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EGPE[®]: A computer decision-support tool for the Eco-management of animal manure as agricultural fertiliser

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Abstract: EGPE[®] is an object-oriented model, which estimates the environmental distribution of contaminants within different environmental compartments and the specific risk associated with these distributions and final concentrations. This model evaluates environmental impacts related to: a) the use of sludge/manure as fertiliser, and b) direct discharges of slurry or effluents from treatment plants to water streams. The program takes into account the physico-chemical interaction processes occurring after the discharge, estimating the downstream evolution of the following parameters: dissolved oxygen, organic nitrogen, ammonia, nitrites and nitrates. Within the estimations it is also included the environmental risk for the aquatic communities related to quantified pollutants and the overall toxicity of the discharge measured using a direct toxicity assessment. For metals, the risk for soil and ground water pollution is also calculated. The risk assessment methodology has been based on the European Union framework for the risk assessment of chemicals, and also additional criteria from other organisations and the results of literature searches. Environmental and climatological conditions are crucial for the estimations. A set of default values for central Spain conditions is offered. To calibrate the model to different conditions, a simple downstream monitoring of an urban discharge should be performed.

Keywords: Animal waste; Manure management; Fertilizers; Environmental Risk Assessment; Modelling.

1. INTRODUCTION

Nutrients leaching and run-off are considered the main water pollution problem related to the agricultural use of manure [Vagstag et al, 2000]. But additionally, other constituents of animal manure can be of environmental relevance. The high level of organic matter and the presence of micropollutants including, heavy metals, inorganic metabolites produced by the degradation of nitrogen (ammonia, nitrites and nitrates), phenolic compounds, or even the presence of disinfectants and veterinary products represent additional risks. This unexpected complexity [Fernández et al, 1995 Belin et al, 2000] must be considered before a sustainable application of animal manure in agriculture.

EGPE is a system dynamic model based on the Forrester's diagram included in Figure 1, which considers different environmental reservoirs and compartments, taking into account their relations, interactions and fluxes through them. Ecological Risk Assessment is considered nowadays the best alternative for the inclusion of scientific support in decision-making processes [Tarazona, 1998]. The model applies basically the risk characterisation approach developed for general chemicals in the EU [EC, 1996]. For each contaminant, the Predicted Environmental

Concentration (PEC), at each relevant environmental compartment (surface water, groundwater, soil), is compared to the ecologically-based Predicted Non Effect Concentration (PNEC); if the concentration of a contaminant exceeds its PNEC, a potential risk is identified.

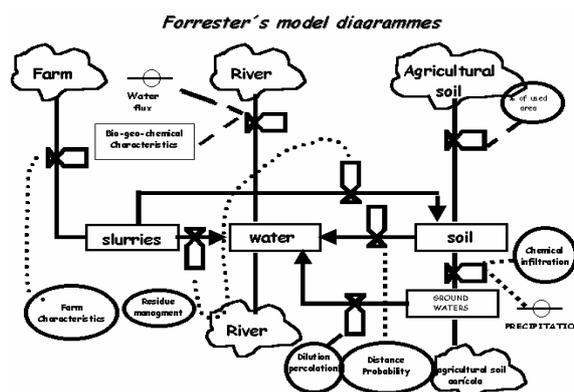


Figure 1. Environmental reservoirs and compartments showing the flux lines among different compartments

To determine/estimate the risk of each manure emission/application, a set of PEC/PNEC ratios is estimate by the model using the available information. Climatological and pedological conditions must be accounted as part of the Environmental Impact Assessment study. The

programme has been calibrated and validated for the Central Spain, but it can be calibrated for any other area, just accounting different water, soil and climatological conditions. Numeric results indicate which parameters represent an unacceptable risk, and the graph shows the evolution of the parameters downstream (organic nitrogen, NH_4^+ , NO_2^- , NO_3^- and O_2), according to the different pollutants added/discharged in the scenarios. The model covers emissions of both, raw and treated manure, and its the use as fertiliser in agriculture. Several emissions/application in the same water catchment area can be integrated, allowing individual and regional estimations. More detailed information about windows/screens, inputs and some examples are showed in Vega et al. [2001].

