lambda_i^{\varpi\kappa} r_i \leq 0$ (EQ 17)

Crop Nitrate load (kg/ha): $e_{cs}^{\varpi} = \delta_{0cs}^{\varpi} + \delta_{1cs}^{\varpi} (n_{cs})^{\delta_{2cs}^{\varpi}}$ (EQ 18)

Livestock Nitrate load (kg/ha): $v_{ts}^{\varpi} = \theta_{0ts}^{\varpi} + \theta_{1ts}^{\varpi} (\mu_{ts})^{\theta_{2ts}^{\varpi}}$ (EQ 19)

Potato Nitrate load (kg/ha): $x_i^{\varpi\kappa} = \xi_{0i}^{\varpi\kappa} + \xi_{1i}^{\varpi\kappa} (\eta_i)^{\xi_{2i}^{\varpi\kappa}}$ (EQ 20)

Overall River concentration (mg/litre):

$$ {}^{w}\wp^{\varpi\kappa} = \frac{\sum_c \sum_s {}^{w}e_{cs} \, {}^{w}\Gamma_{cs}^{\varpi} l_{cs} + \sum_t \sum_s {}^{w}v_{ts} \, {}^{w}\Omega_{ts}^{\varpi} gl_{ts} + \sum_i {}^{w}x_i^{\varpi\kappa} \, {}^{w}\Delta_i^{\varpi\kappa} \lambda_i^{\varpi\kappa}}{{}^{w}R + \sum_c \sum_s {}^{w}\aleph_{cs} l_{cs} + \sum_t \sum_s {}^{w}\lambda\!\!\!^{-}_{ts} gl_{ts} + \sum_i {}^{w}\hbar_i^{\varpi\kappa} \lambda_i^{\varpi\kappa}} \quad \text{(EQ 21)} $$

Environmental Quality Constraint: ${}^{w}\wp^{\varpi\kappa} \leq \Theta$ (EQ 22)

The regulator's objective is to minimise the difference between the unrestricted catchment profit $\Pi^{\varpi\kappa}$ and the catchment profit under different pollution control policies. Where ϖ is the prevailing weather condition that year (dry, mean, or wet) and κ is the catchment river flow restriction (no flow restriction or 98,95 and 90%ile flow restriction) enforced by the regulator. $\Pi^{\varpi\kappa}$ for each $\varpi\kappa$ combination is the outcome of an unrestricted run of the model without any regulation. Thus when considering a particular regulatory policy it remains constant and independent of the optimisation problem. The catchment profit in the objective function is defined as the return to the producer's management and allocation of resources over the cost of total catchment nitrogen consumption $\{\sum_c \sum_s w^n n_{cs} l_{cs}$ (arable crops), $w^n \sum_i \eta_i \lambda_i$ (potatoes), $w^n \sum_t \sum_s \mu_{ts} gl_{ts}$ (silage and grazing grass)} and all other secondary costs of farming C. Where p_c is the market price of arable crop c, ρ_j the market price of potato quality j, and p_b is the market return from one grazing livestock unit (GLU) of livestock type b. w^n refers to the cost of nitrogen fertiliser,

n_{cs} and l_{cs} is the nitrogen applied and land allocated to arable crop c (excluding potatoes and grassland) c on soil type s. gl_{ts} and μ_{ts} refer respectively to land and nitrogen allocated to grassland type t (grazing and cutting), while $\lambda_i^{\varpi\kappa}$ and $\eta_i^{\varpi\kappa}$ refer to land and nitrogen applied to potato crop under irrigation regime i (optimal, restricted or un-irrigated).

Secondary expenses C (EQ 2) refer to all other catchment production costs excluding that of nitrogen fertiliser application: $f_{bm} = (k_{b1},......k_{bm})$ is a vector of m costs per unit of livestock type (b) associated with feeding and other animal husbandry expenses, $z_{tu} = (\chi_{t1},....\chi_{tu})$ is a vector of u per hectare costs of grassland management, $\upsilon_{c\tau} = (v_{c1},......v_{c\tau})$ is a vector of τ per hectare costs associated with the production of each arable crop type and $q_{ix}^{\varpi} = (\omega_{i1}^{\varpi},......\omega_{ix}^{\varpi})$ is a vector of x costs per hectare associated with potato farming including irrigation costs under each weather condition.

The crop production function equation set (EQ 3) yields the output (kg/ha) for each crop soil combination (the source of heterogeneity in the catchment) and is based on estimated coefficients $\gamma_{cs}^0, \gamma_{cs}^1, \gamma_{cs}^2, \gamma_{cs}^3$. The grassland yield for both silage and grazing grass on all soil types is given by the EQ 5, where $\beta_{ts}^0, \beta_{ts}^1, \beta_{ts}^2, \beta_{ts}^3$ are estimated coefficients. EQ 6 ensures that the actual grazing grass and silage production meets the requirements of livestock numbers a_b. If EQ 11 is satisfied then livestock qualifies for certain grants and subsides which are accounted for in p_b. EQ 15 is a constraint on the allocation of land, and ensures that the model allocation is similar to the actual situation on the ground. Most of these constraints were not binding. EQ 16 ensures the land allocation to any soil type does not exceed the actual acreage of each soil type. EQ 17 is a representation of the two representative rotational constraints in the catchment. As the model only allows potato allocation on sandy soils, ψ = 0 for silty and loamy soils and 1 for sandy.

