CHAPTER 2. LITERATURE REVIEW

Banana plantation in the Chaguana river basin, Ecuador

Parts of this chapter were published in

Matamoros D. and Vanrolleghem P.A. (2001) Pesticide assessment of the banana sector in an Ecuadorian watershed. In: Proceedings 53rd International Symposium on Crop Protection. Gent, Belgium, May 8 2001. Med. Fac. Landbouww. Univ. Gent, 66(2b), 863-872.

Herrera P., Matamoros D., Espinel R., Cornejo M.P., Vanhuylenbroeck G., Van Biesen L., Cisneros Z., and Duque J. (2004). Information Use and Water Resources: Laws and Policies in Ecuador. *In* J.S. Wallace, P. Wouters and S. Pazvakavambwa (ed.) Hydrological information in water law and policy: current practice and future potential. UNESCO/WMO/HELP Programme, Kluwer International Publishers and National Water Law and Policy Series (*in press*).

2.1. CURRENT ECUADORIAN WATER QUALITY LEGISLATION

Although Ecuador has a water legal framework, the water resource usage has been traditionally conducted in an irrational way giving more emphasis to immediate needs than resource conservation. The current law enforcement is mainly interested in managing water supply while environmental protection is just beginning its first steps. In Figure 2.1, it can be seen that agricultural activities demand more water than the others. Thus, the probability to pollute water with agrichemicals is significant.
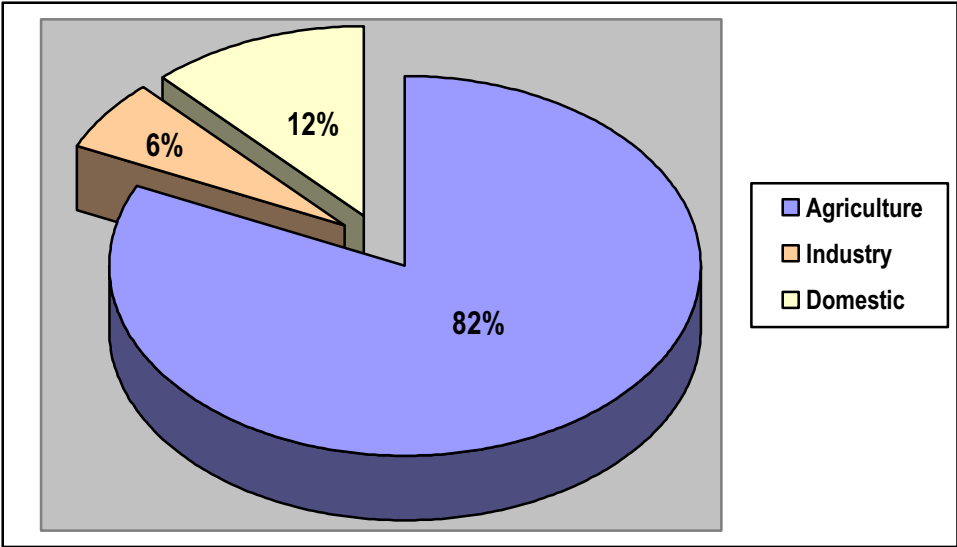
Figure 2.1. Water usage distribution in Ecuador after Herrera *et al.* (2004, *in press*)

Because of the demographic explosion, water demand generally puts more pressure on government to get faster solutions that sometimes do not necessarily involve environmental protection. As a result, many conflicts have arisen, dealing with the use of potentially polluted water in the lower parts of river basins.

Currently, there are several institutions that regulate water resources and this sometimes causes inter-institutional conflicts and regulation overlaps. Table 2.1 provides a brief summary of those institutions; a detailed list of institutions and conflicts can be found in Herrera et al. (2004, in press) and Herrera (2005, in preparation).

Table 2.1. **Some Ecuadorian institutions which regulate water resources (after Herrera *et al.* 2004, *in press*)**

Water issue	Regulator / Enforcer	Main Directive
Irrigation	National Water Resources Council (since 1994)	Water Law
Potable Water and Wastewater	Ministry of Environment	Environmental Management Law
	Ministry of Urban Development and Housing	Ministry Decree
	Municipalities	Municipal Regime Law
Surface Water and Groundwater Quality	Ministry of Environment	Environmental Management Law
	Municipalities	Municipal Regime Law
	Ministry of Agriculture	Law for Agrarian Development
	Ministry of Energy and Mines	Mining Law
		Environmental Regulations for Hydrocarbon Activities
		Law of Oil Fields
	Ecuadorian Navy	Code of Maritime Police
		General Law of Ports
	Ministry of Health	Health Code

As can be seen in table 2.1, the water quality issues are regulated by several directives. However, the Environmental Management Law is the main directive that precedes the others. This Law was published in December 2001 and replaced the old regulation "Law for Prevention and Control of Pollution" that was in rule since 1976.

The current law sets new permissible limits for environmental concentrations which are more rigorous than the old ones. However, Ecuadorian limits are still far less strict than the common standards applied around the world. The main reason for this weakness is that the Law was presented in public debates where several stakeholders made an opinion on what the limits should be. As expected, the stakeholders took sides on two groups:

- Society, ecologists, NGOs and some regulators asked for stronger limits in order to protect the environment and public health.
- On the other side, entrepreneurs and producers did not want an economic shock mainly caused by the implementation of controls to adjust current discharges to the new standards. The main argument was that the country was not in a good economic situation to handle that shock.

Therefore, the Ecuadorian Government that was aided by its consultants decided to establish a balance point based on both positions. Table 2.2 shows a summary of some environmental limits for wastewater discharges to a fresh surface water body, and table 2.3 shows the standards for surface water quality depending on the water resource usage.

Table 2.2. Some environmental standards for wastewater discharges to rivers

Variable	Maximum Allowable Concentration
Biochemical Oxygen Demand	100.00 mg/l
Chemical Oxygen Demand	250.00 mg/l
Total Solids	1600.00 mg/l
Total Suspended Solids	100.00 mg/l
Surfactant Agents	0.50 mg/l
Total Organochlorine Compounds	0.05 mg/l
Total Organophosphorus Compounds	0.10 mg/l
Total Pyrethroids	0.05 mg/l

Source: Ecuadorian Environmental Management Law (2001)

Table 2.3. Some environmental criteria for surface water quality

Variable	Maximum Allowable Concentration			
	Potential Use of Water Resource			
	Aquiculture [a]	Irrigation	Livestock	Recreation
Total Dissolved Solids	Not regulated	3000.0 mg/l	3000.0 mg/l	Not regulated
Surfactant Agents	0.50 mg/l	Not regulated	Not regulated	0.50 mg/l
Total Organochlorine Compounds	0.01 mg/l	0.20 mg/l	0.20 mg/l	[b] 0.20 mg/l
Total Organophosphorus Compounds	0.01 mg/l	0.10 mg/l	0.10 mg/l	[b] 0.10 mg/l
Total Carbamates	Not regulated	0.10 mg/l	0.10 mg/l	[b] 0.10 mg/l
(a) These standards are also applied for preservation of pristine ecosystems				
(b) Limit for each detected compound in a pesticide family				

Source: Ecuadorian Environmental Management Law (2001)

From these tables it follows that pesticides in surface waters are regulated by considering the total sum of compounds detected for any of the four chemical families: organochlorines, organophosphorus, carbamates and pyrethroids. However, other pesticide families are also used in Ecuador (see Section 2.5) and this is obviously a gap in the law. On the other hand, the Ecuadorian limits for pesticides in water used for human consumption are more strict and specific as shown in table 2.4. In the table, the proposed FAO limits are also given.

