Water Quality and Sediment Behaviour of the Future: Predictions for the 21st Century (Proceedings of Symposium HS2005 at IUGG2007, Perugia, July 2007). IAHS Publ. 314, 2007.

Predicting the impact of projected change in agriculture by 2015 on annual mean fluvial suspended sediment concentrations across England and Wales

ADRIAN L. COLLINS[1], STEVEN G. ANTHONY[1], TONY TURNER[2] & JULIA HAWLEY[2]

1 *Environment Systems, ADAS, Woodthorne, Wergs Road, Wolverhampton WV6 8TQ, UK*
adrian.collins@adas.co.uk

2 *Rural Management Group, ADAS, Woodthorne, Wergs Road, Wolverhampton WV6 8TQ, UK*

Abstract With respect to achieving "good ecological status" (GES) for freshwaters by 2015, ADAS has recently been commissioned by the Department for Environment, Food and Rural Affairs (Defra) to estimate the gap between current and target losses of suspended sediment from diffuse agricultural sources across England and Wales. The work required a model for predicting mean annual total suspended sediment loads (SSL) and time-weighted mean fluvial suspended sediment concentrations (SSC). GES was defined in terms of the guideline annual average SSC of 25 mg L^{-1} cited by the EC Freshwater Fish Directive. National scale sediment source apportionment was undertaken to estimate the contributions of diffuse agricultural and urban sector sediment losses, channel bank erosion and point source discharges to the total SSL in all rivers. Landscape sediment retention was taken into account. The total SSL estimated for each Water Framework Directive (WFD) sub-catchment across England and Wales was used in conjunction with predicted flow exceedence to derive corresponding SSC time-exceedence plots. Baseline (year 2000) sediment load reductions required from the agricultural sector for meeting the target threshold SSC of 25 mg L^{-1} were estimated at national scale. Projected change in agriculture (structural and uptake of sediment mitigation methods) by 2015 was incorporated in the modelling exercise to predict the associated changes in SSL and mean annual SSC. The findings suggest that in addition to current agri-environment schemes, e.g. Countryside Stewardship, Catchment Sensitive Farming (CSF), further mitigation will be necessary under the River Basin Management Plans (RBMPs) of the WFD to reduce diffuse agricultural sediment losses for achieving GES in some parts of England and Wales.

Key words agriculture; sediment; good ecological status

INTRODUCTION

The introduction of the EU WFD (European Parliament, 2000) marks an important shift towards the effective co-ordination of water environment policy across member states for the purpose of achieving GES by 2015. Whilst the implementation of the WFD will ultimately rely heavily upon representative monitoring programmes for water quality, policy makers are required to make urgent decisions regarding strategies for the mitigation of diffuse pollution. There are a number of obstacles in association with the identification of suitable monitoring strategies, including the absence of consistent methodologies and the prevalence of approaches that do not explicitly target WFD requirements (Dworak *et al.*, 2005). Consequently, there has been increased emphasis, in the meantime, on the use of modelling to inform and support government decisions on diffuse pollution issues and the delivery of appropriate abatement strategies.

Due to WFD legislation and concerns regarding issues of non-compliance in England and Wales, the CSF initiative, representing a partnership between Defra, Natural England and the Environment Agency was launched in April 2006. Although this initiative is focusing upon the delivery of targeted advice to farmers on mitigating diffuse water pollution from agriculture (DWPA) in designated priority catchments, Defra, in relation to over-arching policy development, is supporting the identification of policy packages for inclusion in Programmes of Measures (POMs) in RBMPs. The POMs are targeting the mitigation of sediment, P, N and pathogens.

The need to address mitigation of sediment transfers is underscored by their wider significance with respect to important environmental impacts. Sediment represents a key vector controlling the transfer and fate of nutrients and contaminants (Warren *et al.*, 2003; Collins *et al.*, 2005). Enhanced sediment loadings can degrade the permeability and porosity of fish spawning gravels thereby reducing egg-to-hatching success and emergence (Greig *et al.*, 2005) and are widely acknowledged to contribute to the loss of macrophyte and macroinvertebrate species diversity and dysfunction of community structure (Ward *et al.*, 1998; Clarke & Wharton, 2001).