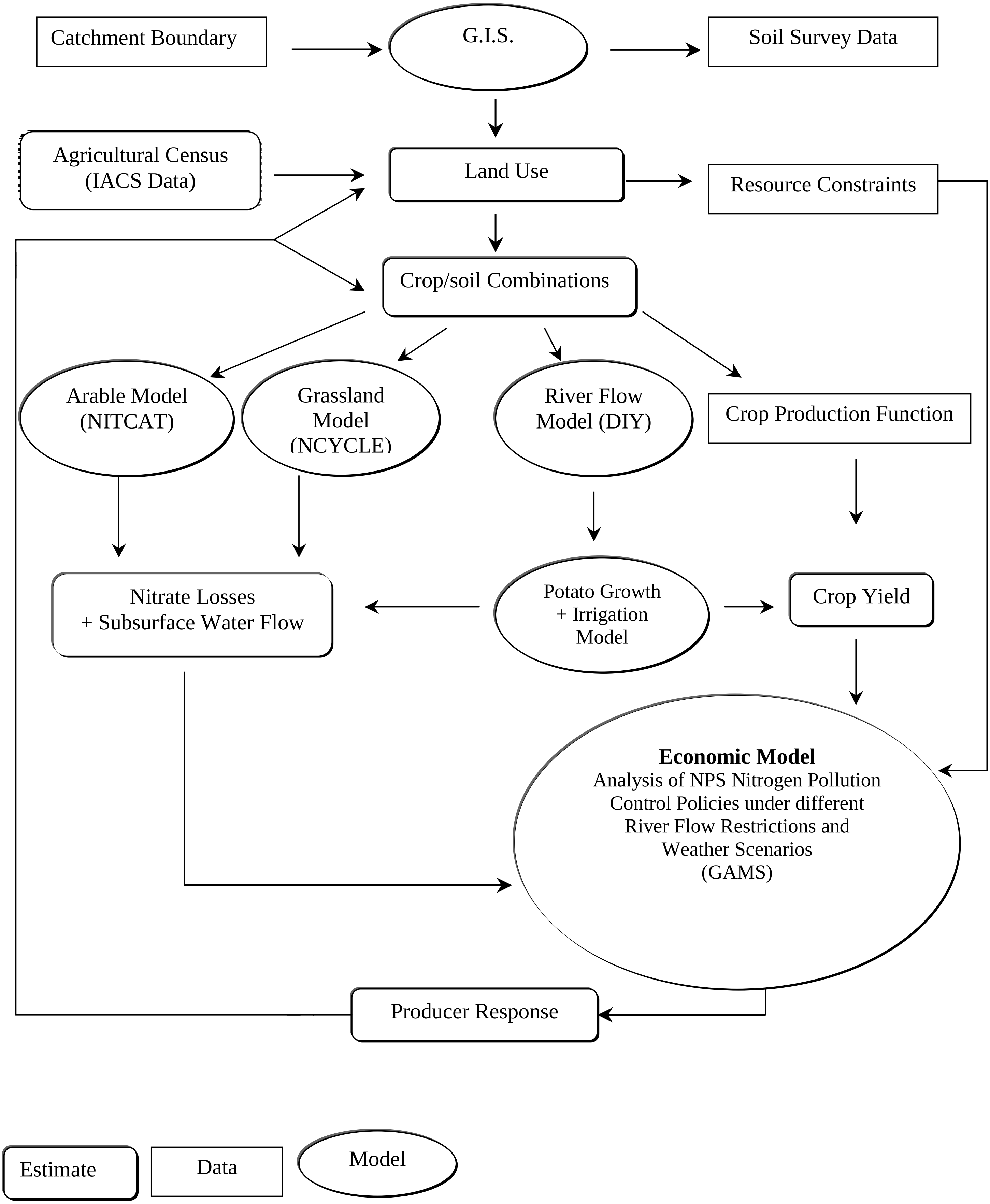
EQ 12 is a set of equations for every weather (ϖ) and river flow restriction (κ) giving the potato yield per hectare under every irrigation regime i (optimal, restricted, and un-irrigated) for nitrogen application η_i. Where $\varepsilon_{0i}^{\varpi\kappa}, \varepsilon_{1i}^{\varpi\kappa}, \varepsilon_{2i}^{\varpi\kappa}, \varepsilon_{3i}^{\varpi\kappa}$ are estimated coefficients for the potato production function. EQ 13, converts potato crop yield into quality categories j (scabbed and scab free), given the available irrigation water under each weather condition. EQ 14, limits the allocation of land to every irrigation category based on the available irrigation water.

