An Operational Model for Managing the Effect of Land Treatment of Wastewater on Groundwater Quality

V. J. Bidwell

Lincoln Ventures Ltd, P O Box 133, Lincoln, New Zealand (bidwellv@lincoln.ac.nz)

Abstract Some land uses, such as land treatment of wastewater, could be operated for protection of the underlying groundwater if appropriate monitoring information were available. It is suggested that leachate quality in the vadose zone be monitored for operational management, by means of lysimetry, in preference to observations of groundwater quality with transport lag of months or years. Leachate data comprise values of solute concentration and associated increments of soil drainage flux, often collected at irregular time intervals, which are highly variable in space and time. These characteristics pose a data processing problem for operational management analogous to the requirement for the techniques of statistical process control in the manufacturing industries. For credible management of potential environmental effects, it is desirable that the quality assurance technique is based on concepts of physical processes which can be openly debated in terms of assumptions and model parameter values. This paper describes a data processing method based on one-dimensional solute transport through the vadose zone to the groundwater surface and subsequently by streamtubes in the groundwater to the designated target region. Smoothing of the leachate data, for real-time comparison with maximum allowable values, is governed only by longitudinal dispersion within the vadose zone and streamtubes. The concept of streamtubes without transverse dispersion addresses issues of equitable use of allowable aquifer contamination by land use managers. The computational algorithm for continual updating of management information is derived from the mixing cell concept for simulating dispersion. A demonstration example is presented using data on nitrate-N concentration and drainage flux of leachate from land treatment of meat processing wastewater, for feasible values of dispersivity in the vadose zone and underlying aquifer.

Keywords: Groundwater protection; Environmental quality; Management

1. INTRODUCTION

The application of wastes onto land, in Australia and New Zealand, has been recognised as an environmentally sound method of disposal, nutrient recycling, and water quality protection [Cameron et al., 1997]. However, there are potential environmental problems if these treatment systems are not carefully managed, and Bond [1998] identifies 3 key limitations to sustainability of land application of effluents: excessive nitrate leaching to groundwater, salinity, and soil sodicity. Management of nitrate leaching is the focus of the model presented in this paper.

Bidwell [2000a] addressed the operational management of the effect on groundwater quality of nitrate leaching from land treatment of meat-processing waste, by considering the soil-based treatment zone as a monitored process. Leachate quality and quantity was monitored, just beneath the soil zone, in preference to the underlying groundwater, because of the delay caused by transport through the vadose zone. The resulting leachate concentration data, in unprocessed form, were found to be unsuitable for operational management purposes because of their variability. The requirement for further data processing was recognised as being similar to the purpose of statistical process control (SPC) for quality assurance in the manufacturing industries.

A single mixing-cell model, to represent advective-dispersive (A-D) transport through the vadose zone, was shown to be mathematically equivalent to the exponentially-weighted-moving-average SPC technique for uneven sampling intervals. This model was extended [Bidwell, 2000b] to a multiple-cell computational method that accurately simulates A-D transport and equilibrium sorption in the vadose zone. The mode of application is to produce, for each new set

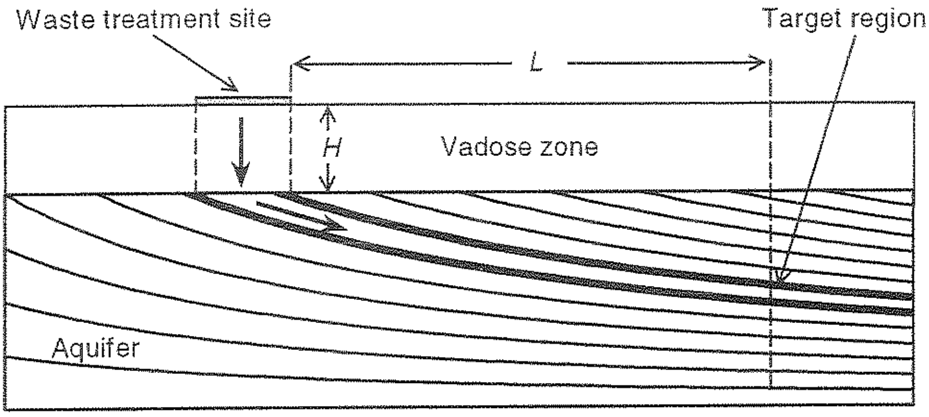

Figure 1. The streamtube concept of leachate transport from a waste treatment site.

of leachate concentrations and cumulative flux increments, a real-time forecast of the concentration effect at entry to the groundwater surface. These forecasts of expected environmental effect constitute a smooth, unambiguous, information signal for operational management.

