ACHIEVING MICROBIOLOGICAL COMPLIANCE OF BATHING WATERS INFLUENCED BY LIVESTOCK INPUTS: REDUCE STOCKING LEVELS OR IMPROVE MITIGATION MEASURES?

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ABSTRACT

Predictions of microbiological compliance of bathing waters have been made for Irvine Beach, Ayrshire, Scotland using a simple model of loading, transport and die-off of faecal indicators derived from diffuse riverine inputs. The spreadsheet based model allows the effects of stocking reduction in the Irvine catchment to be explored, and compared with the potential for improvement using mitigation measures. It is based on observations of E.coli inputs, survival and transport in the Cessnock and Irvine catchments and hydrological and bathing water data from SEPA's database. Results suggest that large reductions in stocking density would be required to improve compliance, if no mitigation measures such as buffer strips, off-stream watering of stock, covering of middens etc, were practiced. However, results were compared with predictions of a soil transport model, calibrated for field plots, which was assumed to give an indication of the potential for improved compliance when these mitigation measures are implemented (ie all E.coli transport is through the soil-drainage system). Even at current stocking rates, this comparison strongly suggests that seeking to mitigate the pollution problems, rather than reduce stock density will be far more effective.

INTRODUCTION

The EC Water Framework Directive requires member states to ensure that designated bathing waters, at both fresh water and coastal sites, comply with microbiological standards (Table 1) for faecal indicator organisms (FIOs). In recent years it has been recognised that catchment sources (surface runoff and field drainage water from fields containing grazing animals, slurry spreading, field middens, farmyard runoff, direct faecal inputs from livestock) make a substantial contribution to faecal indicator loads (Wyer et al., 1996) and that this contribution is particularly important at high river discharges (McDonald and Kay, 1981). Under such "event" conditions, the combination of larger contribution of surface or near surface flow to streamflows (Hunter et al., 1992), shorter travel times of bacteria in streams, entrainment of stream sediment (Wilkinson et al., 1995) and mixing of a larger riverine input with seawater all contribute to orders of magnitude increases in FIO concentrations in Bathing water samples, for beaches influenced by river estuaries (SEPA, 2002). Whilst substantial improvements to bathing water quality have been achieved by reducing sewage inputs, the continued contribution of catchment sources has meant that the expected improvements have not always been realised (eg Wyer et al., 1996). It is recognised that such Best Management Practices (BMPs) as buffer strips, contour cultivations, off-stream watering of livestock, grassed surface drainage channels, covering of middens, controlled walkways for cattle etc. provide a significant potential for reducing FIO inputs to watercourses (Dampney et al., 2002) and Tiedemann et al. (1987) suggested FIO levels may be more related to animal access to streams than to stocking densities. It would be helpful to be able to provide policy makers and planners, as well as EC regulators, with information about the relative level of amelioration which might be achieved by such BMPs, compared with the much more invasive action of reduction in stocking density. With these considerations in mind, we have devised a simple, spreadsheet based model for predicting microbiological compliance of bathing waters influenced by diffuse riverine inputs of FIOs, and applied it to the Irvine catchment in Ayrshire, Scotland, which causes considerable pollution of coastal bathing waters near the resort of Irvine.

Table 1: Interpretation of Microbiological Values for Bathing Waters

	Total Coliforms	**Faecal Coliforms**	**Faecal streptococci**
Pass-Guideline	80% of samples should not exceed 500 total coliforms per 100 ml Must have at least 16 samples with less than, or equal to, 500 total coliforms per 100 ml	80% of samples should not exceed 100 faecal coliforms per 100 ml Must have at least 16 samples with less than, or equal to, 100 faecal coliforms per 100 ml	90% of samples should not exceed 100 faecal streptococci per 100 ml Must have at least 18 samples with less than, or equal to, 100 streptococci per 100 ml
Pass-Mandatory	95% of samples should not exceed 10,000 total coliforms per 100 ml Can only have 1 sample with greater than 10,000 total coliforms per 100 ml	95% of samples should not exceed 2,000 faecal coliforms per 100 ml Can only have 1 sample with greater than 2,000 faecal coliforms per 100 ml	The Directive contains no mandatory standard for faecal streptococci The Directive contains no mandatory standard for faecal streptococci