EQ 18 estimates the total nitrogen load (per ha) E_{cs} for a total nitrogen application of n_{cs} (per ha) based on the weather estimated coefficients $\delta_{0cs}^{\varpi}, \delta_{1cs}^{\varpi}, \delta_{2cs}^{\varpi}$. Whereas EQ 19 and EQ 20 provide the annual load per ha from Livestock/grassland (V_{ts}) and potato (X_i) based on the weather estimated coefficients $\theta_{0ts}^{\varpi}, \theta_{1ts}^{\varpi}, \theta_{2ts}^{\varpi}$ and $\xi_{0i}^{\varpi\kappa}, \xi_{1i}^{\varpi\kappa}, \xi_{2i}^{\varpi\kappa}$ respectively. It is assumed that the nitrogen from animal waste allowed by MAFF regulation is applied to grassland. Λ_b is a vector of the estimated annual N content of one GLU of each livestock type. Therefore EQ 7 provides the per ha availability of Nitrogen from animal waste to grassland, which along with the artificial N fertiliser o_{ts} provides the total Nitrogen application to grassland μ_{ts} per ha (EQ 8). The annual loads from EQ 18, 19, and 20 were converted into the average daily load for every week of a weather condition based on computations of NITCAT which gave three vectors. ${}^{w}\Gamma_{cs} = \left({}^{1}\alpha_{cs}^{\varpi}, \ldots\ldots, {}^{w}\alpha_{cs}^{\varpi}\right)$ is a proportionality vector of the average daily arable crop load for each week (w), ${}^{w}\Omega_{ts}^{\varpi} = \left({}^{1}\infty_{ts}^{\varpi}, \ldots\ldots, {}^{w}\infty_{ts}^{\varpi}\right)$ a proportionality vector of the average daily grassland/livestock crop load for each week , and ${}^{w}\Delta_{i}^{\varpi\kappa} = \left({}^{1}\vartheta_{i}^{\varpi\kappa}, \ldots\ldots, {}^{w}\vartheta_{i}^{\varpi\kappa}\right)$ a proportionality vector of the average daily potato crop load from each irrigation regime for each week.

Likewise the estimated daily average drainage (rainwater / rain + irrigation water) from each catchment activity (${}^{w}\aleph_{cs}^{\varpi}$ arable crops, ${}^{w}\lambda_{ts}^{\varpi}$ grassland, ${}^{w}\hbar_{i}^{\varpi\kappa}$ potatoes) for every week under all three weather conditions was calculated from the nitrate leaching model runs. EQ 21 gives the overall river concentration from farming activities at the mouth of the river assuming instantaneous mixing. ^{w}R is a rough approximation of daily river base flow for ever week under each weather and river flow restriction. Unit conversions have been ignored in EQ 21. EQ 22 is the environmental constraint relating to river nitrate pollution, where Θ is the standard.

As the model was run for every weather condition and river flow control, the potato/irrigation variables, yield/leaching equations, and constraints varied accordingly. Similarly when a regulatory policy was considered corresponding adjustments to the constraints and constants were made.