Given the significance of sediment fluxes for DWPA, Defra recently commissioned ADAS to assess the gap between current and compliant losses of suspended sediment from the agricultural sector across England and Wales. Comparison of the gap with the predicted impact of policy packages permits Defra to demonstrate intent to meet the WFD objective of GES by 2015. Accordingly, this contribution reports the modelling methodology used to evaluate the gap between current and target SSC and the impact of projected change in the agricultural sector associated with structural evolution and the uptake of mitigation methods on that gap.

THE APPROACH

The modelling methodology was founded on developing a statistical relationship between measured SSC and modelled total sediment inputs to watercourses from diffuse and point sources. Although Naden & Cooper (1999) successfully correlated average SSC with percentage land use in individual catchments in Yorkshire, England, explaining 71% of the variance, the use of a similar simple regression model predicting SSC at national scale was precluded by the spatial variability of physical processes and controls on sediment mobilisation and delivery. As a result, a structured regression model was used to ensure inclusion of spatially referenced and physically-based estimates of diffuse sediment source inputs, thereby taking account of spatial variation in sediment transfers. It was, nevertheless, acknowledged that the predictive power of the structured model would inevitably be constrained by the emphasis on national scale.

The WFD does not establish critical SSC standards for GES, reflecting the complexity of the relationships between sediment concentrations and biological impacts (Swietlik *et al.*, 2003). But, on the basis of consultation with ecological experts regarding the critical life cycle requirements of key indicator species (e.g.

salmon, white-clawed crayfish, freshwater pearl mussel), Smith *et al.* (2003) suggested that the annual average SSC should not exceed 25 mg L^{-1}. Because this target threshold is also cited in the EU Freshwater Fish Directive (78/659/EC), it was conveniently adopted as the end member to represent GES in the structured modelling exercise.

Estimating total suspended sediment inputs to rivers across England and Wales

The mean annual total suspended sediment load (SSL) delivered to all rivers across England and Wales was estimated using a simple summation of the individual loads predicted for the diffuse agricultural and urban sectors, eroding channel banks and point source discharges.

Diffuse sediment loss from the agricultural sector Sediment inputs from diffuse agricultural sources at national scale were calculated using the recently developed prototype process-based PSYCHIC (Phosphorus and Sediment Yield CHaracterisation In Catchments) model (Davison *et al.*, 2007). PSYCHIC required as input, statistical data (1 km^2 resolution) on climate, drainage density, slope, soil types and characteristics, land use and cropping, livestock numbers and human population. The core of the model is based upon the source-mobilisation-delivery conceptualisation of land to water diffuse pollution transfers (Heathwaite *et al.*, 2003). The hydrological module of PSYCHIC uses the Mean Climate Drainage Model (MCDM) described by Anthony (2003), which calculates surface and subsurface flow paths for seven key crop types (winter cereals, spring cereals, grass, potatoes, rough grazing, woodland and bare soil). Suspended sediment mobilisation is conceptualised at plot scale in association with detachment and is estimated on the basis of a modified version of the Morgan-Morgan-Finney model (Morgan, 2001) and a parameterisation of rainfall erosivity (Davison *et al.*, 2005). Suspended sediment inputs to watercourses via the surface runoff pathway are calculated by attenuating mobilisation using a source-channel connectivity factor (McHugh *et al.*, 2002) coupled with a particle size correction factor (cf. Walling *et al.*, 2000). The corresponding transfers to rivers via assisted drainage are estimated by attenuating mobilisation using a fixed connectivity coefficient of 0.9 and an allowance for particle size selectivity (cf. Russell *et al.*, 2001). The inclusion of the field drain pathway in the PSYCHIC model is considered to be appropriate for the agricultural landscapes across England and Wales. PSYCHIC assumes the presence or absence of drains on the basis of the Hydrology of Soil Types (HOST) classification scheme (Boorman *et al.*, 1995). Figure 1(a) shows annual average suspended sediment delivery to watercourses, predicted by PSYCHIC. The national mean annual total sediment delivery to all rivers across England and Wales was estimated at 1929 kt, representing a national average of 128 kg ha^{-1} $year^{-1}$.