Source: http://www.sepa.org.uk/data/bathingwaters/2002bathingseason/

MODEL DESCRIPTION AND ASSUMPTIONS

The model is described in detail elsewhere (Vinten et al., 2003) but consists of the following components:

Calculation of Bathing water faecal indicator concentration from river discharge faecal indicator concentration at the river estuary.

The riverine input been estimated from salinity data for weekly samples of bathing water taken for microbiological analysis at Irvine Beach in 2002 (Milne, D., personal communication). This approach assumes a simple functional relationship, whereas in reality tides and wind direction will influence the circulation of river water in the sea (Dempsey et al., 2001).

Calculation of Bathing water faecal indicator concentration at estuary from specific discharge and faecal indicator concentration in calibration sub-catchment.

This approach assumes a constant die-off and sedimentation rate in the river. In reality the die-off rate may vary with sediment concentration and river salinity (Milne et al., 1989, 1991), but we have not considered these in the interests of model parsimony. The model assumes that catchment delivery processes dominate stream sediment entrainment or deposition processes. Hunter et al.(1992) postulate that in upland streams, stream bed entrainment quickly exhausts the burden of stream bed FIOs, and Arnott (2002) found no significant sedimentation of E.coli in a 1 hour period in samples of water taken from the Cessnock Water.

The model also assumes a direct correspondence of area-scaled discharges between sub-catchments and the whole river, after taking into account travel time delay. A plot of hourly scaled discharges for the SEPA river gauge at Newmilns (a sub-catchment of the River Irvine) and at Shewalton at the mouth of the river Irvine shows a good correspondence, with a 6 hour delay at discharge of 5 mm d^{-1} .

Calculation of lumped mean faecal indicator content in landscape.

FIO inputs were estimated from weekly observation of grazing animal stocking density and evidence of recent slurry spreading in the calibration sub-catchment. Input rates from grazing livestock are based on the figures of Lewis et al. (2003). We assumed first order die-off kinetics (Vinten et al. 2002), with a pseudo-steady state soil content developing each week.

Relationship between calibration catchment river discharge, FIO concentration in discharge and lumped mean FIO content in catchment.

This relationship can be obtained in a number of ways:

(a). **Lumped river transport model**. This uses a direct relationship between daily faecal indicator loads, scaled for landscape FIO content, and area-scaled stream discharge for a range of catchment conditions. This we have done using both event data and weekly spot samples in the Cessnock catchment (see below).

(b). **PAMIMO-C**. This uses the data from (a) to calibrate a distributed GIS model of delivery of water and faecal indicators. This is described in detail elsewhere (Lewis et al., 2003), but some of the main results are used here.

(c). **Lumped soil transport model.** This uses a predictive model of transport through soil at a field scale (McGechan et al., 2002, 2003), assuming all areas of similar soils within the catchment make a uniform contribution, with 100% delivery from field to river. model. Results of this approach are given in McGechan et al., 2002, 2003. We have used simulations from this approach to provide an indication of the minimum potential FIO transport to streams at current stocking levels, and the maximum impact of mitigation measures to prevent surface transfer of FIOs from field or point sources. It assumes all FIOs travel through the soil to drains, and the model is calibrated and tested using drained field plot data (Vinten et al., 2002, 2003; McGechan et al, 2003).