2. SCIENTIFIC BASIS OF THE MODEL

2.1. Exposure scenarios

The exposure scenario represents a catchment area with several rivers. Each river is treated individually, accounting for both, direct emissions to the water and applications as fertiliser in the catchment under study. Complex situations (a river and several tributaries) are covered modelling individually each tributary and incorporating the information in the main water body. Homogeneous conditions and instantaneous distributions are assumed within each zone. First order kinetics are assumed for estimations, but modifications in all calculating parameters considered are allowed.

Two types of contaminant sources have been considered, depending on the way it is released to the environment: a) direct emissions: discharged

directly in the river and b) diffuse emissions: due to agricultural applications as fertilizers. Each case must be treated using a specific scenario. The data needed to evaluate the environmental risk assessment for both scenarios, direct and diffuse sources, are:

- In relation to the sludge characteristics: effluent flow and sludge composition (concentration of organic matter, organic nitrogen, ammonia, nitrites, nitrates, copper, zinc, lead, nickel, surfactants and the whole toxicity) and,
- In relation to the catchment and type of application: annual rainfall, catchment surface, surface of the fertilized area, distance to the river and application rates.

For direct emissions, the user only needs to identify the zone in which the effluent is discharged: effluent river concentration at this initial zone is set on the basis of effluent/river flow ratio. For agricultural applications the amount reaching the river is set by a set of default values covering run-off and application drift at different distances. The user is requested to set on a chart of the catchment area, the area in which the manure will be applied, establish the potentially affected zones following the run-off flow, and set the percentage of the catchment area for these zones, at pre-set distances, which will be affected by the application. Default values for metal mobility in soil, climatic conditions, and dilution allows the estimation of the metal concentrations in (agricultural) soil and water. Several factors allow the consideration of the local factors such as groundwater recharge (Table 1).

Table 1. Parameters required for running the model in both scenarios: direct emissions (D.E.) and Agricultural Applications (A.A.) and default values included after the model calibration.

River characteristics	Default value	Explanation or Reference
River longitude (km)	10	
River flow (m^3/seg)	0.3	
Number of zones	(25950 m^3/day)	
pH	50	Default values suggested after the calibration exercise
T ^a (°C)	7.0	
Hardness (mg $\text{CO}_2/\text{ca/l}$)	20	
DQO input (kg/day)	100	
Organic nitrogen input (g/day)	625 (100U)	
Theoretical Dissolved Oxygen (mg/l)	2500 (1U)	
	9	
Transformation rates		
Organic matter degradation	0.022	
Aeration	0.55	
Organic $\text{N}_2 \rightarrow \text{NH}_3$	0.2	Average values obtained for central Spain conditions
$\text{NH}_4 \rightarrow \text{NO}_2$	0.1	
$\text{NO}_2 \rightarrow \text{NO}_3$	0.1	
NO_3 absorption	0.05	
Soil infiltration rates		
Cu	0.1-0.5 %	Domergue and Vedy, 1992
Zn	0.1-2 %	
Precipitation (mm/year)	700	EC, 1996
Infiltration rate	0.25 %	EC, 1996
Dilution factor	10	EC, 1996
Probability factor	1	-
Run-off/Drift rates to the river		
0-2 m	5.5 %	Default values suggested after the literature search
2-8 m	0.8%	
8-15 m	0.4%	
15-40 m	0.1%	
40-100 m	0.003%	
>100 m	0%	

2.2. Mineralisation modelling

The decrease in the river dissolved oxygen due to mineralisation of organic matter and organic nitrogen mineralisation producing the emergence of ammonia, nitrites and nitrates are modelled. Evolutions are modelled versus distance to the dumping area following Tarazona and Muñoz [1989]. After discharging, the slurry components are transformed into the Chemical Oxygen Demand (COD) and equivalent-N, according to the follow equations (1) an (2):

$$(1) \text{ Input COD (COD}_i\text{)} = f([\text{organic matter}]; \text{effluent flow}) = \text{Effluent flow} * \text{organic matter} * 100/625$$

$$(2) \text{ Input equivalent-N} = f([\text{organic N}]; \text{effluent flow}) = \text{Effluent flow} * \text{organic N}_2 * 1000/2500$$