This paper describes an extension of the approach to include transport within the underlying aquifer up to a target region for which contamination effects are being considered.

2. GROUNDWATER PROTECTION STRATEGY

Figure 1 shows a 2-D view of a waste treatment site in relation to the groundwater at a depth H below the ground surface and a target region within the aquifer at a distance L from the site boundary, along the principal direction of groundwater flow. This target region may, for example, be a location for which the groundwater quality is to be protected for abstraction of drinking water. The distance L may be of similar magnitude to the horizontal dimensions of the waste treatment site.

By following the approach of Frind and Matanga [1985], the transporting water flow within the aquifer is considered, at long time scales, to be at steady state. This assumption enables the advantages of the use of stream functions to describe the transport process. As a conceptual departure in the present paper, the stream functions are considered to have a fixed pattern but with intermittent inputs of recharge which transport incoming contaminants. The justification for this approach is that contaminant transport is governed by cumulative recharge flux and transport distance, rather than time-dependent velocity fields.

The streamlines plotted on the cross-section of the simplified aquifer (Figure 1) indicate the water flux from sources of recharge, either vertically from drainage through the vadose zone or from upstream sources such as river recharge. The spacing between the streamlines represents the relative flux contribution. Thus, the leachate flux from the waste treatment site is represented by the bold streamlines in Figure 1. In three dimensions, the leachate flux is bounded by a streamtube with cross-sectional shape determined by the source area.

The proposed strategy for protecting the target region from the waste treatment site is to disallow any assumption of dilution of the leachate stream by recharge from other sources, in effect to assume no contaminant dispersion across streamtube boundaries. The effect on management of leachate quality, monitored just beneath the soil zone, is to require the time-averaged mean contaminant concentration to not exceed that specified for the target region. However, temporal variations in monitored concentrations may be smoothed by longitudinal dispersion, and sorption processes, within the vadose zone and aquifer. This approach allows sustainable use of the contaminant transporting capacity of the aquifer under a regime of incremental development of land use activities which generate contaminated leachate.

3. TRANSPORT PROCESSES

Contaminants leached from the active soil zone of the waste treatment site are monitored by lysimeters which provide concentration data at varying intervals of cumulative drainage flux I, depending on the timetable of sample collection. These data describe the leachate concentration history of an area A of waste treatment site. The total leachate flow Q is:

$$Q = A\frac{dI}{dt} \tag{1}$$

According to the streamtube concept (Section 2), Q is the same at every location s along the streamtube from waste site to target region, at any one time. Advective-dispersive transport of the contaminant solute, with concentration c at location s, is described by:

$$\theta A\frac{\partial c}{\partial t} + Q\frac{\partial c}{\partial s} - \theta AD\frac{\partial^2 c}{\partial s^2} = 0 \tag{2}$$

for which the transporting water fraction θ, dispersion coefficient D, and streamtube cross-sectional area A may vary with location s. The dispersion coefficient is assumed to be related to the local flow velocity V as:

$$D = V\lambda \tag{3}$$

where λ is the local value of dispersivity. By changing the time index variable t to I by use of:

$$\frac{\partial c}{\partial t} = \frac{\partial c}{\partial I}\frac{dI}{dt} \tag{4}$$

then from (3) and (4) the advection-dispersion equation (2) may be written as:

$$\theta\frac{\partial c}{\partial I} + \frac{\partial c}{\partial s} - \lambda\frac{\partial^2 c}{\partial s^2} = 0 \tag{5}$$

Equilibrium sorption processes may be included in (5) by multiplying the transporting water fraction θ by a "retardation factor" R [e.g., Jury et al., 1991; p.227]. The probability density function of water flux I to transport solute a distance S is:

$$f(I,S) = \frac{S}{I\sqrt{4\pi\lambda I/R\theta}}\exp\left[-\frac{(S - I/R\theta)^2}{4\lambda I/R\theta}\right] \tag{6}$$

which has mean $SR\theta$ and variance $2S\lambda(R\theta)^2$.

4. MIXING-CELL ANALOGUE

There is a long history [Bidwell, 2000b] of simulating the advective-dispersion process (6) by means of a series of conceptual cells, within each of which solute is instantaneously mixed as it is transported. Figure 2 illustrates this conceptual representation of the processes shown in Figure 1.