Appendix 2: Catchment Model



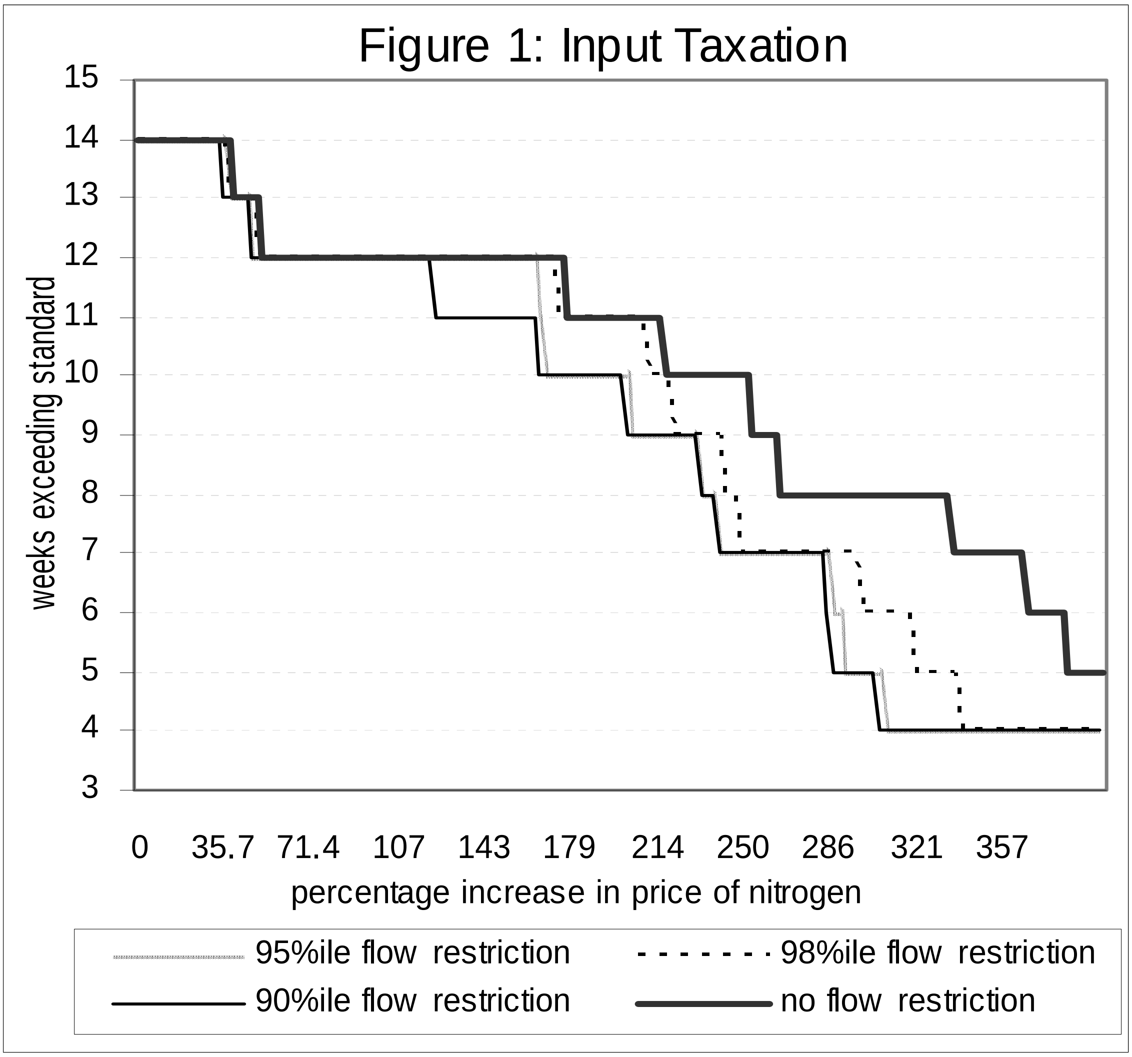


Figure 1: Input Taxation
15
14
13
12
11
10
9
8
7
6
5
4
3
weeks exceeding standard
0
35.7
71.4
107
143
179
214
250
286
321
357
percentage increase in price of nitrogen
95%ile flow restriction
98%ile flow restriction
90%ile flow restriction
no flow restriction