Table 2.4. Ecuadorian pesticide limits for water consumption

Variable	Maximum Allowable Concentration	FAO
Glyphosate	200.00 µg/l	700.00 µg/l
Diquat	70.00 µg/l	N/A
DBE	0.05 µg/l	N/A
DBCP	0.20 µg/l	0.20 µg/l
Toxaphene	0.01 µg/l	N/A
Total Carbamates	100.00 µg/l	(a)
Total Organochlorinated Compounds	10.00 µg/l	(a)
Total Organophosphorus Compounds	100.00 µg/l	(a)
N/A: not available (a) varies depending on pesticide		

2.2. FATE OF PESTICIDES IN A WATERSHED

2.2.1. CHEMICAL FATE MODELLING IN GENERAL

In the early days of modelling, chemicals were generally divided in two groups: biodegradable (i.e. organic matter) and "non-biodegradable"[2] chemicals (i.e. toxic compounds). The fate of a chemical was initially related to its disappearance rate after a certain period of time. As modelling evolved, other factors were considered such as transport and dispersion. The majority of the chemical fate models in rivers assumes first-order reactions for the chemical removal (Boeije 1999), as shown in the following equations

$$C_X = C_0 \, e^{-k\frac{X}{v}} \tag{2.1}$$

$$C_X = \frac{C_0}{\sqrt{1 + \frac{4\,k\,D}{v^2}}} \, e^{\frac{X\left(v - \sqrt{v^2 + 4\,k\,D}\right)}{2\,D}} \tag{2.2}$$

Where

C_X Predicted environmental concentration at distance X from the sources

C_0 Initial concentration at the point of discharge

k First-order degradation rate of the chemical

v Velocity of the river

D Dispersion coefficient of the chemical in the water

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[2] Chemicals with a little biodegradation rate were usually assigned to this category.

The main drawback of the above equations is that they only assume a point discharge into the river. However, there are several environmental problems where point sources are not the main concern. In general, agricultural activities including livestock operations are considered the largest contributors of non-point source pollution. This type of pollution normally acts depending on hydrological conditions, and it can not be easily monitored or controlled. As a definition, non-point source water pollution is the contamination in which the pollutants have no obvious point of entry into receiving watercourses. On the other side, point source pollution represents the routing of pollutants directly into receiving water bodies (Ongley 1996).

In agricultural activities, there are several ways to introduce non-point pollutants such as fertilizers and pesticides. Figure 2.2 shows that not all pollutants represents the same level of environmental assessment. As can be seen, pesticides represent a very high scientific complexity while their knowledge base is still very low. In addition, producing information related to pesticides is extremely expensive.
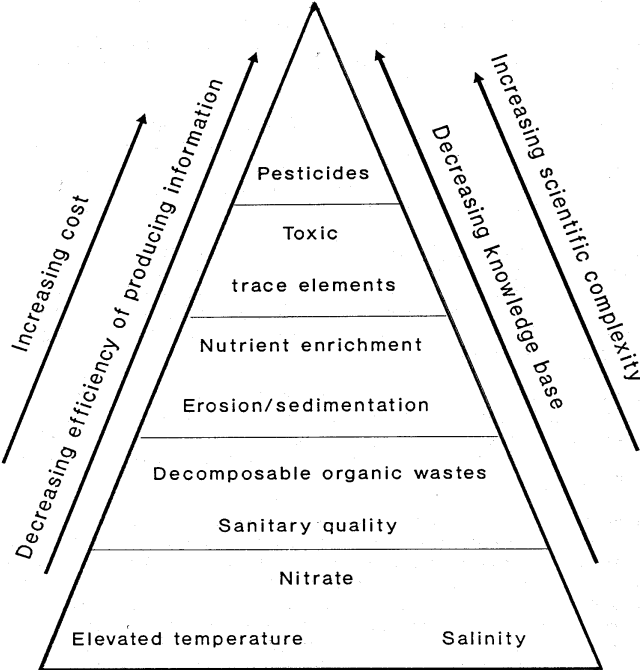
Figure 2.2. Hierarchy of pollutants from agricultural activities (Rickert 1993; Ongley 1996)

When pesticides reach the environment, their fate is governed mainly by three processes: transport, transformation and retention (Cheng 1990). Once a pesticide is applied in a watershed, a mass balance should indicate that the pesticide input must be equal to all

pesticide sinks: losses, erosion, degradation, accumulation, runoff, leaching, crop, soil retention, drift (Bailey *et al.* 1985). Figure 2.3 shows potential pathways in the movement of pesticides between compartments in the environment.
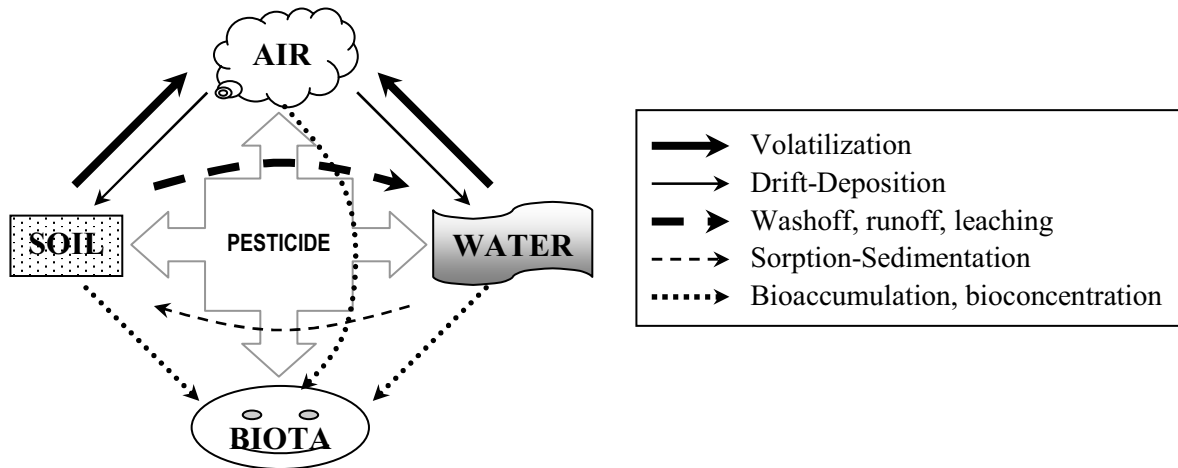
Figure 2.3. Movement of pesticides between compartments of the environment

2.2.2. AIR

When a pesticide enters the air compartment, it can undergo interaction processes within three potential zones: the air mass, the foliage-air interface and the canopy zone. Pesticide transport in air is influenced by pesticide droplet characteristics and climate conditions on the compartment. Due to this, a pesticide could drift away from the application zone producing losses[3] ranging from 66 to 95%. Wind speed is the main climatic condition that contributes to pesticide transportation in air: bigger droplets fall near the point of application while smaller droplets could fall far away from the source. However, air turbulence has a more dramatic effect because: the greater the turbulence, the faster the transport and the greater the probability of reaching the foliage canopy and being filtered out within that canopy (Himel *et al.* 1990).

A turbulence model was proposed after Csanady (1973) and Johnson and Sayer (1970) by applying a standard Gaussian dispersion equation which considers heights of application and reception.

$$C_Z = \frac{2\,C_h\,h\,(h-z)}{\left(\sqrt{2\pi}\right)\sigma^2}\,e^{-\frac{h^2}{2\sigma^2}}$$

[2.3]

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[3]   These losses are related to pesticide falling directly on the soil and on peripheral foliage, volatilization losses and drift losses.

Where

C_Z Pesticide concentration at the height of reception

C_h Pesticide concentration at the height of release

σ Standard deviation of the cloud distribution depending on climate characteristics (wind speed, atmospheric stability, downwind distance and height of release)

Figure 2.4 illustrates the principle of the above equation in which the pesticide cloud grows with time and it is affected by turbulence and wind speed.
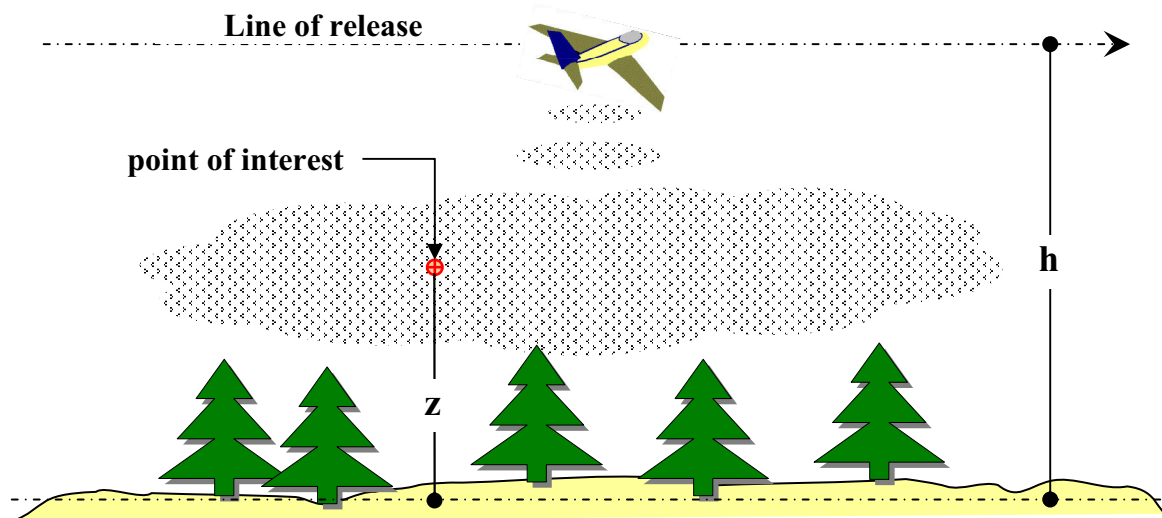
Figure 2.4.   **Pesticide cloud dispersion after Johnson and Sayer (1970) and Csanady (1973)**

2.2.3. SOIL

Basically three processes affect pesticide movement in the soil compartment of the watershed: foliar washoff, runoff and leaching.

