GIS-based risk assessment of water supply intakes in the British uplands

J.A. Foster, A.T. McDonald,
School of Geography, University of Leeds, Leeds. LS2 9JT. U.K.
Tel: +44 113 233 3327 / 3344 Fax: +44 113 233 3308
E-mail: J.Foster@geog.leeds.ac.uk, Adrian@geog.leeds.ac.uk

S.M. Macgill
The Environment Centre, University of Leeds, Leeds. LS2 9JT. U.K. E-mail: lecsmm@leeds.ac.uk

I. Mitchell
Yorkshire Water Services Ltd., Bradford. BD6 2LZ. U.K.
E-mail: Ian_Mitchell@yorkshirewater.plc.uk

Abstract

The process of pollution risk assessment requires the assimilation of data that are spatially variable in nature, making geographical information systems (GIS) an ideal tool for such assessments. Over half of Britain's drinking water is obtained from surface water abstractions, many of which are situated in upland areas. In order to optimise the quality of abstracted waters it is important to assess the possible risks of pollution upstream of the point of abstraction.

This paper describes a case study of a risk assessment procedure developed using the PC-based WINGS GIS, illustrating how this technology can assist in environmental decision making. Examples are given showing how GIS techniques can be used to produce maps indicating areas of potential hazard to water quality, and coupled with existing models to identify and quantify risks. The assessment of pollution risks is used to formulate a raw water monitoring programme to assist in intake operation and land-use planning in the catchment.

Keywords

Geographical information systems (GIS); environmental risk assessment; hazard mapping; catchment characteristics; drinking water quality; monitoring strategies.

Environmental Software Systems Vol.2 R. Denzer, D.A. Swayne & G. Schimak (Eds.)
 Published by Chapman & Hall

1 INTRODUCTION

The uplands of Britain, defined as areas more than 250m above sea level, occupy approximately one third of the land area. The combination of low intensity land-use, topography and high rainfall make these areas ideally suited to the collection and storage of water. Much of Britain's drinking water is obtained from upland catchments through a combination of impounding reservoirs and surface water abstractions. One third of all drinking water in Yorkshire is abstracted from surface water intakes, several of which are located in upland areas. Water quality problems affecting upland rivers include agricultural pollution, discoloration, microbial and trace metal contamination. River intakes throughout Britain have also been polluted by industrial spills, road accidents and sewage effluent.

In order to comply with drinking water quality standards and minimise water treatment costs, supply companies need to be aware of the characteristics of their water gathering grounds and how these may affect raw water quality. One approach to reviewing such impacts is environmental risk assessment. Assessing pollution risks involves the assimilation of large spatially variable datasets. The intrinsic capacity of geographical information systems (GIS) to store, analyse and display such data makes them ideal tools for assisting in such assessments.

This paper describes four examples of how environmental data in a PC-based GIS have been used in the development of a generic procedure to assess pollution risks in river catchments, illustrating how GIS technology can aid environmental decision making. The risk assessment methodology has been developed through example application to the Upper Wharfe catchment in Yorkshire. The River Wharfe is a major drinking water resource in the Yorkshire region, with two intakes in the catchment abstracting in excess of 260 mega-litres of water per day

This study utilises a customised version of the Yorkshire Water GISLAB application incorporating a wide variety of spatial data such as soil, rainfall, land cover, terrain contours and river networks. GIS operations used in the derivation of hazard maps and risk assessments include on-screen digitising, polygon algebra and textual reporting facilities. Spatial analysis of environmental data is used to identify the location and extent of hazards. The coupling of GIS to suitable models is used to estimate hazard probability and magnitude. A raw water monitoring programme to assist intake operation and help prioritise catchment planning activities has also been formulated using GIS.

2 IDENTIFYING POTENTIAL POLLUTION HAZARDS

The pollution of a watercourse may originate from point or diffuse sources within the catchment. The significance of both of these pollution sources will be strongly influenced by the catchment hydrology. The runoff of water over the land surface after a rainfall event may transport pollutants quickly and efficiently into the stream network. It is therefore extremely important when considering pollution sources on the land surface to assess the potential for runoff occurring on a given area of land. In order to assess the significance of such areas, a Runoff Potential Index (RPI) was calculated in the GIS to assist in hazard identification. The RPI, displayed as a ranking from 1 (very low) to 5 (very high), was created by combining the annual effective rainfall, land slope, soil hydrology and proximity to a watercourse. One example application of the RPI is in the identification of *cryptosporidium* source areas.

Mapping Cryptosporidium hazards

Cryptosporidium parvum is a protozoan parasite that can cause *cryptosporidiosis* in human and animal populations. Fatalities may occur in immuno-suppressed populations. The protozoa are transported in the raw waters via microscopic oocysts, which are extremely difficult to remove by conventional drinking water treatment. Large numbers of oocysts ($>10^{10}$ animal^{-1} day^{-1}) may be deposited on the ground in animal faeces and subsequently washed off the land surface by overland flow events. *Cryptosporidium* represents a major potential hazard to public health through the contamination of water supplies obtained from upland catchments and it is important to identify sources areas of this harmful pathogen.