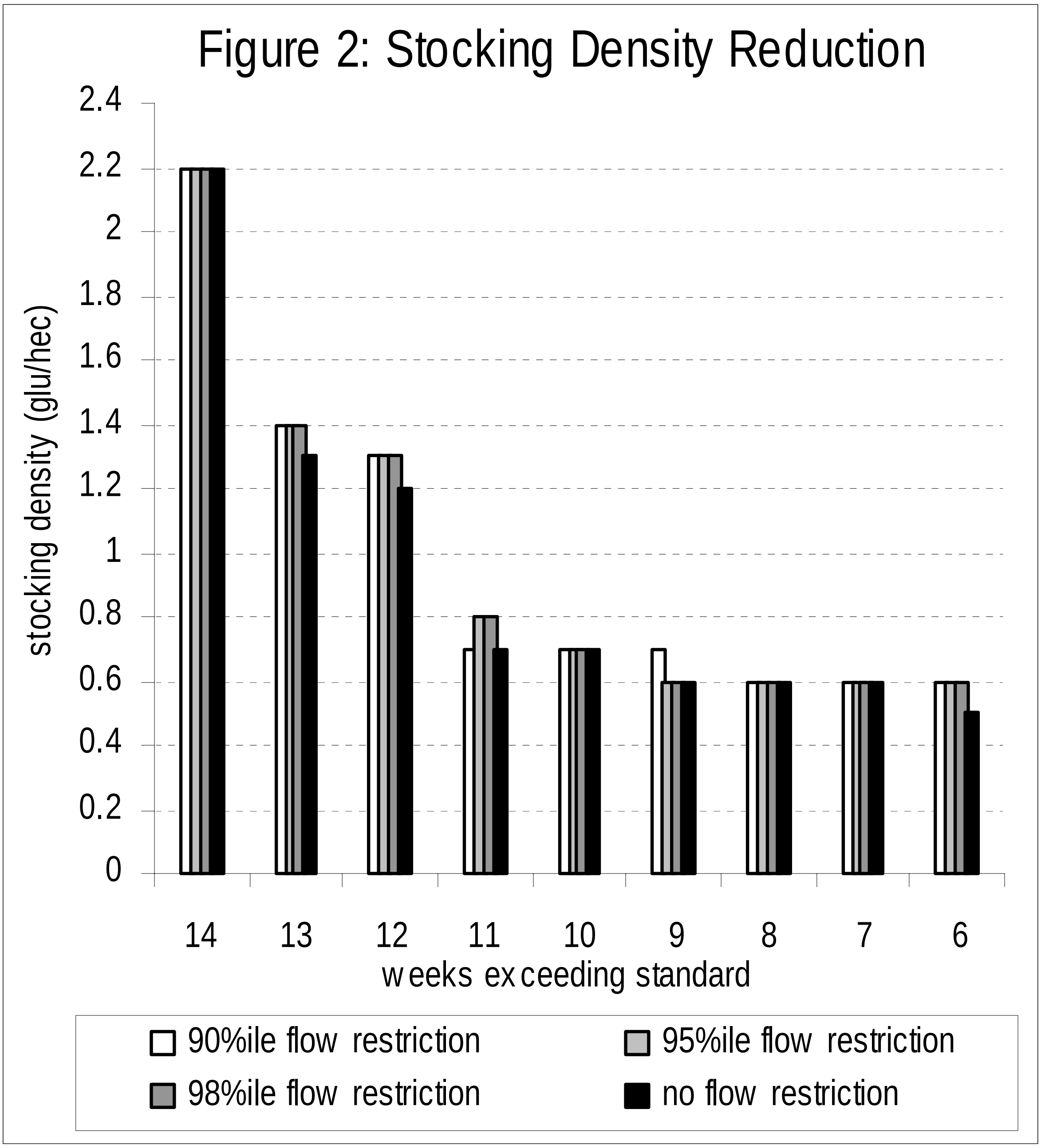


Figure 2: Stocking Density Reduction
stocking density (glu/hec)
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
14
13
12
11
10
9
8
7
6
weeks exceeding standard
90%ile flow restriction
95%ile flow restriction
98%ile flow restriction
no flow restriction