2.2.3.1. *Washoff*

This process is normally known as foliar washoff which is the way a chemical is wiped out from the plant foliage after a certain amount of rain falls over the canopy. Several approaches have been followed to model that process; however, the approach proposed by Smith and Carsel (1984) is generally used in several environmental models. This approach also considers degradation of the chemical (photolysis, chemical reaction, biodegradation and volatilization) before leaving the foliage by washoff (equation [2.4]).

$$\frac{dM_{foliage}(t)}{dt} = \left[-k_F \ M_{foliage}(t) - W_{pesticide}(t) + A_{pesticide}(t) \right]$$

[2.4]

Where

$M_{foliage}(t)$ Mass of pesticide on foliage at time t

$W_{pesticide}(t)$ Washoff rate of pesticide wiped out from foliage, which depends on rainfall falling at time t.

$A_{pesticide}(t)$ Application rate of pesticide applied to the plant at time t

k_F Pesticide first-order degradation rate on the foliage including photolysis, chemical reaction, hydrolysis, biodegradation and volatilization.

2.2.3.2.   *Runoff*

There are several definitions of runoff in literature, but the one stated by Leonard (1990) is more suitable for pesticide assessment purposes: "Runoff is the water and any dissolved or suspended matter it contains that leaves a plot, or small single cover watershed in surface drainage." After application, washoff may occur and pesticides can be adsorbed by soil particles. The entity soil particle – attached pesticide is later transported into a river by gravity forces pulling rain water through the ground slopes.

Pesticides could also be dissolved into the runoff water either by instantaneous dissolution (depending on its solubility properties) or desorption from transported soil particles once these are in the water mass. The amount of pesticide that can be attached to a soil particle depends on the solid-liquid partitioning coefficient (K_d) whose behaviour usually is assumed by a linear sorption isotherm.

$$C_S = K_d \ C_W$$

[2.5]

Where

C_S Pesticide concentration attached to the soil particle

C_W Pesticide concentration in the surrounding water

Runoff can be considered as the main supplier of non-point pesticide pollution into a river. When modelling pesticides in the runoff, the available pesticide in the soil surface is important as well as the soil thickness with which runoff can interact by scouring. The available pesticide in the soil depends on how much pesticide is attached to soil particles. The

soil thickness is frequently called the effective surface soil mass. Several authors have assumed different values of this thickness in their proposed models as shown in Table 2.5.

Table 2.5. Effective soil surface thickness that interacts with runoff

Thickness	*References*
10 mm	Haith and Tubbs (1981) Steenhuis and Walter (1980) Leonard et al. (1979) Williams and Hann (1978)
3 mm	Crawford and Donigian (1973)

Erosion is linked to runoff and this process is the main source of solid particles that could serve as pesticide carriers into the river. In 1965, Wischmeier proposed a simple empirical relationship to estimate the amount of erosion produced by a specific runoff event in a drainage basin. This model was named the Universal Soil Loss Equation (USLE) which is actually a field management tool and is a product of five factors:

$$S_{LOSS} = R \times P \times C_M \times LS \times K_S \qquad [2.6]$$

Where

S_{LOSS} Estimated soil loss

R Rainfall energy factor

K_S Soil erodibility factor mainly depending on soil characteristics

LS Slope-length factor which is based on topography of the study area

C_M Cropping management factor

P Erosion-control practice factor

There have been modifications to this equation such as RUSLE (Renard *et al.* 1996) and MUSLE (Williams and Berndt 1972) to improve erosion estimates by considering more site-specific information.

2.2.3.3.   *Leaching*

All chemical movement within the soil matrix is related to water flow through soil pores due to gravity and capillary forces. This liquid entering the soil helps in transporting chemicals into the underlying soil layers. Therefore, flow is essential for modelling pesticide movement in the soil compartment. When water falls on the ground as rainfall, some amount enters the soil by percolating through its unsaturated zone, and finally reaches the saturated zone where

an aquifer is. For most environmental conditions, water flow can be considered as laminar and as a Newtonian fluid (Enfield and Yates 1990)

The flow in the unsaturated zone is normally considered as steady-state and can be modelled by using an equation developed by Richards (1931), also known as the transient water-flow equation (equation [2.7]).

$$\frac{\partial \theta}{\partial \psi} \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x}\left[K(\psi) \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial y}\left[K(\psi) \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial y} \right] + \frac{\partial}{\partial z}\left[K(\psi) \frac{\partial \psi}{\partial \theta} \frac{\partial \theta}{\partial z} \right] + Sink_{water}$$

$$\frac{\partial \psi}{\partial t} = 0 \quad (for\ steady\ state)$$

[2.7]

Where

ψ Soil-water potential

K Effective hydraulic conductivity which is function of the soil-water potential

θ Volumetric soil-water content

$Sink_{water}$ Water transported by other mechanisms than flow (e.g. evapotranspiration)

Once water reaches the saturated soil zone, the flow can be modelled by using Darcy's equation where the effective hydraulic conductivity corresponds to the saturated condition. The chemical then could be modelled by using mass balances and considering sorption-desorption and diffusion processes (equation [2.8]). This approach assumes that the groundwater flow is horizontal, continuous and uniform.

$$R_F \frac{\partial C}{\partial t} + V \frac{\partial C}{\partial x} = D_X \frac{\partial^2 C}{\partial x^2} + D_Y \frac{\partial^2 C}{\partial y^2} + D_Z \frac{\partial^2 C}{\partial z^2} - R\ k_T\ C$$

[2.8]

Where

C Concentration of the chemical

V Uniform horizontal groundwater flow velocity

k_T Transformation rate coefficient (hydrolysis, biodegradation, volatilization)

D_X, D_Y, D_Z Diffusion coefficients in x, y and z direction respectively

R_F Retardation factor which is function of soil properties and soil partition coefficient. This value physically describes how faster the groundwater seepage velocity (V) is compared with the average velocity of the migrating pollutant (V_P)[4].

2.2.4. WATER[5]

Normally pesticides enter the water body by runoff and leaching from the soil compartment or by direct application into the water. Transport of chemicals in surface water is affected by two processes: advection and dispersion. Advection is the movement of particles or substances within the water body dragged by the flow velocity. Dispersion refers to the mixing of substances within the water column by considering Fick's Law. Both advection and dispersion can occur in three dimensions, and can be modelled by using equation [2.9].

$$\frac{\partial C}{\partial t} = \left(D_X \frac{\partial^2 C}{\partial x^2} + D_Y \frac{\partial^2 C}{\partial y^2} + D_Z \frac{\partial^2 C}{\partial z^2} \right) - \left(V_X \frac{\partial C}{\partial x} + V_Y \frac{\partial C}{\partial y} + V_Z \frac{\partial C}{\partial z} \right) \pm \text{Reactions}$$

[2.9]

Where

C Concentration of the chemical

V_X, V_Y, V_Z Uniform flow velocity in x, y and z direction respectively

Reactions   Processes that change chemical concentration (hydrolysis, biodegradation, volatilization)

D_X, D_Y, D_Z Diffusion coefficients in x, y and z direction respectively

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[4]   This parameter describes the extent to which the migration of dissolved contaminants can be slowed down by sorption to the aquifer matrix. It can be calculated by using the equation proposed by Freeze and Cherry (1979)

$$R = \frac{V}{V_P} = 1 + \frac{\rho_b K_d}{n_T}$$

[2.10]

where

ρ_b Bulk density of the aquifer matrix
n_T Total porosity of the aquifer matrix
K_d Soil partition coefficient which is function of the chemical and soil characteristics

[5]   In this study, the water compartment involves surface water bodies. Groundwater is considered as part of the soil compartment.