Diffuse sediment loss from the urban sector Suspended sediment inputs to all rivers from diffuse urban sources were estimated using an Event Mean Concentration (EMC) methodology. A representative EMC of 100 mg L^{-1} was selected for urban areas across England and Wales on the basis of measured inter-quartile ranges of 18–140 mg L^{-1} for industrial areas, 38–193 mg L^{-1} for residential areas and 62–396 mg L^{-1} for major roads (Mitchell *et al.*, 2001). The EMC was combined with calculations

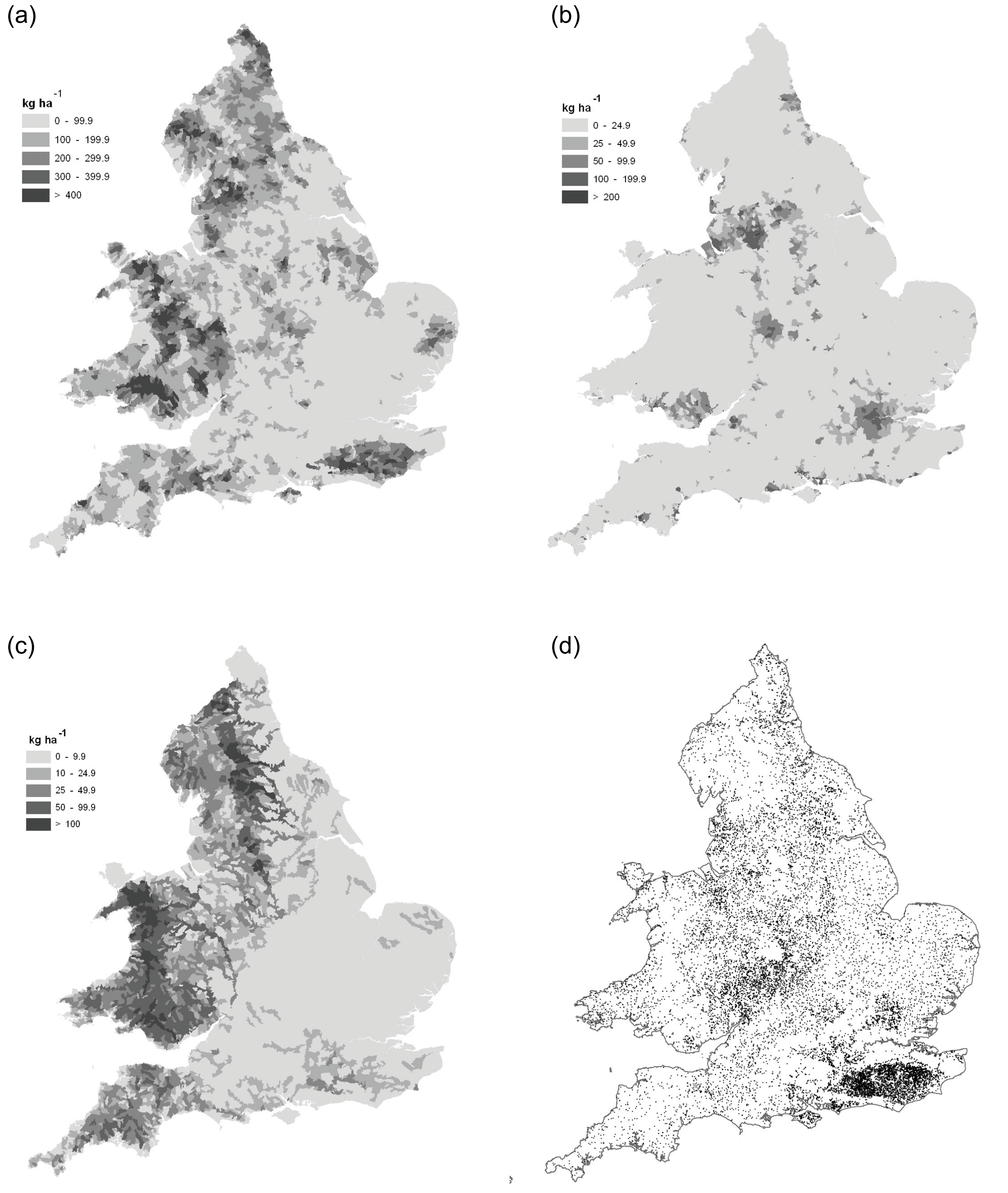

Fig. 1 Mean annual sediment delivery to watercourses from: (a) diffuse agricultural, (b) urban, and (c) channel bank, sources; and (d) the location of consented sewage effluent discharges.

of annual average runoff from urban areas provided by the Wallingford procedure:

$$L = R \times (0.829 \times P + 0.078 \times U - 20.7) \quad (1)$$

where L is annual average runoff (mm), P is proportion of impermeable land and U is the catchment wetness index determined using annual average rainfall (Mitchell *et al.*, 2001). Impermeable land was determined from the density of households in the Ordnance Survey Address Point database and assumptions used in sewer modelling systems (Ellis, 1986). Figure 1(b) presents annual average sediment inputs to watercourses across England and Wales from all urban areas. The national mean annual total sediment delivery to rivers was estimated at 147 kt, equivalent to a national average loss of 10 kg ha^{-1} $year^{-1}$.