In each case we need to obtain a functional relationship between calibration catchment discharge, faecal indicator concentration in discharge and lumped mean faecal indicator content in landscape. The form of this relationship is important and we prefer to use a sigmoid functional relationship of the form:

$$P_{ca} = 1/(1+10^{(a+bDca)}) \qquad (1)$$

Where P_{ca} is the proportion of landscape FIO content transported from the catchment per day, based on D_{ca}, the area-scaled hourly discharge measurements and a and b, empirical constants to be determined by fitting. Good fits were obtained to such a relationship for both single event and weekly spot sample data from the calibration sub-catchment of the River Irvine (Cessnock Water).

DATA COLLECTION

Data from the Cessnock Water

The Cessnock water catchment in Ayrshire, SW Scotland discharges into the River Irvine, and has been linked with problems with Bathing Water Directive compliance suffered by the beaches at Irvine (SEPA, 2001, 2000). It has also been part of a survey of livestock management practices affecting water pollution (SEERAD, 2002). A weekly visual survey of livestock numbers and waste spreading activity was carried out across the whole catchment from April to July 2002, generally on a Monday. These data allowed estimates of FIO inputs to catchments and sub-catchments within the

Cessnock Water to be made. These observations achieved approximately 75% areal coverage of the catchment area. At the main exit point of the Cessnock Water from the catchment a manual stage recorder was installed and calibrated. On Wednesday 12th to Thursday 13th June, frequent water sampling and stage and manual rain gauge recording was undertaken at this point (22 samples over 34 hours). In all water and soil samples total coliform and *E.coli* numbers were determined by the "Colilert" defined substrate method (Edberg et al., 1990; IDEXX Laboratories Inc., 2001). This test uses the Most Probable Number technique to determine FIO counts.

Figure 1 shows plots of the June 12th-13th event data, weekly spot sample data, and fits of these data (ie river transport model) using equation (1). To extend the range of the calibration for the event data, we have also included data gathered for a larger event

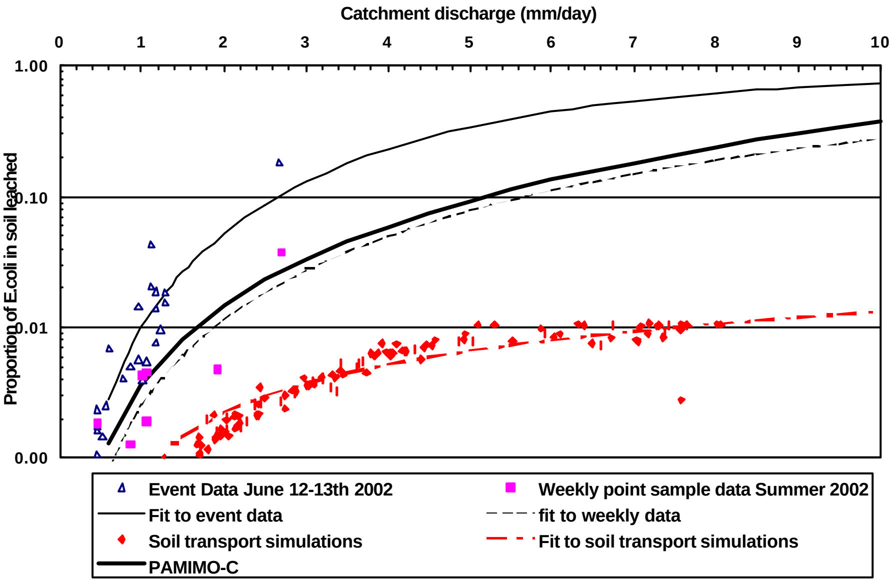

Figure 1. Fits of river transport model to event and weekly point data, soil transport model and PAMIMO-C.