2.2.5. BIOTA

Pesticides can enter an organism by three routes of exposure: ingestion, respiration or/and exterior contact. The significance of the resulting impact depends on the pesticide applied, the organism involved and the biological interactions produced: biomagnification and synergism (Madhun and Freed 1990).

Two factors affect the way a pesticide is transported into the biota: the solution behaviour of the pesticide and the uptake/accumulation processes in the organisms. The first factor influences the amount of pesticide that is available in the water to enter the organisms[6]. The second factor is related to a property called partition coefficient which basically shows the pesticide distribution between a lipophilic and a hydrophilic environment (equation [2.11])

$$C_{lipophilic} = K_{OW} \; C_{hydrophilic}$$
[2.11]

Where

$C_{lipophilic}$ Pesticide concentration in the lipophilic state

$C_{hydrophilic}$ Pesticide concentration in the hydrophilic state (water phase)

K_{OW} Octanol-Water partition coefficient for the pesticide

The accumulation of ingested chemical in the aquatic food chain can be approached by equation [2.12] (Connolly and Thomann 1992).

$$\frac{dC_i}{dt} = k_{uptake\,i}C_d - k_{excretion\,i}C_i - \frac{C_i}{W_i}\frac{dW_i}{dt} + \sum_{j=1}^{n}\alpha_{ij}F_{ij}C_j$$
[2.12]

Where

$C_i\,,\,C_j$ Pesticide concentration in organism i and j respectively

C_d Pesticide concentration dissolved in the water

F_{ij} Consumption rate of organism i on organism j

W_i Weight of organism i

α_{ij} Chemical assimilation efficiency of organism i on organism j

$k_{uptake\,i}$ Uptake rate of organism i

$k_{excretion\,i}$ Excretion rate of organism i

n Total number of organisms preyed on by organism i

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[6] Note that pesticides attached to fine suspended sediment can also enter the organism by filtration or ingestion.

2.3. MODELLING ENVIRONMENTAL BEHAVIOUR OF PESTICIDES

Pesticide behaviour has been modelled by several approaches in the last decades trying to capture the complexity of chemical transport and transformation mechanisms through the environment. This complexity increases as the system boundary goes from the plant entity to a big river basin. As a result, it also influences the way the interaction between all environmental compartments (soil, water, air and biota) is considered. Most of the equations used on these approaches were introduced in the previous section. In addition, it is also important to model other phenomena that help in transporting and in transforming pesticides in the environment such as runoff, hydraulics, climate or farm management.

Depending on the type of approach, the amount of data needed to run the model may be overwhelming. However, data for all pesticide models could be generally summarized in three types (Donigian and Huber 2001):

1. System Parameters
    a. Site-specific parameters (watershed size, watershed subdivision)
    b. Topographic parameters (slope, drainage length, drainage pattern)
    c. Soil parameters (texture, permeability, erodibility, thickness, soil-water content)
    d. Crop parameters (crop cover, runoff coefficient)

2. Transformation parameters
    a. Climate parameters (temperature, solar radiation)
    b. Pollutant parameters (reaction rate coefficients, adsorption coefficients, mass discharged)
    c. Crop parameters (growth rate, root mass)

3. Input Variables
    a. Climate variables (precipitation, atmospheric conditions, evaporation rate)
    b. Pollution loads

Important is the goal of the model which can be achieved by answering questions such as

- What model will best fit the purpose?

- Is it better to use an existing model or to develop a new one?

Before answering such questions, an analysis should be made based on several interlinked facts such as research budget, study objectives and available time. For example, developing a new model could take several years before it can be successfully applied in a specific situation. In addition, it is doubtful whether any new approach than the existing one would be cost effective for the purpose of the study (Charnock *et al.* 1996).

Basically, pesticide models can be grouped in three categories: screening or compartmental models, field-scale models and integrated/spatially-variable models. A very detailed evaluation of those models has been made by several authors such as Doningian and Huber (2001), Parsons et al. (2001), USBR (1991), REM (2003), Melancon (1999) and Wilson (1996).

2.3.1. SCREENING MODELS – COMPARTMENTAL MODELS

Screening models are mainly used only for checking purposes and results can only be taken as reference levels due to the usage of gross estimation techniques. In order to assess chemical fate, the model performs the division of the environment in compartments of known dimensions. After the chemical enters the environment, the analysis usually is performed until equilibrium is reached between compartments. Two screening models were evaluated in this research: EXAMS and EQC.

2.3.1.1.   Exposure Assessment Modelling System - EXAMS (Burns et al. 1982)

The EXAMS model was first published in 1982, and it is continuously supported and upgraded by the Athens Environmental Research Laboratory, U.S. Environmental Protection Agency. It evaluates the fate, transport and exposure concentrations of synthetic organic compounds in aquatic ecosystems (water and sediment compartments). The model is a deterministic model that uses valid theoretical concepts to track down chemical distribution, and it is considered a compartmental model. In summary, EXAMS is a set of different "second-order" models which describe the chemical behaviour by linking its properties with average limnological parameters of the aquatic compartments. These sub-models deal with ionization-sorption, transformation, transport processes and chemical loadings.

In the analysis, aquatic systems are divided into subsystems, in which a chemical moves by transport between those subsystems. The main assumption in the subdivision is that the compartment is "well-mixed". Therefore, compartments should not be too large, in order to avoid internal gradient effects. This could be achieved by considering up to 100 interconnected subdivisions of the evaluated aquatic system representing:

- Epilimnion and hypolimnion of lakes
- Littoral zones
- Benthic sediments
- River streams

The calculated chemical concentrations are called Expected Environmental Concentrations (EEC) and represent the exposure levels of the evaluated chemical. The percentage distribution of the chemical in each environmental compartment can also be estimated. Results from EXAMS are mainly used for identifying the adverse effects caused by new chemicals released in aquatic compartments. For that reason, EXAMS is considered by its developer as a "hazard evaluation system," which consists of three levels of analysis:

- Mode 1: A steady-state analysis gives a long-term EEC resulting from specific time-averaged chemical loadings.
- Mode 2: The analysis can be done with "pulse" chemical loadings.
- Mode 3: Forces affecting the environment can be input on a time basis (mainly monthly), so that results can be linked to the PRZM model (see Section 2.3.2.2) as a time-series.

2.3.1.2. Equilibrium Criterion Model – EQC (Mackay et al. 1996)

The theory behind the EQC model is based on the Fugacity concept (Mackay and Paterson 1981), which expresses the tendency of the chemical to escape from one phase to another phase. This model assesses the behaviour of a chemical in a "divided" environment by using its chemical-physical properties with transport and transformation processes. In the model, the environment, called the unit world, is divided in compartments (air, water, soil, sediment, aerosols, and suspended sediment) of known dimensions. The analysis can be done with three types of chemicals:

- Chemicals that partition into all media by assuming a thermodynamic equilibrium between phases.

- Chemicals with a negligible volatilization value. The analysis also assumes a thermodynamic equilibrium. Advective and reaction processes are considered in the analysis.

- Chemicals with zero or near-zero solubility. The analysis is done as a steady state assessment, and the chemical is in a non-equilibrium state.

This model is also useful to assess the behaviour of a new or existing chemical, including exploration of various emission scenarios. The model can perform four levels of analysis:

Level 1: The environment is at equilibrium and the chemical has a fixed input. There is just distribution of the chemical between compartments with no degradation, no advection, no intermedia transport (only intramedia).

Level 2: The environment is at equilibrium, and the chemical enters at a constant rate. It is considered that the chemical is non-conservative, so there are transformation processes involved. Advection and intramedia transport are included in the analysis.

Level 3: The environment is at steady state, and the chemical enters at a constant rate. Each compartment is at a different fugacity. The chemical is non-conservative (degradation processes). Chemical transport involves intermedia and intramedia transfer rates.

Level 4: The environment is at non-steady state during the analysis. However, steady state will be reached at the end of the analysis. The chemical is non-conservative, and undergoes intermedia and intramedia movement.

2.3.2. FIELD-SCALE MODELS

Field-scale models are models developed to assess an environmental problem for specific site conditions. Therefore, a physical boundary should be first defined to solve the problem. Then, it is assumed that the entire area enclosed by this boundary has the same climate conditions, physical properties and management practices. Finally, the model outcome (i.e. the pesticide concentration) will be representative for the whole surface area. There are several field-scale models available; however, only two of them are described below. The first one was indirectly evaluated in this research because this model is part of an integrated

model used later on. The second one is described here only as a reference, although it was not used in this research.