Diffuse sediment loss from eroding channel banks Diffuse sediment inputs from eroding channel banks (Fig. 1(c)) were estimated using a prototype national scale index. The bank erosion index was based on the calculation of river regime and the corresponding duration of excess shear stress. River bank shear stress for each flow depth during the year was calculated according to Guo & Julien (2005):

$$\frac{\tau}{\rho \cdot g \cdot s \cdot h} = \frac{b}{2 \cdot h} \cdot \left[1 - \frac{4}{\pi} \cdot \tan^{-1} \exp\left(\frac{-\pi \cdot h}{b} \right) - \frac{\pi \cdot h}{4 \cdot b} \cdot \exp\left(\frac{-h}{b} \right) \right] \tag{2}$$

where b is the channel width (m), h is the water depth (m), g is the acceleration due to gravity (9.81 m s^{-2}), ρ is the mass density of water (kg m^{-3}), and s is the channel slope (m m^{-1}). The flow exceedence distribution for each catchment was calculated according to the model of Gustard *et al.* (1992) in which standard flow duration curves are indexed by the runoff-weighted catchment average Q_{95} statistic. Values of Q_{95} for each soil series across England and Wales were identified by querying the HOST classification (Boorman *et al.*, 1995). Assuming a rectangular form, bankfull channel width W (m) was estimated according to Hey & Thorne (1986):

$$W = 4.33 \cdot Q^{0.5} \tag{3}$$

where Q is the bankfull flow (m^3 s^{-1}), estimated as the flow exceeded 0.6% of the time (Nixon, 1959). Accordingly, the depth of water at any flow value was determined as:

$$h = \frac{Q}{w \cdot v} \tag{4}$$

where v (m s^{-1}) is the flow velocity, estimated according to the general flow velocity formula of Round *et al.* (1998):

$$V = 10^{-0.583} \cdot \overline{Q}^{0.283} \cdot \left(\frac{Q}{\overline{Q}} \right)^{0.495} \tag{5}$$

where $\overline{Q}$ is the long-term mean flow (m^3 s^{-1}) and Q is the instantaneous flow (m^3 s^{-1}) on the day. Application of the bank side shear stress model required information on the critical shear stress (τ_c) for river banks across England and Wales, which was estimated using the relationship of Julian & Torres (2006):

$$\tau_c = 0.1 + 0.1779 \cdot SC + 0.0028 \cdot SC^2 - 2.34E^{-5} \cdot SC^3 \tag{6}$$

where SC is the total silt-clay content of the channel banks at a given location. The duration of excess shear stress (as a percentage of the year) was calculated for the main river channel in each catchment across England and Wales. Channel density is also likely to influence channel bank erosion sediment yields on account of the increased opportunity for bank erosion associated with higher density channel systems and because drainage density reflects a number of catchment characteristics likely to influence bank erosion, including rainfall and flow regime. Consequently, the bank sediment loss index also incorporated channel density. Estimates of lateral erosion rate were converted into sediment yields using information on the total channel length and average bank height within each catchment. The combined bank erosion index (r^2 =

60%) was calibrated using sediment source fingerprinting estimates of the net sediment loss from eroding channel banks (Walling & Collins, 2005). On this basis, the mean annual total sediment input to all rivers across England and Wales from eroding channel banks was estimated at 394 kt, representing a national average loss of 26 kg ha^{-1} $year^{-1}$.

Point source sediment contributions Suspended sediment contributions to all rivers across England and Wales from point sources were estimated using a database of consented effluent discharges from sewage treatment works (Fig. 1(d)). The database provided information on the maximum consented SSC for individual discharges (<1–800 mg L^{-1}). Missing data were interpolated using regional flow-weighted average SSC. Total suspended sediment inputs from effluent works were calculated on the basis of the relationship between measured and consented average SSC (Roberts & Williams, 1997):

$$C_{observed} = 0.29 \times C_{consented} + 4.8 \quad (7)$$

Using this approach, mean annual total suspended sediment loss to all rivers was predicted at 76 kt.