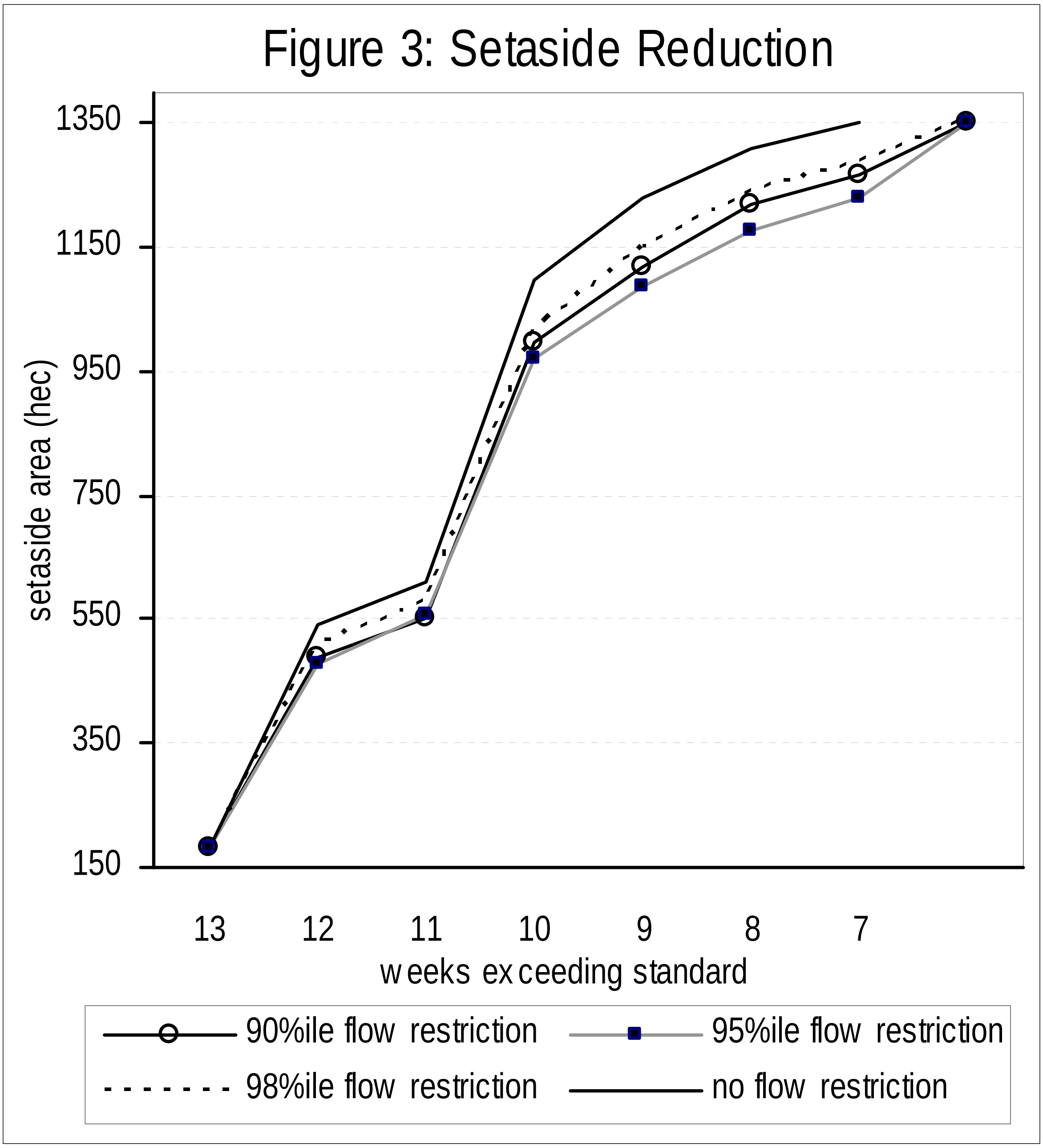


Figure 3: Setaside Reduction
setaside area (hec)
1350
1150
950
750
550
350
150
13
12
11
10
9
8
7
weeks exceeding standard
90%ile flow restriction
95%ile flow restriction
98%ile flow restriction
no flow restriction

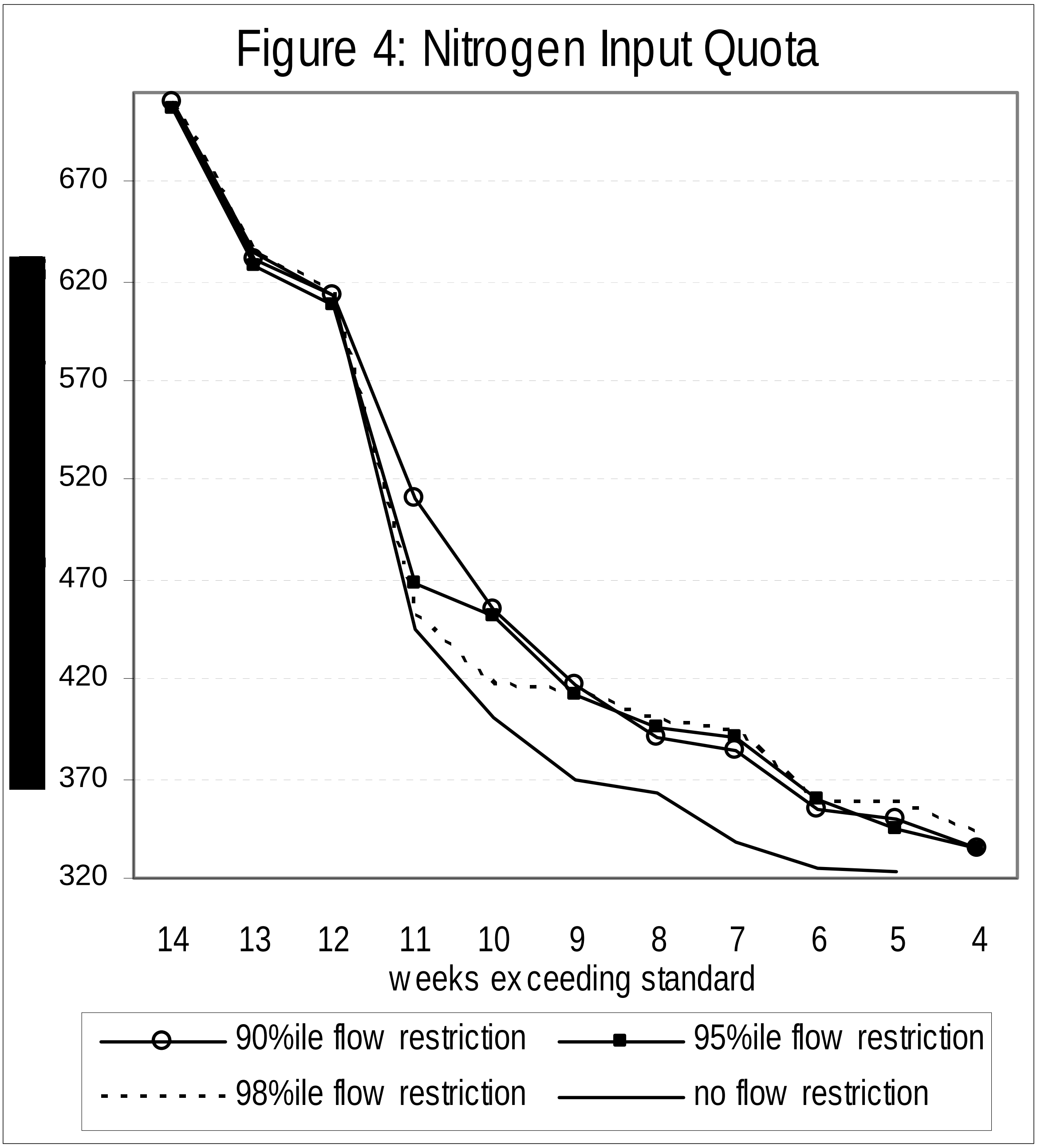


Figure 4: Nitrogen Input Quota
[redacted]
670
620
570
520
470
420
370
320
14
13
12
11
10
9
8
7
6
5
4
weeks exceeding standard
90%ile flow restriction
95%ile flow restriction
98%ile flow restriction
no flow restriction