2.3.2.1. *Chemicals, Runoff and Erosion from Agricultural Management Systems – CREAMS (Foster et al. 1980)*

This model was developed by the United States Department of Agriculture (USDA). It performs analysis of runoff, erosion, and chemical transport from agricultural activities caused by individual storms. However, it can also make predictions on long term periods, up to 50 years. It is a field-scale model because all data required to run the model may include temporal variability, but not spatial variability. The model must be executed in a single management unit with unique land use, soil type and management practices.

For the hydrologic analysis, the model can perform two different types of calculating runoff:

- Soil Conservation Service (SCS) Curve Number technique for evaluating daily rainfall data. The *Curve Number* is a runoff coefficient assigned to a piece of land which depends on a combination of land use and one of four hydrologic soil groups. It ranges from 30 (low potential of runoff) to 100 (high potential of runoff).
- An infiltration-based model for hourly data.

The model evaluates erosion by applying the USLE approach, and the transport of sediment is evaluated in the overland flow. Nutrient analysis includes plant uptake, leaching, sediment adsorption/transport, mineralization, and nitrification/denitrification processes. Finally, pesticides can also be evaluated by considering foliar interception, washoff, sorption/desorption, and degradation in the soil/water environment.

The approach developed for the CREAMS model has also been applied in several integrated models, such as AGNPS and SWAT.

2.3.2.2. *Pesticide Root Zone Model – PRZM (Carsel et al. 1984)*

PRZM was developed by a team of the United States Environmental Protection Agency (USEPA). The current version of the model is PRZM-3 (Carsel *et al.* 1999).

PRZM is known as a groundwater loading model because it evaluates pesticide movement from the plant through the root zone in the soil to finally reach the groundwater table. It is also considered a compartmental model because the study site was originally divided in two compartments (plant – root zone). The current version, PRZM-3, is actually a linked model because it integrates the analysis of the root zone (PRZM module) with the vadose zone analysis[7] by using a module called VADOFT. Both modules simulate water flow and solute transport.

The model is one-dimensional and simulates chemical movement in unsaturated soils. In the model, some inputs may vary along depth (Z axis) from homogeneous to heterogeneous root and vadose zones. However, the model itself could not be considered as a spatially variable model because the water and chemical transport parameters at the surface (X and Y axis) remain constant for the analysis as field-averaged values. In the current version, PRZM-3, this issue is being addressed by running the model in a Monte Carlo framework, producing distributional values as inputs (MONTE CARLO module). Thus, the current version could be considered as a pseudo-spatially variable model.

In this research, this model was not used because groundwater is not the main concern in the study site. However, it is mentioned here as a reference point for future research in other watersheds in Ecuador.

2.3.3. INTEGRATED SPATIALLY VARIABLE MODELS

Within this context, an environmental model is called integrated when it accomplishes coupling tasks between more than one modelling processes to solve a specific problem. Integrated environmental models are useful to explain linkages between phenomena that contribute to the same problem. Because of the non-point characteristics of pesticide usage, the evaluated models should deal with spatial variability (inputs and outputs should vary spatially in the study area).

Two integrated models have been evaluated in this research: AGNPS and SWAT. These models deal with pesticide evaluation by considering hydrology, erosion, runoff and management processes.

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[7] The vadose zone is located between the root zone and the groundwater table

2.3.3.1. Agricultural Non Point Source Model – AGNPS (Young et al. 1987)

AGNPS was developed by a team of the Agricultural Research Service (ARS) at USDA. Nowadays, the model is supported by the National Sedimentation Laboratory (ARS-USDA) in Mississippi. The current version is AGNPS 2001.

It is a distributed parameter model which evaluates agricultural activity as a source of erosion, sedimentation and pollution in a watershed due to climate influences (precipitation events). Basically, the watershed is divided into elemental units called cells where three main lumped models are applied:

- An erosion model which considers either the RUSLE or USLE approach depending on the simulation event (continuous or single event, respectively).
- A hydrology model based on the SCS Curve Number technique
- A pollutant model based on the CREAMS model to predict nutrient and pesticide concentrations on surface water.

To model pesticide fate, a pesticide database must be created where the physical-chemical properties of the evaluated pesticides are stored. In addition, the pesticide application procedure should be entered into an operation-management database which includes application date, application rate and kind of pesticide applied in the field. AGNPS can handle several application dates with different pesticides applied at a time. The model output will show results for each pesticide considered in the analysis.

The model is useful for assessing large scale non-point pollution problems in urban and agricultural areas. Due to the spatial variability of the required data, the model can be linked to a Geographical Information System to perform several tasks (entering data, generating intermediate data and displaying results as maps). Several interfaces have been developed for AGNPS interacting with GIS platforms such as ArcView, ArcInfo (Jankowsky and Haddock 1993) and GRASS (He *et al.* 1993).

2.3.3.2. Soil and Water Assessment Tool – SWAT (Arnold et al. 1995)

SWAT was developed by another team, located in Texas, from the same institution that developed AGNPS. The current version, SWAT 2000, is supported by the Grassland, Soil

and Water Research Laboratory (ARS-USDA) located at Temple, Texas. SWAT's approach was developed based on other models, such as:

- Simulator for Water Resources in Rural Basins – SWRRB (Williams *et al.* 1985; Arnold *et al.* 1990)

- Chemicals, Runoff, and Erosion from Agricultural Management Systems – CREAMS (Foster *et al.* 1980)

- Groundwater Loading Effects on Agricultural Management Systems – GLEAMS (Leonard *et al.* 1987)

- Erosion-Productivity Impact Calculator – EPIC (Williams *et al.* 1984)

The model is useful to evaluate agricultural management options (at surface and ground water, landuse, and farm levels) on large river basins related to sediment and agrochemical yields. As in the previous model, SWAT requires a pesticide database to perform the pesticide fate prediction. However, this model has built-in pesticide database with the most commonly used pesticides including their physical-chemical properties. New pesticides can also be added to this database. In addition, SWAT also requires a pesticide operation plan to model pesticide routing. Although SWAT can accept different pesticide applications at the same time, it can route only one pesticide for each running process. Therefore, several runs should be performed to evaluate more than one pesticide.

SWAT also performs a basin subdivision to account for spatial variability. However, the methodology is different from the one used in AGNPS. Temporal variability in the model is considered by using a daily time step, thus SWAT is a continuous time model which can perform evaluations up to 100 years. However, the original model could not handle simulation of detailed single events. The evaluated processes in the model are handled by using lumped models (modules) in each watershed subdivision (Table 2.6)

Table 2.6. Some of the methods used in SWAT to solve several processes

Process	*Approach*
Hydrology	Water balance equation
Runoff	SCS Curve Number Technique
Infiltration	Green & Ampt Method
Sediment Yield	Modified Universal Soil Loss Equation (MUSLE)
Channel erosion	Bagnold's stream power equation
Chemical fate	CREAMS and GLEAMS models

Interfaces to GIS platforms (ArcView, ArcInfo and GRASS) have also been developed, such as:

- SWAT-ArcView (Diluzio *et al.* 1997)
- SWAT-GRASS (Srinivasan and Arnold 1994)
- SWAT-ARC (Diluzio *et al.* 1997; Bian *et al.* 1996)

After its release, several authors and institutions have been developing modifications and extensions to SWAT model such as ESWAT (Van Griensven 2000) which main modification is the use of an hourly time step in the modelling process.

2.3.4. SENSITIVITY AND UNCERTAINTY ANALYSIS

All the models described in the previous paragraphs do not have a way to automatically perform sensitivity and uncertainty analyses within their running platform. Therefore, those analyses should be done separately by performing several sub-simulations to tackle all the parameter interactions affecting a specific process.

In compartmental physically-based models such as EXAMS, some criteria are recommended to optimise the number of sub-simulation steps in performing the sensitivity analysis of the model:

- First, it is necessary to determine in which ecosystem of the study area the largest chemical residues are developed. All the required properties of the evaluated ecosystems in a watershed must have been entered in the model's database to perform this step. In addition, the potential loading rates must also be set in the input's database.
- After selecting the most sensitive ecosystem, the second step involves the determination of the most dominant process affecting the compound degradation. In the case of EXAMS, this step can be done by reviewing results in the output tables after every run. There are two output tables produced by the model: the kinetic profile and the overall steady-state fate of the compound. By checking the input data against the reported error bounds of each parameter, the sensitivity analysis can be documented. This analysis is totally controlled and directed by the model user. A complete and detailed text of the physics behind the model can be found in the user's manual of the model.