The suspended sediment concentration model

In order to validate the total SSL model, the sum of the predicted sediment contributions from the individual sources was compared with PARCOM measurements of riverine sediment delivery (1999–2003) to the UK maritime area. The relationship was positive (r^2 = 68%). Annual average SSC at a given monitoring station was estimated as the weighted sum of the time-average annual concentrations originating from both diffuse and point sources. Sediment loads contributed from diffuse and point sources were diluted using predicted flow exceedence distributions for individual catchments (Gustard *et al.*, 1992). Optimal weightings for diffuse and point sources (0.68 for diffuse agricultural, 0.70 for diffuse urban, 0.33 for diffuse bank and 0.45 for point sources) were identified using a nonlinear solver function. The calibrated model provided a realistic national scale predictive relationship (r^2 = 33%) between modelled and measured annual average SSC at Environment Agency routine water quality monitoring stations (Fig. 2). Calculation of confidence intervals suggested that the modelled time-average SSC was required to be <19.1 mg L^{-1} to provide an 80% guarantee that the corresponding measured annual average SSC will be less than the critical threshold (25 mg L^{-1}) for GES (Fig. 2).

IMPACT OF PROJECTED CHANGE IN AGRICULTURE BY 2015

The modelling methodology provided a basis for predicting annual average SSC across England and Wales due to sediment inputs from all sources and from the agricultural sector alone (Fig. 3). These predictions reflected present day (year 2000) environmental conditions and agricultural practices. Those catchments currently most at risk of exceeding an annual average SSC of 25 mg L^{-1} are predominantly located in SE, E, NE and midland England as well as in the Welsh borders. Approximately 83% of the total catchment area of England and Wales appeared to require no further reductions

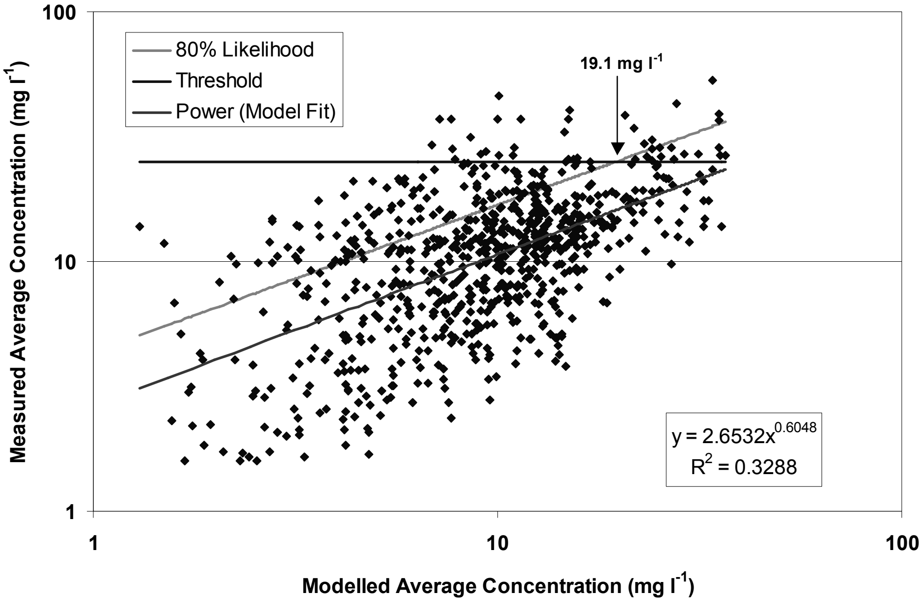

Fig. 2 The relationship between modelled and measured annual average SSC, showing the 80% likelihood interval and the critical threshold modelled concentration for GES.

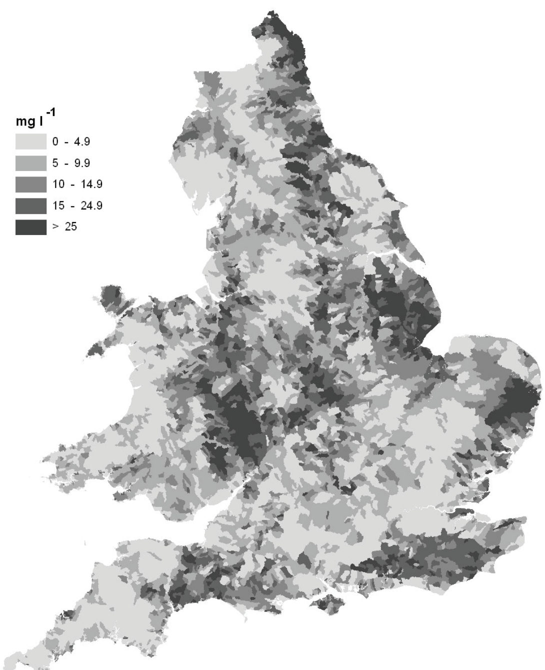

Fig. 3 Modelled contemporary (year 2000) annual average SSC across England and Wales due to sediment contributions from the agricultural sector only.