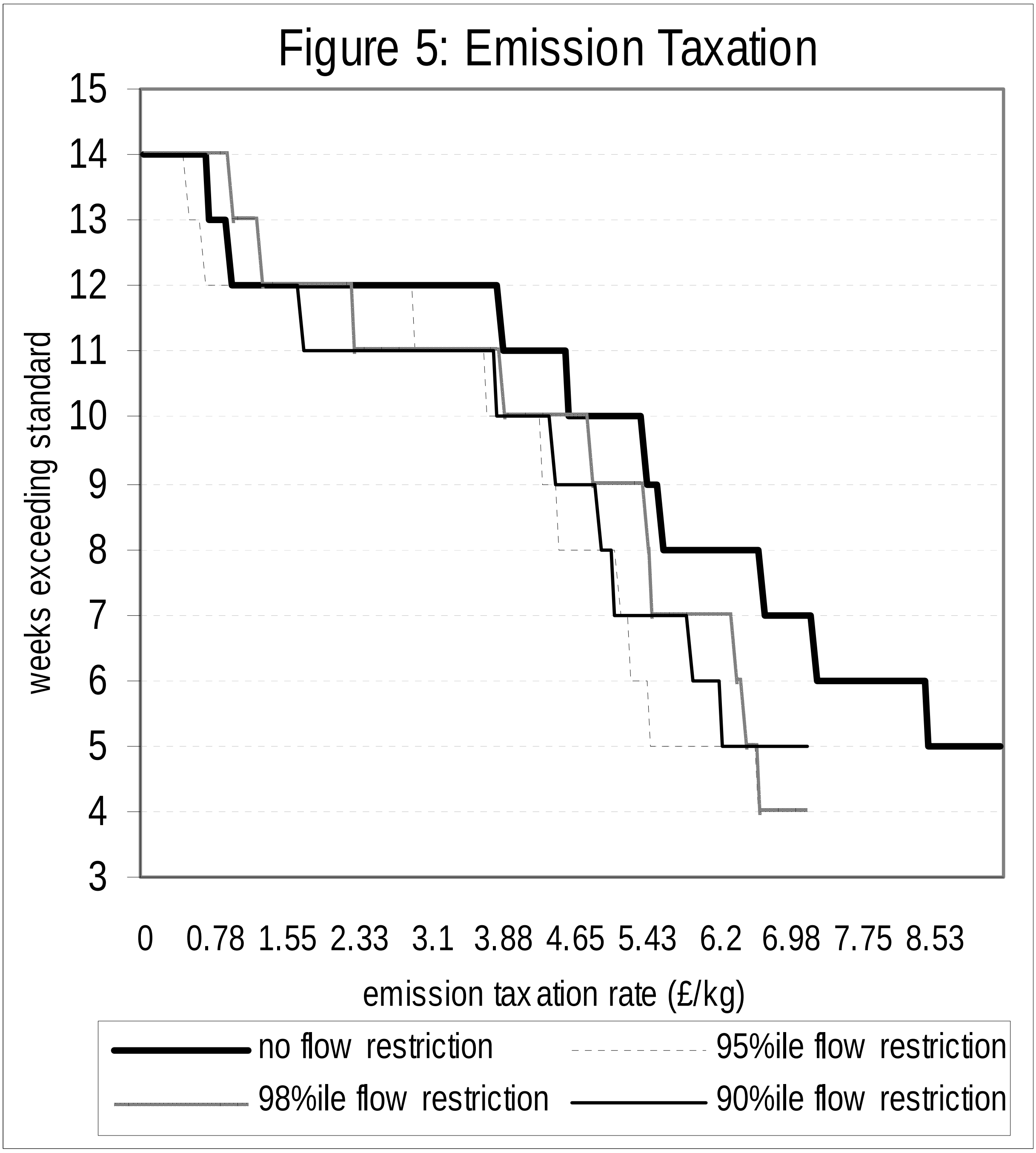
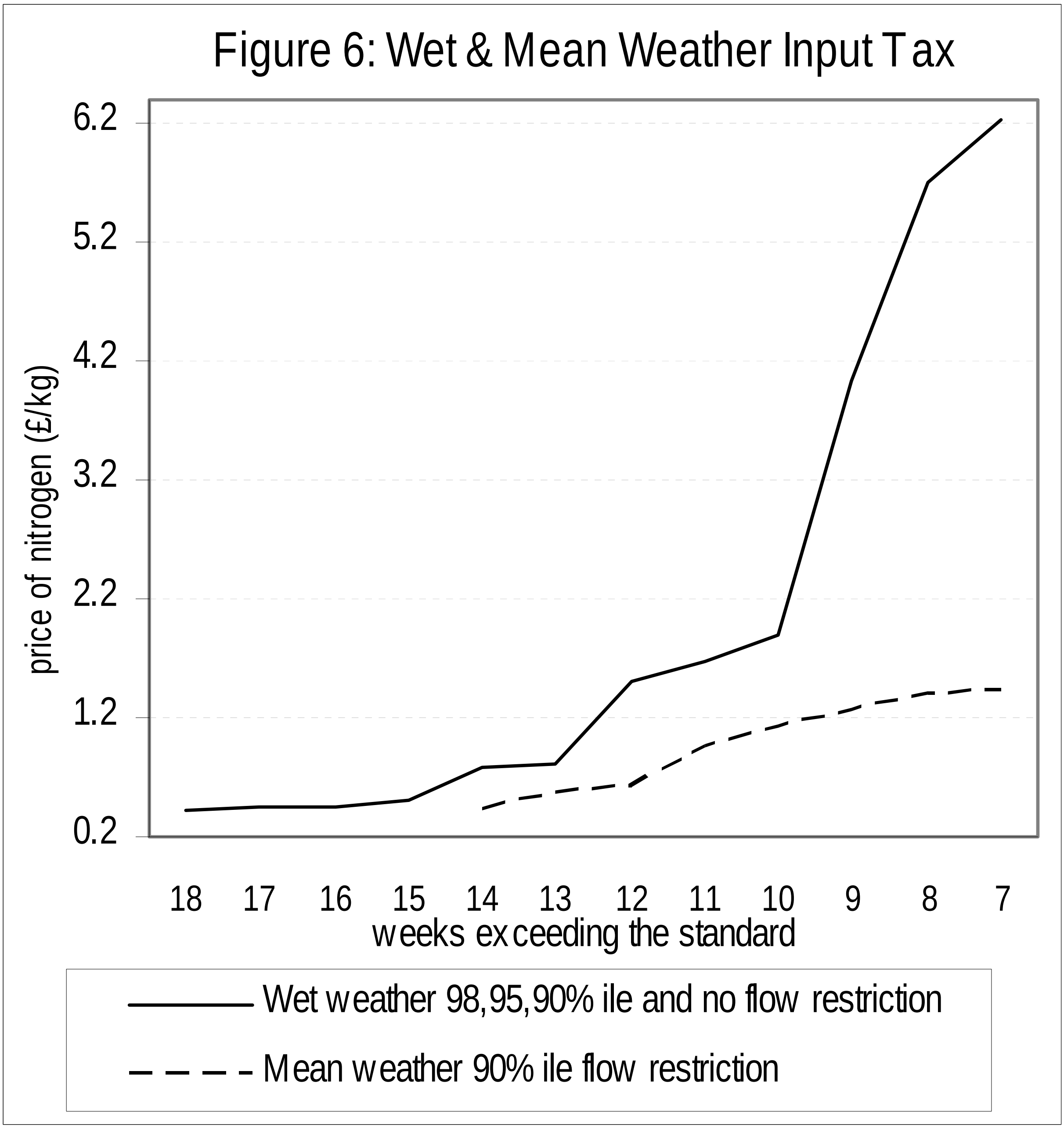