Average animal infection rates were combined with faecal production rates and data on animal stocking densities from the annual agricultural census. The total estimated oocyst production for each spatial unit was calculated and combined with the runoff potential index to identify *cryptosporidium* source areas. Figure 1 shows a *cryptosporidium* hazard map for part of the Upper Wharfe catchment. Darker (high risk) areas represent land where conditions promote *cryptosporidium* deposition and transport.

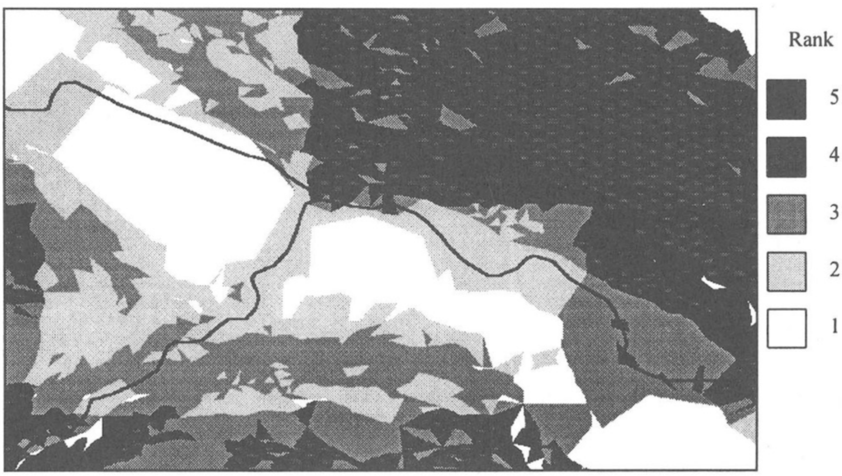

Figure 1 *Cryptosporidium* hazard map for part of the Upper Wharfe catchment

3 INTEGRATION OF GIS ANALYSIS AND PROBABILITY CALCULATIONS: ROAD TANKER SPILLS

Road traffic accidents are another source of pollution that may have a major impact on a water supply intake. The main hazards that exist are from the bulk transport of liquid substances in large tankers. Information about the road network can be combined with accident and spill statistics to give a probabilistic assessment of a spill occurring in the catchment. This is done automatically in WINGS by creating a DUMP macro that extracts the relevant information from the selected data layers and inputs this information into Equation 1 (adapted from Cole and Lacey, 1995).

$$Total\_Road\_Spill\_Risk = \sum_{i>0}^{i=n}\left[L \times F(0.1) \times A \times P_i\right]. \qquad (1)$$

Where: L = total length of road of a particular class in the catchment, F = average flow of Heavy Goods Vehicles (HGVs) per year, 0.1 = proportion of HGVs that are bulk tankers, A = accident involvement rate per million vehicle kilometres travelled, P_i = probability of a spill of size *i* occurring as a result of an accident. Expected probabilities were calculated for two classes of road, Primary routes and Minor routes. The results are shown in Table 1.

Table 1 Probability (per year) of a tanker spill occurring in the Wharfe Catchment

Spill size (kg)	*Primary Routes*	*Minor Routes*	*Total*
Less than 150	0.0360	0.0048	0.0408
150 - 1500	0.0090	0.0010	0.0100
1500 +	0.0200	0.0030	0.0230
Total	0.0650	0.0088	0.0738

Two primary routes present a major potential hazard in the Wharfe catchment due to their extended proximity to the watercourse. Table 1 shows that a spillage from such a route is predicted approximately once every 15½ years of operation (p=0.0650), compared to once every 188 years (p=0.0088) for minor roads. The potential exists for this approach to be enhanced by using link-specific traffic flow data and accident rates, and determining the extent of highway drainage.

4 COUPLING GIS ANALYSIS WITH WATER QUALITY MODELS: WATER DISCOLORATION AND TRACE METAL MOBILISATION

Past research (e.g. Mitchell and McDonald 1992 and 1995) has yielded a number of predictive models describing the relationship between catchment characteristics and stream water quality. Here the ability of the GIS to analyse several complex spatial datasets is used to quantify water colour and trace metal (aluminium) content at a subcatchment outlet. The models, based on step-wise multiple regression, are as follows:

$$\log_{10} \text{Colour} = 0.00512\ (\%TCLA_5^{\,0}) - 0.609\ (MSS) + 0.00368\ (\%1011b) + 0.21435. \quad (2)$$

$$\log_{10} \text{Aluminium} = 0.034\ (\%TCLA_5^{\,0}) - 10.0019\ (RR) - 0.653. \quad (3)$$

Where: $\%TCLA_5^{\,0}$ = percentage of total channel length in areas of less than or equal to 5° slope, MSS = main stream slope (slope between 10 and 85 percentiles of main stream), %1011b = percentage of catchment area of soil type 1011b (Winter Hill Peat), RR = Relief ratio (Basin relief / basin length).