in sediment loss from the agricultural sector in order to meet the critical standard for SSC. The potential impact of projected change in agriculture by 2015 on annual SSC across England and Wales was assessed by incorporating the Business as Usual forecast of structural evolution (University of Cambridge, 2004) and an expert assessment of the extent and efficiency of implementation of a number of sediment

Table 1 Estimated percentage effectiveness of mitigation methods appropriate for the reduction of sediment losses from the agricultural sector in England and Wales.

Mitigation method	Arable		Grass	
	Clay loam	Sandy loam	Clay loam	Sandy loam
Convert arable land to extensive grassland	30	80	-	-
Establish cover crops in the autumn	5	10	-	-
Cultivate land for crop establishment in spring, not autumn	5	10	-	-
Adopt minimal cultivation systems	5	-	-	-
Cultivate compacted tillage soils	5	5	-	-
Cultivate and drill across the slope	1	1	-	-
Leave autumn seedbeds rough	5	5	-	-
Avoid tramlines over winter	5	10	-	-
Establish in-field grass buffer strips	5	50	-	-
Loosen compacted soil layers in grassland fields	-	-	1	1
Maintain and enhance soil organic matter levels	1	5	-	-
Allow field drainage systems to deteriorate	1	-	1	-
Reduce overall stocking rates on livestock farms	-	-	10	10
Reduce the length of the grazing day or grazing season	-	-	5	5
Reduce field stocking rates when soils are wet	-	-	20	20
Move feed and water troughs at regular intervals	-	-	5	5
Fence off rivers and streams from livestock	-	-	10	20
Construct bridges for livestock crossing rivers and streams	-	-	5	5
Re-site gateways away from high-risk areas	1	1	5	5
Establish new hedges	5	20	5	5
Establish riparian buffer strips	5	30	5	15
Establish and maintain artificial (constructed) wetlands	40	-	40	-