Figure 5: Emission Taxation
weeks exceeding standard
15
14
13
12
11
10
9
8
7
6
5
4
3
0
0.78
1.55
2.33
3.1
3.88
4.65
5.43
6.2
6.98
7.75
8.53
emission taxation rate (£/kg)
no flow restriction
95%ile flow restriction
98%ile flow restriction
90%ile flow restriction



Note that the required nitrogen tax rate is higher under wet weather conditions than under mean conditions

FOOTNOTES

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[i] By law a minimum requirement of 5 holdings of any activity per catchment must exist before disclosure, therefore not all the required data was made available. This meant approximating certain livestock values such as the stocking rate which was assumed to be 2.2 glu/ha.

[ii] The 95%ile flow defines a flow exceeded naturally on 95% of days in a ‘average’ year (1989 – 1998 period) during which no abstraction took place.

[iii] The 90%ile imposes the greatest restriction on irrigation extraction while 98th percentile the least (i.e. the greatest river flow).

[iv] For details on the potato growth model, naturalised flow estimation, reservoir storage, borehole capacity, irrigation dates, extraction points, application of flow related bans and other assumptions see Crabtree, et al.

[v] The results were confirmed by using the MINOS 5 solver which yielded similar results within reasonable bounds.

[vi] Limited livestock statistics were disclosed due to confidentiality issues.

[vii] It is assumed that setaside land is not rotational. Rotational setaside is exacerbates diffuse nitrogen leaching.