More detailed information regarding sensitivity analysis in EXAMS model can be found in Burns (1981). As EXAMS, the EQC model also requires several manual runs to perform the sensitivity analysis. The sensitivity analysis of this kind of models is strongly related to the input data uncertainty because the model outcome is sensitive to each input parameter (Webster and Mackay 2003). In addition, the sensitivity will depend on the quality of the information entered in the model, which can be grouped in chemical and environmental parameters.

Regarding the AGNPS and SWAT models, there are not many studies for sensitivity regarding pesticide analysis. Both models use many concepts that are not necessarily physically-based such as the Curve Number and the Universal Soil Loss Equation approach. Some efforts have been done to evaluate sensitivity such as by Chinkuyu *et al.* (2003).

2.4. GEOGRAPHIC INFORMATION SYSTEMS AND ENVIRONMENTAL MODELLING

Generally, environmental modelling, especially pesticide assessment, is characterized by spatial and temporal variability both in output and input data. Geographic Information Systems (GIS) can currently handle this variability by using multivariate functions as spatial phenomena representations f (r), where r = x,y,z,t (Mitas *et al.* 1997). Discretization is then applied to these functions to represent them as multidimensional raster maps, which can be used as input data in environmental modelling.

GIS also can be used either as a tool to develop a stand-alone model or as an intermediate step for deriving input to existing models (Melancon 1999). However, the majority of GIS applications have shown to be just a way to organize model inputs and display model predictions (Wilson 1996). One example of GIS-model interaction is the GREAT-ER model (Geography-referenced Regional Exposure Assessment Tool for European Rivers) developed to be used by the European Centre for Ecotoxicology and Toxicology of Chemicals – ECETOC (Schowanek *et al.* 2000). This model was built to predict environmental concentration distributions of down-the-drain chemicals (mainly wastewater treatment plant discharges). In this model, a GIS is used to stored data and visualize results (PECs) in colour-coded maps or concentration profiles. In addition, GREAT-ER can aggregate results into a single value which is the representative PEC within the watershed.

Although GIS tools have clear advantages, they sometimes are not adequate for environmental modelling (from a cost effective point of view) because data availability perhaps is the main disadvantage (Table 2.7). Thus, an important initial step in using GIS-based environmental models will be the analysis of their advantages and disadvantages.

Table 2.7.   Some of the advantages and disadvantages in using GIS for environmental modeling

Advantages	Model data (input and output) can easily be managed by the user
	Output data can be visualized through comprehensible maps instead of tables
	Spatial variability is handled by GIS
Disadvantages	Generally, available input data is not in the appropriate format to be used in the GIS tools. Thus, some extra processing should be done such as interpolation
	Limitations in handling multiple inputs that vary in different ways
	Environmental processes cannot be readily applied in a specific GIS platform (macro programming, complex mathematics and statistical analysis)
	For small projects, GIS-based data such as remote sensing data, and aerial/satellite photos could be very expensive

Several authors have worked to solve or overcome some of these disadvantages and also to improve GIS usage in environmental modelling. For example, ten basic steps have been proposed to deal with GIS-based environmental/hydrologic modelling of watersheds (Maidment 1996):

1. Definition of basic model requirements (spatial/time domain, variables, processes needed)
2. Determination of watershed and stream network based on terrain analysis
3. Determination of surface characteristics (soil types, land usage, management practices)
4. Subsurface analysis (aquifers, groundwater movement, root/vadose zone analysis)
5. Hydrologic evaluation (historical flow records, flow measurements, weather data evaluation)
6. Mass water balance determination in watershed (precipitation, runoff, infiltration, evaporation)
7. Water flow (runoff/infiltration) analysis as the main transport carrier of contaminants.
8. Determination of environmental concentrations (chemicals and nutrients) based on transport, partitioning and transformation processes.
9. Analysis of water usage impacts (withdrawals/discharges, reservoir locations)

10. Developing of the appropriate way to present results to the final user (maps, tables, reports, internet, etc.)

Based on previous research done elsewhere, a general GIS-based pesticide modelling scheme is suggested to include three components (input, modelling and output phases) as shown in Figure 2.5.
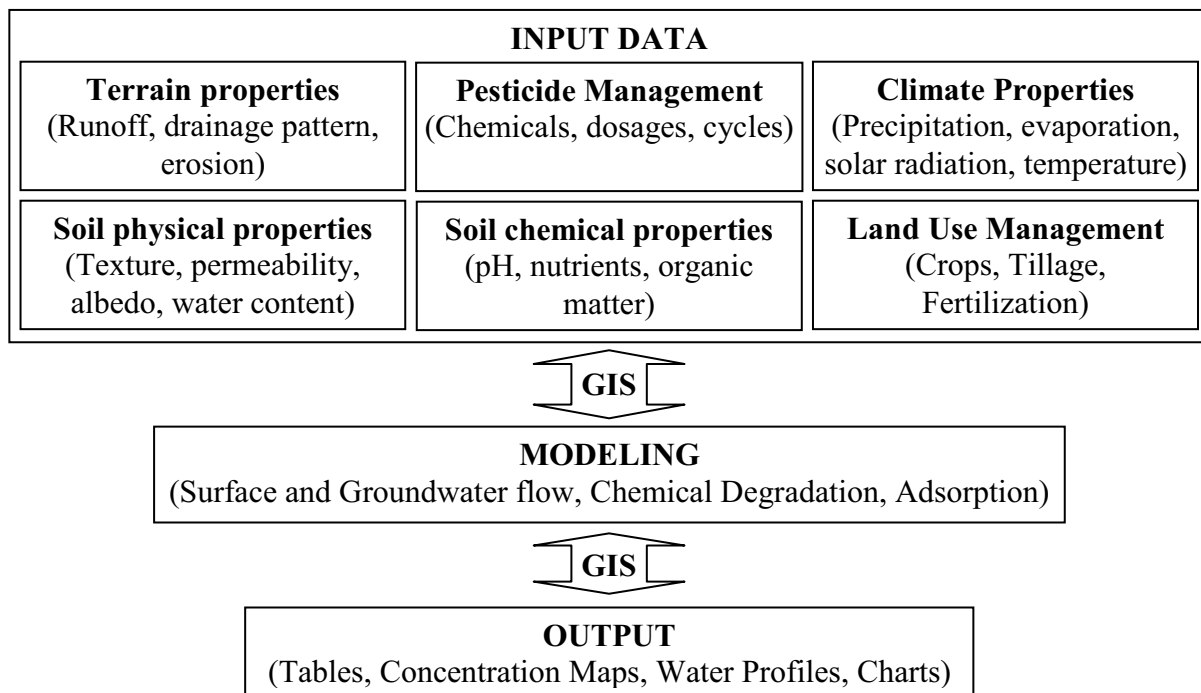
Figure 2.5. GIS-based pesticide modelling scheme

The research presented here will use GIS to model pesticide concentrations from banana plantations in an Ecuadorian watershed. In a first step, a GIS was used as a tool to build a database where all available information is stored according to their class (soil, climate, landuse, and so). This step can also be called the creation of the Data Dictionary. At the same time, some maps were digitized from printed sheets which were only available at 1:50000 scale. Other sources of information were also added, such as weather stations and soil sampling points. This level of information is called primary data.

A second step involved the application of interpolation procedures from primary data to generate secondary data in raster format. This format is useful to show spatial variability on data. Two issues were fixed first: the size of the raster cell and the extension of the interpolation area. It was necessary to develop some macros in the GIS software language (i.e. Avenue) to ease the process.

Once data were obtained and processed, GIS was used to extract information into the models. There were two ways to perform this operation: manually and interactively. The models evaluated in the research have GIS interfaces that can handle some interactive data extraction such as terrain information. However, some data had to be extracted manually by doing some data aggregation from the raster maps, such as for soil information. Aggregation was done based on the unit of analysis of each model (i.e. sub-basin).

Depending on the model, the execution can be done within or outside the GIS. Once the model is run, results are mainly displayed as tables. Some models can directly handle the results as colour maps. However, results from other models should be processed first in spreadsheets, and only then maps can be built. In the current research, both ways of output processing are handled.