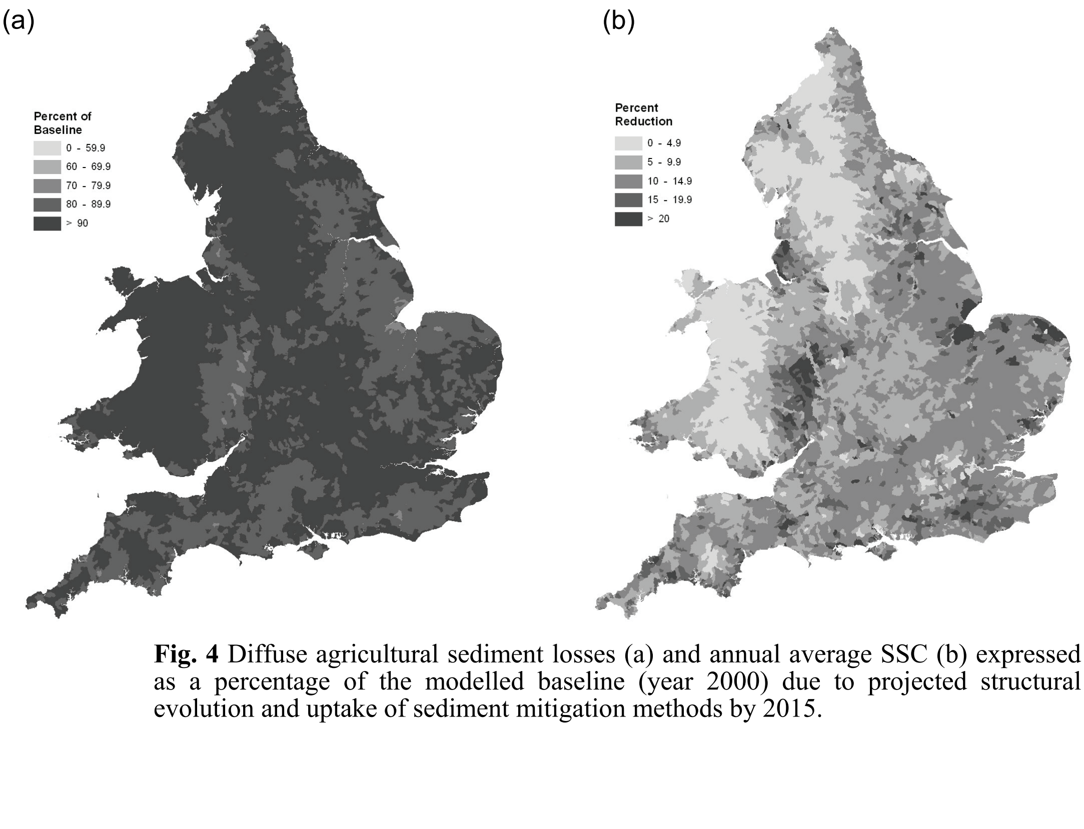

Fig. 4 Diffuse agricultural sediment losses (a) and annual average SSC (b) expressed as a percentage of the modelled baseline (year 2000) due to projected structural evolution and uptake of sediment mitigation methods by 2015.

mitigation methods by farmers (Table 1) into the modelling routine. The findings suggested that reductions in total SSL (Fig. 4(a)) and annual average SSC (Fig. 4(b)) by 2015 would be small in most areas, but that the most significant reductions would at least target some of the catchments at risk of failing the critical sediment threshold (Figs 3 and 4(b)). Approximately 88% of the total catchment area in England and Wales could be expected to meet the SSC criterion for GES by 2015. In addition to existing agri-environment schemes, e.g. CSF, further sediment abatement will therefore be required from RBMPs to reduce diffuse agricultural sediment losses sufficiently for achieving GES in some parts of England and Wales.

CONCLUSION

The work reported in this contribution represents a preliminary attempt at modelling the total mean annual SSL and annual average SSC in all rivers across England and Wales. Future work will target improving the prediction of sediment losses from specific sources, e.g. channel banks, and within specific regions, e.g. Wales. The scenario analysis will be projected to the year 2025.

Acknowledgements This research was funded by the Department for Environment, Food and Rural Affairs (Defra) under project WQ0106. Alan Edwards produced the figures.

REFERENCES

Anthony, S. G. (2003) The MCDM model: a monthly calculation of water balance for use in decision support systems. Unpublished ADAS internal report.

Boorman, D. B., Hollis, J. M. & Lilly, A. (1995) *Hydrology of Soil Types: A Hydrologically-Based Classification of the Soils of the United Kingdom*. Institute of Hydrology Report no. 126, Wallingford, UK.

Clarke, S. & Wharton, G. (2001) Sediment nutrient characteristics and aquatic macrophytes in lowland English rivers. *Sci. Total Environ.* **266**, 103–112.

Collins, A. L., Walling, D. E. & Leeks, G. J. L. (2005) Storage of fine-grained sediment and associated contaminants within the channels of lowland permeable catchments in the UK. In: *Sediment Budgets 1* (ed. by D. E. Walling & A. J. Horowitz), 259–268. IAHS Publ. 291, IAHS Press, Wallingford, UK.

Davison, P. S., Hutchins, M. G., Anthony, S. G., Betson, M., Johnson, C. & Lord, E. I. (2005) The relationship between potentially erosive storm energy and daily rainfall quantity in England and Wales. *Sci. Total Environ.* **344**, 15–25.

Davison, P. S., Withers, P. J. A., Lord, E. I., Betson, M. J. & Stromqvist, J. (2007) PSYCHIC – a prototype process-based model of phosphorus and sediment mobilization and delivery within agricultural catchments in England and Wales: model description and parameterisation. *J. Hydrol.* (in press).

Dworak, T., Gonzalez, C., Laaser, C. & Interwies, E. (2005) The need for new monitoring tools to implement the WFD. *Environ. Sci. Policy* **8**, 301–306.

Ellis, J. B. (1986) Pollutional aspects of urban runoff. In: *Urban Runoff Pollution* (ed. by H. C. Torno, H. C. Marsalek & M. Desbordes), Springer Verlag, Berlin, Germany.

European Parliament (2000) Establishing a framework for community action in the field of water policy. *Directive EC/2000/60*, EU, Brussels.