The values 625 and 2500 included in these equations reflect the characteristic of the effluent used for the calibration (Table 1). The use of man-equivalent units for these values is recommended although other units can be used (the values for the rates will also depend on the units selected for this transformation). These equivalents represent relative values allowing the comparison of sludge and urban effluents characteristics. This transformation has been included to facilitate the calibration of the model by the user monitoring the effect of an urban effluent expressed as habitant-equivalent-discharge. The dissolved oxygen concentration [O.D.] is modelled as a function of the decrease produced by the COD degradation (3) and the increase related to the aeration (4), where:

$$(3) \text{ O}_2 \text{ depletion due to oxidation of organic matter: } \nabla[\text{O.D.}]_i = f([\text{COD}]_{i-1}; \text{Degradation Rate}]$$

$$(4) \text{ O}_2 \text{ increment due to aeration processes: } \Delta[\text{O.D.}]_i = f([\text{O.D.}]_t - [\text{O.D.}]_{i-1}); \text{Aeration Rate}]$$

The $[\text{O.D.}]_t$ represents the theoretical concentration in the zone assuming no discharges. Both ratios can get different vales for each zone. DR is also used to estimated the decrease of the COD from zone i-1 to zone i. Additional COD inputs can be considered in each zone, and therefore the final COD concentration in an specific zone “i” will depend on (5):

$$(5) [\text{COD}]_i = f(\text{COD}_{i-1}; \text{input COD}_i; \text{DR}_{i-1}), \text{ where “DR”, Degradation Rate}$$

Each process has a specific rate (related to a length unit), which is also estimated during the calibration exercise. Transformations due degradation rates are taken into account for the

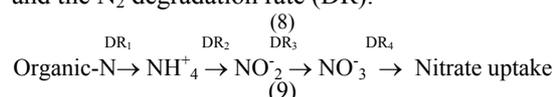
calculations of the final COD in each zone. The Total COD in a specific zone “i” will be(6):

$$(6) \text{ Total COD}_i = \text{COD}_{i-1} * (1-\text{DR}_i) + \text{input COD}_n$$

In the same way, the final $[\text{O}_2]$ in a specific zone “i” will be (7)

$$(7) [\text{O}_2]_i = [\text{O}_2]_{i-1} - (\text{Total COD}_i * \text{DR}_i) + ([\text{O}_2]_t - [\text{O}_2]_{i-1}) * \text{DR}_i$$

Nitrogen mineralisation is represented by a complex process characterised by the conversion of organic nitrogen (e.g. amino acids) into ammonia, and the oxidation of ammonia into nitrite and nitrate, which finish with the uptake of nitrate by living organisms. The process occurs before and after emission/application. The transformations inside the sludge are accounted by the manure characterisation. The evolution inside the river (8,9)is covered by three ratios (organic-N to ammonia(10); ammonia to nitrite(11); nitrite to nitrate (12)) regulated by the level of dissolved oxygen, the nitrate uptake ratio and the N_2 degradation rate (DR).



$$[\text{Total org-N}]_i = [\text{org-N}]_{i-1} * (1-\text{DR}1_i) + [\text{input org-N}]_i$$

$$[\text{NH}_4^+]_i = [\text{NH}_4^+]_{i-1} * (1-\text{DR}2_i) + [\text{input-NH}_4^+]_i + (\text{N}_2 * \text{DR}1_n)$$

$$[\text{NO}_2^-]_i = [\text{NO}_2^-]_{i-1} * (1-\text{DR}3_i) + [\text{input-NO}_2^-]_i + (\text{NH}_4^+ * \text{DR}2_n)$$

$$[\text{NO}_3^-]_i = [\text{NO}_3^-]_{i-1} * (1-\text{DR}4_i) + [\text{input NO}_3^-]_i + (\text{NO}_2^- * \text{DR}3_n)$$

The model estimates the concentration in each zone assessing the transformations occurred in the previous zone and the new inputs, keeping the total nitrogen balance. No time evolutions are considered. For continuous emissions the model estimations represent the expected concentration (average, maximum or minimum depending on the input data on flow and effluent composition) while for episodic concentrations the predictions represent the highest (lowest for dissolved oxygen) values expected in that zone.