2.5. PESTICIDES USED IN THE ECUADORIAN BANANA SECTOR

2.5.1. EXISTING STATISTICAL RECORDS ON PESTICIDES AND BANANA PLANTATIONS

In Ecuador, all pesticides are imported. In 1998, total pesticides importation was twice the importation in 1990, and three times the importation in 1980 (Table 2.8). Based on these data, herbicides represented an average of 37 %, fungicides 22 %, nematocides 16 % and insecticides 12 % in the total importation. The majority of the pesticides is used in agricultural activities including banana plantations. A very small amount of the pesticides is used for domestic, commercial and industrial activities.

Table 2.8. Total pesticide importation in Ecuador since 1978 to 1998

Year	Insecticides	Herbicides	Fungicides	Nematocides	Others	Total Amount (kg)
1978	9.1 %	29.9 %	13.1 %	9.6 %	2.3 %	5544330
1980	14.1 %	40.0 %	32.6 %	11.2 %	4.7 %	4149985
1982	9.5 %	50.1 %	25.3 %	8.9 %	6.2 %	4436257
1989	12.0 %	32.8 %	13.1 %	24.4 %	2.1 %	7164096
1990	12.1 %	30.6 %	23.9 %	14.2 %	3.0 %	6184874
1992	12.6 %	41.8 %	12.0 %	27.8 %	5.8 %	10196179
1998	12.6 %	31.0 %	36.9 %	13.5 %	6.1 %	13509801

Source: Ecuadorian Ministry of Agriculture, Teran (1999) and a statistical report from a pesticide importer.

On the other hand, all imported pesticides in Ecuador are grouped in around 30 chemical families including more than 150 generic pesticide names (or more than 250 trade names). Table 2.9 shows the first twenty chemical families of pesticides sold in Ecuador in 1992 and 1998 representing around 93% of total importation. In the table, the distribution among the chemical families varies in time. Many factors affect the necessities of pesticides in a country including climate, pesticide market, product market, type of pests, local and foreign pesticide regulation, and so on. In 1992, organophosphorus insecticides (29%) and bipyridilium herbicides (23%) were the most imported pesticides to Ecuador. On the other hand, the use of both pesticide groups decreased significantly during 1998. However, the importation of triazole fungicides increased from 1.4% in 1992 to 19.7% in 1998.

Table 2.9. Pesticides in Ecuador: Distribution of chemical groups in 1992 and 1998

Chemical Group	*Generic Pesticide Name*	*1992*	*1998*
Organophosphorus	Pyrazophos, Dimethoate, Temephos, Pirimiphos-methyl, Monocrotophos, Diazinon, Dichlorvos, Chlorpyrifos, Terbufos, Profenofos, Trichlorfon, Triazophos, Malathion, Ethoprophos, Fenamiphos, Methidathion, Azametiphos	28.9 %	17.0 %
Carbamate	Carbofuran, Oxamyl, Methomyl, Carbaryl, Thiodicarb	10.1 %	5.9 %
Pyrethroid	Cyhalothrin, Cypermethrin, Cyfluthrin, Permethrin, Allethrin, Tetramethrin, Deltamethrin	0.9 %	1.1 %
Organochlorine	Endosulfan, DDT	0.5 %	0.5 %
Bipyridilium	Paraquat Dichloride, Diquat Dibromide	23.3 %	8.7 %
Amide	Propanil, Butachlor, Alachlor	8.0 %	5.5 %
Phenoxy	2-4-D, MCPA, Fenoxaprop	3.9 %	5.3 %
Glycine Derivative	Glyphosate	2.8 %	8.1 %
Triazine	Atrazine, Ametryn, Terbutryn, Metribuzin	2.3 %	1.2 %
Urea	Diuron, Linuron, Diflubenzuron	0.9 %	0.8 %
Dinitroaniline	Pendimethalin	0.6 %	1.5 %
Dithiocarbamate	Mancozeb, Maneb, Zineb, Ferbam, Propineb	2.5 %	6.5 %
Benzimidazole	Thiabendazole, Benomyl	2.3 %	1.8 %
Inorganic	Sulfur, Copper	2.3 %	4.2 %
Triazole	Propiconazole, Penconazole, Imazalil, Tebuconazole, Triadimefon, Bitertanol	1.4 %	19.7 %
Morpholine	Tridemorph, Dodemorph	1.0 %	1.4 %
Mixtures	Carboxin + Captan, Copper + Mancozeb, 2,4-D + Picloram, Fosetyl-Al + Mancozeb, MCPA + Bentazon, Molinate + Propanil, Propineb + Cymoxanil, Mancozeb + Oxadixyl, Copper + Benalaxyl, Chlorpyrifos + Cypermethrin, Propanil + Triclopyr	1.3 %	3.2 %
Other Groups	They represent less than 0.50% per chemical group.	7.0 %	6.6 %

Source: Ecuadorian Statistical records from a pesticide importer.

Most of the banana plantations (74% of total area available for banana) in Ecuador have a surface area less than 100 hectares per plantation (Table 2.10). Therefore, it can be considered representative to analyze a farm within that area range.

Table 2.10. Distribution of banana producers in Ecuador

Surface Area per banana plantation (Ha)	Percentage of surface area	Number of producers	Percentage of farms
1 to 30	36 %	3956	80 %
31 to 50	38 %	480	10 %
51 to 100		366	7 %
More than 100	26 %	139	3 %

Source: Banana National Program and Ministry of Agriculture of Ecuador (1998)

In a typical farm, the production of bananas is divided into cycles through the year. Each cycle represents the application of fertilizers, herbicides, nematocides and formulations to control pests such as sigatoka. A typical formulation is a mixture of one or two active ingredients (fungicides) and crop oil (adjuvants). Most of the time, aerial application is used to spread the formulation over the farm. When it is necessary to use more than one formulation, each formulation is applied at different cycles. Depending on the formulation, it can be applied two, three, five or six times a year. There can also be more than one herbicide and nematocide application in banana plantations. However, not all types of pesticides are used in all cycles. Some of them might be used in every cycle, others can be used on the first cycles and others can be used during the last cycles.

Table 2.11 shows the types of pesticides normally used at banana plantations including chemical groups, trade and generic names. From that table, it can be seen that around 6040 Tons of pesticides were imported in 1999 to Ecuador to be used in the banana sector. That year, there were around 135000 Ha of productive banana farms in the country (Ecuadorian Central Bank 1999). Assuming that all imported pesticide was effectively used that year, it is estimated 43.78 kg of pesticide per hectare per year as a maximum pesticide usage, which represents around 33 kg of active ingredient per ha year. Comparing with other banana countries in Latin America, Ecuador is using less pesticide to cultivate bananas (Table 2.12). The high pesticide usage in the other countries is related to climatic events such as hurricanes and tropical storms that do no occur in Ecuador. In addition, the majority of the banana pests develop better under very humid conditions.

Table 2.11. Pesticides used in banana production in Ecuador.

Type	Chemical Group	Trade Name	Generic Name	Amount Imported in 1999	Recommended Dose per cycle of application
NEMATOCIDE	Organophosphorus	Mocap 15G	Ethoprophos	464799 kg	Not available
		Counter 15G	Terbufos	200000 kg	30 g.a.i. / plant
		Rugby	Cadusafos	79080 kg	10.0 kg/Ha
		Nemacur 15G	Fenamiphos	35410 kg	7.5 kg/Ha
	Carbamate	Carbofuran 10G, Furadan 10G, Carboroc	Carbofuran	481362 kg	0.41 g/Ha
		Vydate L azul	Oxamyl	46195 kg	12 l / Ha
FUNGICIDE	Dithiocarbamate	Dithane FMB, Dithane OS, Ridodur 25, Ridodur 40, Vondozeb 33 OF, Vondozeb 42 SC	Mancozeb	580331 kg	3 – 4.5 l / Ha
	Conazole	Sanazole, Tilt 250	Propiconazole	171000 kg	0.4 l / Ha
		Baycor 300 EC	Bitertanol	51612 kg	
		Folicur	Tebuconazole	14991 kg	
		Anvil 25	Hexaconazole	3740 kg	0.4 l / Ha
		Imazalil, Fungaflor	Imazalil	9900 kg	Not available
	Benzimidazole	Benocor 50 OD, Benopac, Pillarben OD, Benlate OD, Benomyl OD	Benomyl	186831 kg	0.25 kg/Ha
		Mertect	Thiabendazole	15310 kg	Not available
		Cercobin OD	Thiophanate-methyl	908 kg	Not available
	Strobilurin	Bankit	Azoxystrobin	47620 kg	Not available
	Inorganic	Kumulus DF	Sulfur	44728 kg	Not available
	Morpholine	Calixin 86 OL	Tridemorph	165650 kg	0.50 l / Ha
	Aromatic	Bravo 720	Chlorotalonil	150810 kg	Not available
INSECTICIDE	Organophosphorus	Basudin 600 EC	Diazinon	25300 kg	0.3 l / 200 l of water 0.5 – 0.75 g.a.i./Ha
		Perfekthion	Dimethoate	14186 kg	
		Dipterex 80 SP, Trichlorfon 95	Trichlorfon	8882 kg	0.4 – 0.5 kg/Ha
		Hostathion 40	Triazofos	3450 kg	Not available
	Microbial pesticide	Dipel 8L, Dipel 2X, Dipel SC, Novo Biobit XL, Turex, Thuricide	Bacilus thuringiensis	20354 kg	0.6 l /Ha 500 – 1000 g/Ha
	Carbamate	Sevin 80 WP	Carbaryl	10510 kg	2 – 2.5 l /Ha
	Pyrethroid	Dominex	Alphamethrin	3275 kg	Not available