Grieg, S. M., Sear, D. A. & Carling, P. A. (2005) The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. *Sci. Total Environ.* **344**, 341–258.

Guo, J. & Julien, Y. P. (2005) Shear stress in smooth rectangular open-channel flows. *J. Hydraulic Engng ASCE* **131**, 30–37.

Gustard, A., Bullock, A. & Dixon, J. M. (1992) *Low Flow Estimation in the United Kingdom*. Institute of Hydrology Report 108, Wallingford, UK.

Heathwaite, L., Sharpley, A. N. & Bechmann, M. (2003) The conceptual basis for a decision support framework to assess the risk of phosphorus loss at the field scale across Europe. *Soil Sci. Plant Nutrition* **166**, 447–458.

Hey, R. D. & Thorne, C. R. (1986) Stable channels with mobile gravel-beds. *J. Hydraul. Engng ASCE* **112**, 671–689.

Julian, J. P. & Torres, R. (2006) Hydraulic erosion of cohesive riverbanks. *Geomorphology* **76**, 193–206.

McHugh, M., Wood, G., Walling, D., Morgan, R., Zhang, Y., Anthony, S. & Hutchins, M. (2002) Prediction of sediment delivery to watercourses from land: phase 2. *R & D Technical Report No P2-209*, Environment Agency, Bristol, UK.

Mitchell, G., Lockyer, J. & McDonald, A. T. (2001) Pollution hazard from urban nonpoint sources: a GIS-model to support strategic environmental planning in the UK. Technical Report, School of Geography, University of Leeds, UK.

Morgan, R. P. C. (2001) A simple approach to soil loss prediction: a revised Morgan-Morgan-Finney model. *Catena* **44**, 305-322.

Naden, P. & Cooper, M. (1999) Development of a sediment delivery model for application in large river basins. *Hydrol. Processes* **13**, 1011–1034.

Nixon, M. (1959) A study of bankfull discharges of rivers in England and Wales. *Proc. Instn Civil Engrs* **12**, 157–175.

Roberts, G. & Williams, R. J. (1997) A review of the treatment of household and industrial wastes and the characterisation of sewage effluents. Institute of Hydrology Internal Report, Wallingford, UK.

Round, C. E., Young, A. R. & Fox, K. (1998) A regionally applicable model for estimating flow velocity at ungauged river sites in the UK. *J. Chartered Inst. Water Environ. Manage.* **12**, 402–405.

Russell, M. A., Walling, D. E. & Hodgkinson, R. A. (2001) Suspended sediment sources in two small lowland agricultural catchments in the UK. *J. Hydrol.* **252**, 1–24.

Smith, B., Naden, P. & Cooper, D. (2003) Siltation in rivers. 3: Integrated assessment procedure. *Conserving Natura 2000. Rivers Conservation Techniques Series*. English Nature, Peterborough, UK.

Swietlik, W., Berry, W., Gardner, T., Hill, B., Jha, M., Kaufmann, P., Melzian, B., Norton, D., Paul, J., Rubinstein, N., Shippen, R. & Spehar, R. (2003) Developing water quality criteria for suspended and bedded sediments (SABS). Potential approaches. US EPA Office of Water, Office of Science and Technology, Health and Ecological Criteria Division, USA.

University of Cambridge (2004) Business as usual projections of agricultural outputs. Final report to Environment Agency, Centre for Rural Economics Research, University of Cambridge, UK.

Walling, D. E. & Collins, A. L. (2005) Suspended sediment sources in British rivers. In: *Sediment Budgets 1* (ed. by D. E. Walling & A. J. Horowitz), 123–133. IAHS Publ. 291. IAHS Press, Wallingford, UK.

Walling, D. E., Owens, P. N., Waterfall, B. D. & Leeks, G. J. L. (2000) The particle size characteristics of fluvial suspended sediment in the Humber and Tweed catchments, UK. *Sci. Total Environ.* **251/252**, 205–222.

Ward, J. V., Bretschko, G., Brunke, M., Danielpol, D., Gibert, J., Gonser, T. & Hildrew, A. G. (1998) The boundaries of river systems: the metazoan perspective. *Freshwater Biology* **40**, 531–569.

Warren, N., Allan, I. J., Cater, J. E., House, W. A. & Parker, A. (2003) Pesticides and other micro-organic contaminants in freshwater sedimentary environments – a review. *Applied Geochemistry* **18**, 159–194.