2.3. Effect assessment and risk characterisation

The effect assessment employs a deterministic approach. The Predicted No Effect Concentrations (PNECs) were settled as equal to a set of toxicity criteria recommended by different national or international organisations. These criteria can be easily modified to adapt the model to technical progress and/or particular local regulations. The default toxicity criteria have been selected from EIFAC (European Inland Fisheries Advisory Committee, FAO), the European Union

Table 2. PNECs default values and equations suggested for the determination of PNECs in soil and aquatic compartments, according to different criteria.

Parameters	Criteria for PNEC determination on Surface water		Soil (kg/ha-year)	
	PNEC	Source	PNEC	Source
D.O. (mg/l)	5	EIFAC*	-	-
Nitrites (mg/l)	0.06	EIFAC*	-	-
NH ₄ (mg/l)	0.025	EIFAC*	-	-
Cu (µg/l)	$e^{(0.8545 \cdot (\ln(\text{hardness}) - 1.465) \cdot 0.960)}$		12	EU
	Hardness ≤ 10 mg/L CaCO ₃	5		
	10 ≤ Hardness ≤ 50 mg/L CaCO ₃	22		
	50 ≤ Hardness ≤ 100 mg/L CaCO ₃	40		
	mg/L CaCO ₃ ≥ 100	120		
Zn (µg/l)	$e^{(0.8473 \cdot (\ln(\text{hardness}) + 0.761) \cdot 0.986)}$		15	EU
	Hardness ≤ 10 mg/L CaCO ₃	30		
	10 ≤ Hardness ≤ 50 mg/L CaCO ₃	200		
	50 ≤ Hardness ≤ 100 mg/L CaCO ₃	300		
	mg/L CaCO ₃ ≥ 100	500		
Pb (µg/l)	$e^{(1.273 \cdot (\ln(\text{hardness}) - 4.705) \cdot 0.791)}$		80	EU
	50			
Ni (µg/l)	$e^{(0.846 \cdot (\ln(\text{hardness}) + 1.1645) \cdot 0.96)}$		3	EU
	Hardness ≤ 50 mg CaCO ₃	50		
	50 ≤ Hardness ≤ 100 mg/L	100		
	100 ≤ Hardness ≤ 200 mg/L	150		
	mg/L CaCO ₃ ≥ 200	200		

and the USEPA and are summarised in Table 2. EIFAC values were selected for setting the criteria for dissolved oxygen, unionised ammonia and nitrites in surface water. US EPA Ecotox Threshold values (1996a and 1996b) were selected as toxicity criteria for metals in surface water, these criteria are expressed as a function related to water hardness (13):

(13) Criteria = $e^{(m[\ln(\text{hardness})] + bc)} \cdot CF$,
 where m: slope; bc: y intercept and CF: conversion factor, ratio of total recoverable concentration to dissolved concentration

The European Union maximum metal concentration values established for the application of sludge were considered as criteria for metals in soil. The application factors recommended by the EU for the derivation of PNEC values [EC, 1996] were used to establish the criteria for the direct toxicity assessment. The risk is estimated comparing the model-calculated PECs with the PNECs (default toxicity criteria or user values). PEC/PNEC ratios higher than 1 represent a potentially unacceptable environmental risk. For dissolved oxygen (lowest PEC values represent higher risks) an equivalence between the estimated concentration and the expected risk was established using an expert

panel. This equivalence was integrated within the computer programme in order to express the risk of oxygen deficiency in the standard way, PEC/PNEC ratio where 1 represents the acceptability threshold and the higher the ratio the higher the risk.