These models, developed by Mitchell and McDonald (1992), have been found to explain 82% and 68% of variations in colour and aluminium respectively in upland catchments similar to the one being studied here. Considering a small subcatchment as an example, Table 2 shows predictions of Colour and Aluminium and how these compare to values obtained by on-site sampling. In general the mean values were over predicted for this subcatchment, with the predictions actually closer to the maximum values obtained from the sampling.

Table 2 Predicted and actual values of Colour and Aluminium for the outlet of Littondale subcatchment

	Colour (Hazen)	*Aluminium ($mg\ l^{-1}$)*
Predicted value (mean)	46.54	5.52
Maximum (from sampling)	43.20	0.24
Mean (from sampling)	20.68	0.05

These models will be further calibrated when the final results of the sampling regime are in place. The potential exists for more complex water quality transport models to be integrated with the GIS to predict failures of the Drinking Water Regulations at the point of abstraction and to assist in pollution risk assessment.

5 GIS-BASED RISK ASSESSMENT AND RAW WATER MONITORING STRATEGIES

The approaches described above, especially hazard identification and water quality modelling, can be combined to facilitate the design of a raw water monitoring network. Detailed knowledge of the raw water quality at strategic points in the catchment will enable the targeting of catchment management activities and the optimisation of treatment processes and costs. The results obtained from such a sampling strategy will also be of use in the validation and refinement of the risk assessment methodology.

The subcatchments, designated by digitising topographical watersheds, were ranked according to their relative impact on several water quality parameters. The optimum location of sample sites was then based on the location of high and low risk areas and subcatchment outlets. The hazard mapping exercises also helped to identify the primary parameters that should be monitored at each site. Table 3 shows an example monitoring site identified by this approach, together with some of the parameters to be monitored.

Table 3 Major hazards and parameters to monitor at the outlet of Littondale subcatchment

Location:	*Major Hazards*	*Parameters to monitor*
Grid reference:	high grazing intensity,	Bacteria, *cryptosporidium*,
SD 971691	sheep-dips, caravan site.	pesticides, phenolics, ammonia.

This approach is relatively generic in application enabling a consistent approach to raw water monitoring and could be stored as computer program or procedure to allow less experienced staff to formulate sound sampling strategies.

6 CONCLUSIONS

This paper has illustrated the potential application of a geographical information system to the assessment of risks to a public water supply intake. The examples given include GIS overlay to identify areas of potential hazard, the use of GIS in the probabilistic modelling of risks, and the prediction of stream water quality. The functionality of the GIS has also been shown to be suitable for the derivation of raw water monitoring strategies.

The approaches described in this paper illustrate the potential use of computing techniques, and GIS in particular, in pollution risk assessment for water resource protection. The areas of application have concentrated on hazard identification and estimation, however, the potential for such approaches to be refined and applied to subsequent stages of the assessment process has been identified. Geographical information systems therefore have considerable ability to enhance pollution risk assessment through the storage, analysis and management of environmental data.

7 ACKNOWLEDGEMENTS

The authors are grateful to the Soil Survey and Land Research Centre and Institute of Hydrology for permission to use the digital data. Agricultural census data were provided by Edinburgh University Data Library. Ordnance Survey map data are reproduced with the permission of the controller of Her Majesty's Stationary Office, Crown Copyright. Licence No. WU298581.

8 REFERENCES

Cole, J.A. and Lacey, R.F. (1995) Estimation of the frequency of spills of liquids from road tankers involved in traffic accidents. CIWEM seminar on intake protection and pollution risk assessment. London, 03/05/95.

Mitchell, G.N. and McDonald, A.T. (1992) Predicting the spatial distribution of coloured water in North Yorkshire. School of Geography Working Paper 92/9. School of Geography, University of Leeds, Leeds, UK.

Mitchell, G.N. and McDonald, A.T. (1995) Catchment characterisation as a tool for upland water quality management. *Journal of Environmental Management*, **43**, 83-95.

9 AUTHOR BIOGRAPHIES

J.A. Foster is a postgraduate research student in the School of Geography, University of Leeds. Prior to this he completed a BSc (Honours) degree in Geography and worked for the National Rivers Authority.

A.T. McDonald is Professor of Environmental Management in the School of Geography and co-director of The Environment Centre.

S.M. Macgill is Principal Research Scientist in The Environment Centre, specialising in environmental risk assessment and management.

I. Mitchell is an Analyst in Mapping Services, Yorkshire Water Services Ltd. Ian has pioneered the development of GISLAB within Yorkshire Water.