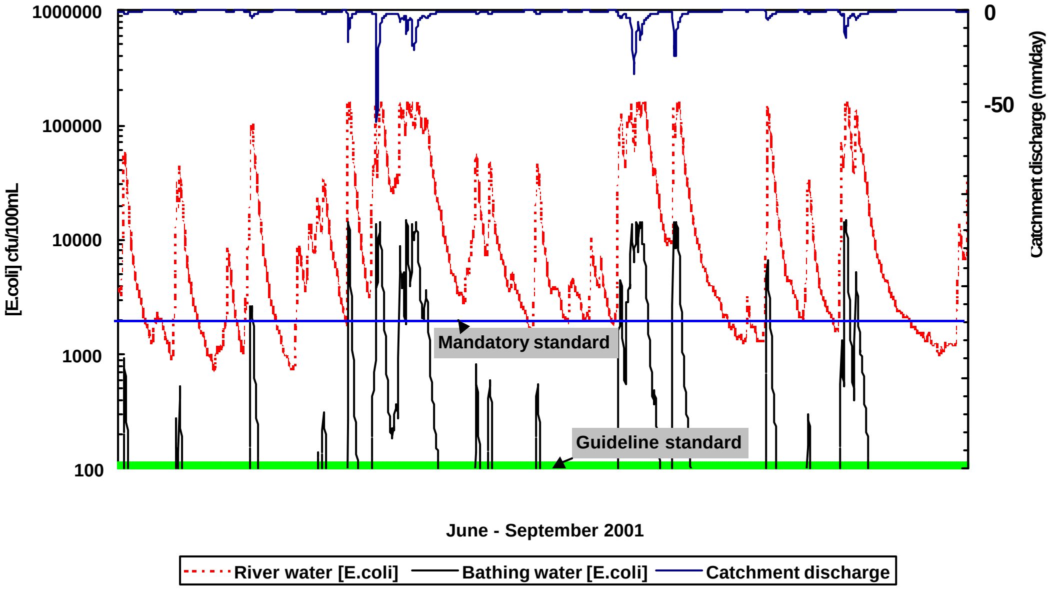

Figure 2. Dynamic simulation of river and bathing water quality, for Irvine river and beach.

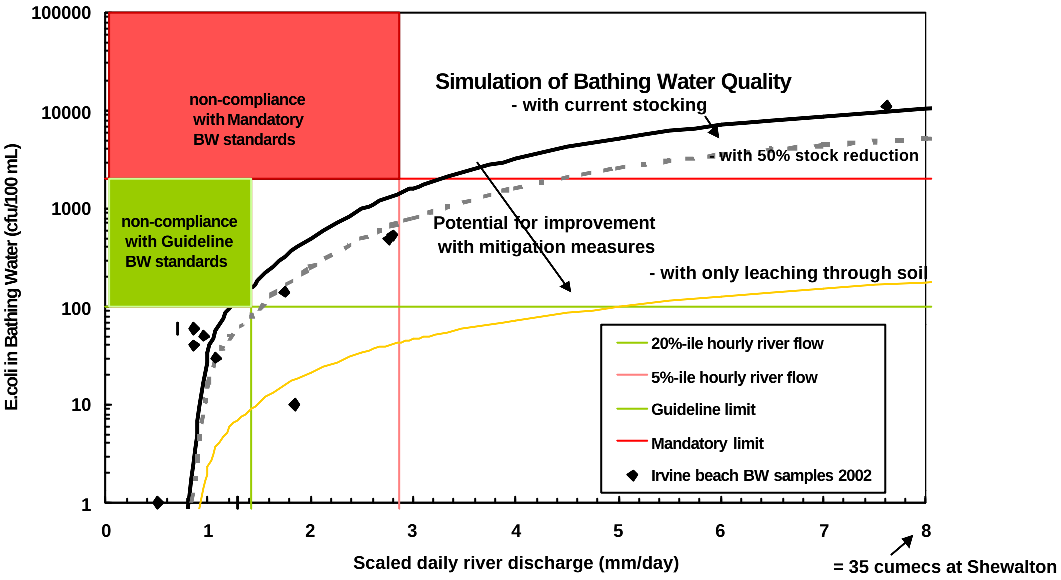

Figure 3. Predictions of Bathing Water Quality and potential effects of stock reduction And mitigation measures.

for the Killoch Burn, a sub-catchment of the Cessnock water, collected by CREH/MLURI on 1 July (Edwards, A., personal communication). Also shown are fits of PAMIMO-C data (Lewis et al., 2003) to equation (1) as well as output from an extended data run of the soil transport model, using field plot scale conditions representative of the soils and climatic conditions in the catchment (McGechan et al., 2003). A fit of these simulation output data to equation (1) was not possible, so a polynomial fit is shown.