2.4. Model calibration

The degradation and aeration rates can be set, to these particular conditions, after a monitoring study in an area following a discharge of an urban or equivalent effluent. To offer default values, a calibration exercise was conducted using the characteristics of middle size rivers (main tributaries of Tajo River) in central Spain [Muñoz et al., 1988; Tarazona and Muñoz, 1988; 1989]. Similar comparisons were performed among rivers representing equivalent situations. The averaged rates included as default values are presented in Table 1. The specific calibration to the different conditions of each area is strictly recommended, and is essential to get validated values. Regarding the mobility of metals in soil and the potential for groundwater pollution, default values were also selected. The values recommended after the literature search appears in Table 1.

Default conditions associated to the re-emergence of groundwater, as source for surface water, were

selected from the generic scenario developed for the risk assessment of chemicals in Europe [EC, 1996]. Additional refinement of the following is allowed by the model combining three specific parameters: a) Infiltration rate (annual percentage of renewal of an aquifer with water polluted by manure), b) Dilution factor (percentage of ground water that emerge/return to superficial waters, i.e., into spring waters) and, c) Probability factor (capability of the contaminant to reach superficial waters through drift and run-off processes).

For agricultural applications the potential for surface water pollution is related to drift during application and run-off. After a literature search [Hall et al., 1992; Ganzelmeier, 1995; Steele, 1995; Behrendt 1996; EC, 1996; and different Internet access sources] a set of selected default values for applications at different distances of the water stream were selected. The applied values are also presented in Table 1 and were selected to represent realistic worst-case conditions in central Spain. The user can modify all default values.

3. CONCLUSIONS

EGPE is a system dynamic model that not only estimates distributions of contaminants within different environmental compartments, but also assess the potential environment risk of these distributions. The model includes default values based on the agricultural conditions of central Spain and regulatory/scientific recommendations of selected recognised organisations (European Union, US EPA; FAO) or selected after a literature search. All default values can be modified to adapt the model calculations to the real conditions. The set of required data has been minimised to facilitate the users' work. The model can be calibrated by a simple monitoring of the river downstream a known (urban effluent) discharge measuring dissolved oxygen, ammonia, nitrites and nitrates.

Model applications include:

- Predictive assessment the environmental risk of a real sludge discharge or agricultural applications
- Study of alternatives (e.g. level of treatment for direct discharges; rate and application area for the use as fertiliser)
- Evaluation of all farm and urban emissions in a river basin (main river and tributaries).
- Study of alternatives for river basin management (under a real situation, the model can estimate the contribution of each individual source and predict the expected

effects of adding/reducing discharges/applications)

The model combines simplicity and capability as decision-support tool. The use of single approaches, such as modelling the degradation on the basis of distance related rates [Tarazona et al., 1993], allows a simple in situ calibration. This calibration and basic information on the river, the catchment area and the sludge composition fulfil the requirements to run the model.

The main user of this model is expected to be the farm's or farmer association technical staff. They are not expected to have information on other nutrient loads (e.g. in urban and industrial effluents) located in the area, and therefore those factors requiring this information have been excluded from the model. The main exclusions are the risk of groundwater nitrate contamination and surface water eutrophication. Toxicity due to unexpected chemical can be included easily, using the metal or organic pollutant input systems, and selecting appropriate PNEC values for each pollutant. Direct toxicity assessment has proved to be an excellent parameter for the characterisation of these wastes [Fernández et al, 1995; Belin et al, 2000; Pablos, 2000]. This assessment covers those unknown toxic chemicals that can appear in the sludge including metabolic products, veterinary medicines, biocides, etc. Therefore, EGPE would provide additional information on how to handle the manure to avoid environmental risks associated to local management, especially on regards to those substances not included in legislation related to agricultural products.

Using generic values of sludge composition the model can be used as quantitative tool for the Environmental Impact Assessment of new farming projects.

4. ACKNOWLEDGEMENTS

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