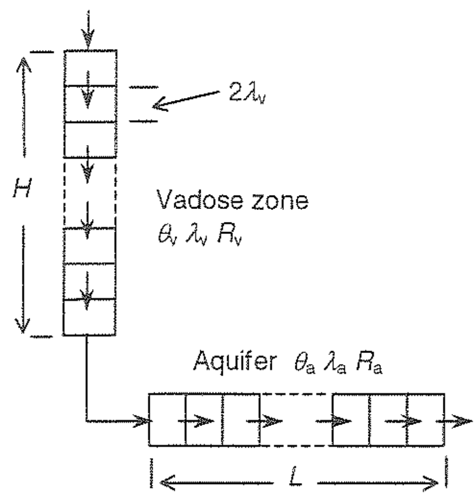

Figure 2. Mixing-cell model of advective-dispersive transport in the streamtube.

The number of cells n is determined from the dispersivity λ and the distance S at which prediction is required, according to:

$$n = \frac{S}{2\lambda} \tag{7}$$

Each cell has an equivalent water volume of $2\lambda\theta R$, and the dynamic response (transfer function) of the series of cells has the same mean and variance as (6). It is theoretically possible for the parameters λ, θ, and R to vary from cell to cell, if there is sufficient data support. In this case, the response of the mixing-cells-in-series to solute flux inputs requires the use of mathematical software for analysis of complex linear systems [e.g., Bidwell, 1999]. For a model with the same lumped values of these parameters in all cells, a simpler computational algorithm [Van der Molen, 1973] is available.

For the purpose of operational management of a waste treatment site, the simpler algorithm of the lumped model is better suited to implementation of the technology. However, the values of θ and λ are likely to be quite different between the vadose zone and aquifer. A lumped model can be used for each zone, but the connection between them needs to be addressed. The reason is that the computational algorithm implicitly assumes that solute flux inputs to the first cell are a series of pulses with constant value over the duration of each drainage increment dI. The output from the last cell of the vadose zone model, which becomes the input to the first cell of the aquifer model, is a series of instantaneous values of a continuous curve. The assumption incorporated into the present model is that these values are a good approximation to input pulses to the aquifer model, given the degree of smoothing of the treatment site signal by the vadose zone model.

5. COMPUTATIONAL METHOD

Monitoring of a waste treatment site may be done, for example, by means of soil monolith lysimeters from which leachate is collected at time intervals of about one month. The leachate volume collected at the kth monitoring event is expressed as a drainage interval $dI(k)$, and the corresponding bulk concentration $c_{in}(k)$ is considered to be constant during $dI(k)$.

The effect of each leachate event $\{c_{in}(k), dI(k)\}$ on the solute concentration profile within the vadose zone and aquifer streamtube can be expressed in terms of the solute concentration for the rth cell of the analogue model as [Bidwell, 2000b]:

$$\alpha(k) = \frac{dI(k)}{2\lambda R\theta}$$

$$c_r(k) = \exp[-\alpha(k)]\sum_{m=0}^{r-1}\frac{\alpha(k)^m}{m!}c_{r-m}(k-1) \quad (8)$$

$$+\left\{1-\exp[-\alpha(k)]\sum_{m=0}^{r-1}\frac{\alpha(k)^m}{m!}\right\}c_{in}(k).$$

The formula (8) is unconditionally stable for any magnitude of drainage interval and assures conservation of solute mass. This property means that predictions can be calculated for any interval, in one step, without the need to simulate every intervening state.

The algorithm (8) is first applied to the $n_v=D/2\lambda_v$ cells of the vadose zone model, and then the solute concentration of the last cell (n_v) is used as the input to the $n_a=L/2\lambda_a$ cells of the aquifer model.

In order to estimate the ultimate effect of each leachate event at the target region, the input $c_{in}(k)$ must be transported through the vadose zone and aquifer models with a water flux $dI'(k)$ given by:

$$dI'(k) = HR_v\theta_v + LR_a\theta_a - dI(k). \quad (9)$$

This constitutes a real-time forecast, and the solute concentration $c'_{in}(k)$ of the transporting flux increment $dI'(k)$ is not known. One arbitrary rule is to use the current mean solute concentration within each model so that:

$$c'_{in}(k) = \frac{1}{n}\sum_{r=1}^{n}c_r(k-1). \quad (10)$$

The operational effect of (10) is that occasional values of monitored leachate concentration above the maximum allowable value (MAV) are less acceptable if there is a recent history of elevated values, given that the forecasted target region concentration must not exceed the MAV.