PREDICTION OF BATHING WATER QUALITY

Input and parameter values for the spreadsheet model are given in Table 2 and further details are in Vinten et al., 2003.The model was run using the river transport calibration (event data) and hourly data from SEPA’s Newmilns gauge, for the period June-September 2001. Figure 2 gives an example of hourly output for the default stocking density for the Cessnock Water catchment (that for 11th June 2002). To obtain a more general picture, the compliance frequency can be linked to observed 5%-ile and 20%-ile data for river discharges. Figure 3 shows the relevant percentile lines for the scaled hourly discharges of the River Irvine at Shewalton for summer 2002, as well as 80%-ile and 95%-ile lines for microbiological compliance of bathing water, and the prediction of Irvine Beach Bathing water quality, based on the **river transport model** (using the event data)**, the soil transport model** and on **PAMIMO-C** lumped river calibration model, assuming June 2002 stocking density. If the model line transgresses into the darkly shaded area, this implies mandatory failure and if into the lightly shaded area, guideline failure. The actual microbiological sample data (faecal coliforms) for Irvine Beach in summer 2002 are also shown. A reasonable fit is evident, although there is some tendency to under-predict faecal coliform concentrations at intermediate flows. The dotted lines show the effect of reducing stocking density by 50%.

These simulations clearly show that there is much more scope for improving bathing water quality at Irvine Beach by using catchment mitigation measures such as buffer strips, contour cultivations, off-stream watering of livestock, grassed surface drainage channels, covering of middens, controlled walkways for cattle, than by reducing stocking level.

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Table 2. Parameters used in model (see Vinten et al., 2003 for details)

Variable	Description	value	Notes
k_{sea}	die-off rate in sea water (d^{-1})	4.6	Milne et al., 1986
T_{sea}	mean travel time from estuary to bathing water sample site on beach (d)	1	Note 1
$D_{es,min}$	Specific discharge of river at estuary at which river flow begins dilute salinity of bathing water sample (mm d^{-1})	0.7	
a_{dil}	Slope for dilution calculation of seawater by river water (d mm^{-1})	-0.043	
$D_{es,max}$	Scaled discharge of river at estuary at which river flow causes 50% dilution of salinity of bathing water sample (mm d^{-1})	12.5	
k_{sed}	sedimentation rate in river (d^{-1})	0.2	Tian et al., 2002
k_{fresh}	die-off rate in freshwater (d^{-1})	0.25	Evison et al., 1989
a_{trav}	travel time at unit scaled discharge d/(mm d^{-1})	1.25	note 2
p_{fast}	proportion of faecal indicator inputs in fast die-off pool	0.95	Vinten et al., 2002
k_{fast}	die-off rate in landscape of fast die-off pool (d^{-1})	0.27	
p_{slow}	proportion of faecal indicator inputs in slow die-off pool	0.05	
k_{slow}	die-off rate in landscape of slow die-off pool (d^{-1})	0.06	
G_{sheep}	Sheep E.coli production (cfu d-1)	3.7×10^{10}	Lewis et al., 2003
G_{lambs}	Lamb E.coli production (cfu d-1)	1.5×10^{10}	
G_{cows}	Cow E.coli production (cfu d-1)	2.1×10^{10}	
G_{calves}	Calf E.coli production (cfu d-1)	1.0×10^{10}	

1. optimisation of correlation between hourly river discharge and bathing water salinity
2. based on comparison of scaled hydrographs at Shewalton (estuary) and Newmilns subcatchment