6. DEMONSTRATION EXAMPLE

An example of the computational procedure (8)-(10) is demonstrated with a series of flux-averaged nitrate-N concentration data, collected from four monolith soil lysimeters used for monitoring a land treatment site for meat-processing wastewater [Bidwell, 2000a]. These data were collected at approximately monthly time intervals during a 2-year trial for which the average drainage was 400 mm/y. The record (Figure 3) includes a significant "contamination event" when the treatment area was temporarily overloaded.

For the purpose of this demonstration the assumed parameter values are: H = 10 m, λ_v = 0.5 m, θ_v = 0.1, L = 100 m, λ_a = 5 m, θ_a = 0.3, and R = 1 for nitrate. The assumed values of longitudinal dispersivity are 0.05 times the travel distance. Therefore, from (7), each of the mixing cell models has 10 cells. The initial nitrate-N concentrations in the cells were set to the flux-averaged value of the monitored data for the first year, of 4.4 g/m^3. This example was implemented on an Excel spreadsheet. Figure 3 shows the monitored leachate concentrations near the ground surface, in relation to the cumulative drainage flux, and the corresponding forecasts of solute concentration at the bottom of the vadose zone and at the target region within the aquifer.

7. DISCUSSION

The monitoring data (Figure 3) are highly variable and ambiguous for decision-making, because a new value above the MAV may be either a random effect or the precursor of a failure in the treatment facility. However, forecasts of the nitrate-N effects at the target zone in the aquifer, from the continually updated cell model, exhibit a smooth response. The event with peak of 76 g/m^3 in the monitored data, shows a steady rise to about 9 g/m^3 for the target region forecast. This value is near the MAV and of sufficient concern to warrant consideration of the cause. An earlier indicator of possible system failure is provided by the forecasts at the groundwater surface immediately below the treatment site. These values are the forecasted output from the vadose zone section of the model. They are still unambiguous and would be useful as

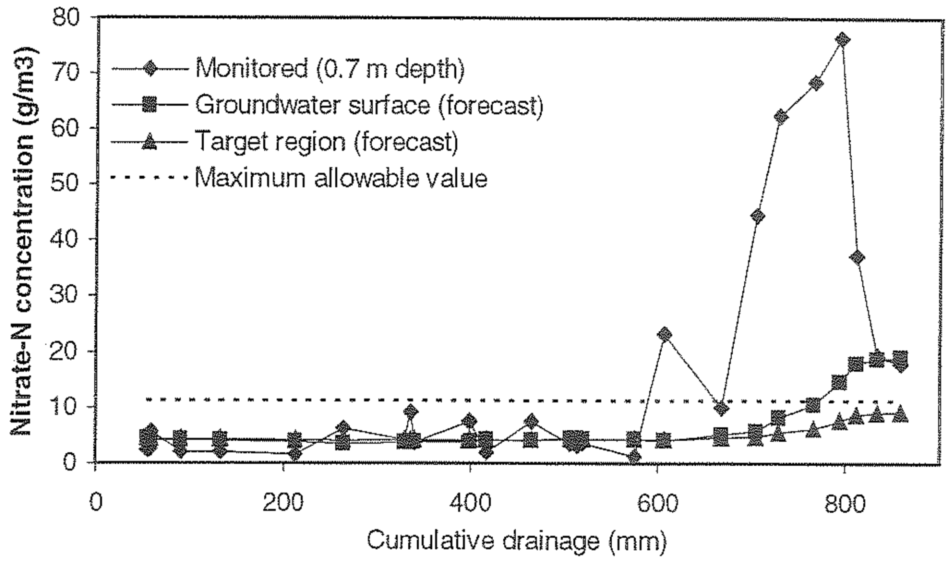

Figure 3. Forecasts of nitrate-N concentrations associated with monitored leachate data from a waste treatment site

a "first alert" for operational management. The target region forecasts would then have value more as a record of performance of the treatment facility in terms of potential effects.

8. CONCLUSIONS

The model described in this paper provides a method of smoothing data, on a real-time basis, from monitoring of solute concentration of leachate from land treatment of wastes. The conceptual basis of advective-dispersive solute transport does not allow for any transverse dispersion, but this departure from reality is a conservative assumption that supports sustainability of groundwater quality under changes in land use. The processed data are a credible and unambiguous signal of the likely effects on groundwater quality, and can support operational management of the waste treatment site. The smoothing algorithm is a linear system model of advection-dispersion with equilibrium sorption in porous media, which can be operated as a real-time forecasting procedure within spreadsheet software.

9. ACKNOWLEDGEMENTS

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