Type	Chemical Group	Trade Name	Generic Name	Amount Imported in 1999	Recommended Dose per cycle of application
HERBICIDE	Glycine Derivative	Glyfocor, Gliphosate, Coloso, Roundup, Rocket, Agrosato, Pillarsato, Ranger	Glyphosate	1588688 kg	480 - 2880 g.a.i./Ha (1.5 – 4 l /Ha)
	Bipyridilium	Killer, Paraquat, Malexone, Herbaxon, Gramoxone	Paraquat	1524973 kg	0.54 l /Ha (216 – 256 g a.i./Ha)
		Reglone	Diquat	24400 kg	1.5 – 4 l /Ha (200 g a.i./Ha)
	Mixture	Gramocil	Paraquat + Diuron	34050 kg	Not available
	Urea Derivative	Diuron Flo, Stavron	Diuron	21010 kg	0.5 – 3 kg/Ha (800 g.a.i. / l)
	Phosphinic Acid	Finalle	Ammonium Glufosinate	12100 kg	150 g a.i./liter

Source: Statistical records of a pesticide importer, statistical record of a banana producer and recommendations of pesticide manufacturers.

Note: g.a.i. means grams of active ingredient.
Usage of amount imported is distributed in banana and sometimes in other crops

Table 2.12. Pesticide usage in other banana countries

Country	Pesticide Application Rate
Panama	75 a 250 kg.a.i. / ha / year
Costa Rica	36.4 kg.a.i. / ha / year

Source: UNEP (2001)

2.5.2. PESTICIDE MANAGEMENT IN THE ECUADORIAN BANANA INDUSTRY

According to the Ecuadorian Ministry of Agriculture, the banana sector still represents more than 30% of total exportable items in the country. Petroleum and shrimps are the other national incomes. In 1998, there were more than 135000 Ha of banana crops located in five provinces along the coastal region in Ecuador (El Oro, Guayas, Los Ríos, Esmeraldas and Manabi). The first three provinces have more than 80% of the cultivated surface area, and are shown in Figure 2.6.

Figure 2.6. **Map of Ecuador with political and province boundaries. White circles show the sites visited during this research which can represent more than one farm**

Due to weather and sometimes soil conditions, it has not been an easy task for Ecuadorian banana farmers to maintain the production at sufficiently high level because of several pests such as black sigatoka, several types of insects, nematodes and viruses. However, the number of pesticide applications in Ecuador is still less than in other banana countries (CORPEI 1999). Nowadays, the Ecuadorian banana sector uses more than 30 agrochemicals that are randomly distributed in all farms. During the year, an average of 10 different pesticides is used per banana farm (Matamoros 1999). On the other hand, farms can be managed to harvest fruit all year round.

In order to make an accurate assessment of the pesticide management in the Ecuadorian banana sector, a two step approach to get the information was followed:

1.   Searching existing bibliography, pesticide fact sheets and public available data.
2.   Conducting field visits to some farms.

However, some difficulties were encountered during the research to get enough environmental data to assess the actual condition of the sector:

- The majority of public and private institutions in Ecuador do not have the training to collect environmental records on a periodical basis. In addition, the few stored records are difficult to access for the average citizen.

- Most of the farmers are not willing to open their plantations to research. Sometimes, they claim that this type of investigation would be "dangerous"[8] for their activity.

- Some farmers are more interested in their product sales than in environmental issues, and there is no specific environmental enforcement for the banana sector. This is the main reason why farmers do not keep environmental records at all.

Due to the difficulties exposed above, only seven farms were visited to get the needed information. Visits were conducted between May and August 2000. Visited sites are depicted in Figure 2.6, as white circles. The farms were selected on the basis of the following criteria:

- Acceptance of farmers to visit their plantations based on previous contacts or meetings with banana corporations.

- Fair distribution of visited farms among the three most productive provinces in Ecuador: three banana farms in Guayas, three banana farms in El Oro and one banana farm in the Los Ríos province.

- Two of the farms belong to a big national producer corporation. This banana corporation has 39 farms (in total) distributed over the entire country, representing approx. 6000 Ha. Importantly, all of the 39 farms have the same pesticide management.

Table 2.13 shows a summary of the farm characteristics obtained from the field trips. The characteristics related to the number of farms and the area can be projected to other sites since it is considered that two of the visited farms belong to a big corporation that manages 39 farms almost in the same way. Thus the numbers related to characteristics 2, 3 and 4 would change into 6770 Ha, 5.01% and 0.89% respectively.

It is important to note that every application cycle does not always use the same pesticide. Different pesticides are applied depending on specific needs on the plantation and weather conditions on the area: usually, herbicides and nematicides are used in the rainy season and

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[8] Because the bad environmental management could be traced by environmental regulators.

fungicides in the dry season. Thus, a specific pesticide could be applied a maximum of 5 times a year.

Table 2.13. Summary of characteristics found in the visited banana farms

Number of farms visited	7
Total Cultivated Area within visited sites	1407 Ha
% Area relative to Banana Sector (135000 Ha.)	1.04%
% Number relative to total farms in Ecuador	0.14%
Average banana plant population	1478 plants / Ha
Average production	650 kg per week per hectare
Average number of packaging facilities	1 per every 100 Ha
Average number of pesticides used in a farm	≈10 agrichemicals per farm
Average number of application cycles	≈15 applications per year
Pesticides most used in the farms	Imazalil (packaging) Thiabendazole (packaging) Tridemorph (aerial spray) Propiconazole (aerial spray) Glyphosate (manual spray)

In banana plantations, pesticides are used in two ways in the production process: direct application on the plant (via fumigation or direct manual spray) and mixed with water after washing the fruit in a pool (classification of the fruit).

The first type of application is related to non-point pollution discharges into a river. When the pesticide is applied on the ground (by airplane or by manual spray), the chemical is distributed over a surface area which is affected by different runoff patterns. The pesticide is transported over the entire area and discharged at multiple points across the river. In banana plantations, the frequency of this application is up to 24 times per year in the entire farm area. The most common pesticides applied by this method are propiconazole, benomyl, tridemorph and glyphosate.

The second type of application is related to point pollution discharges. After spraying the fruit with a mixture of pesticide and water, the mixture droplets fall into a channel system that ends up in the river at a specific location. This type of discharge is produced every week during two days (a typical packaging period in a banana plantation) at the packaging facility. Based on data from visited farms, there is a packaging facility every 100 hectares (Table 2.13). The pesticides most used in this method are thiabendazole and imazalil.

2.5.3. LABORATORY AVAILABILITY FOR PESTICIDE ANALYSIS IN ECUADOR

An important part of the current research is the pesticide analysis. It is necessary to evaluate pesticide concentrations in water and eventually in sediments along some irrigation channels and main streams in the study area. Based on that, five pesticides are found to be the most used in the banana sector: glyphosate, tridemorph, propiconazole, thiabendazole and imazalil (Matamoros and Vanrolleghem 2001). The first one is a herbicide and the others are fungicides. Table 2.14 shows the recommended techniques to detect concentrations in water and soil for these pesticides.

An assessment was conducted in the available labs in Ecuador in 2000 and 2001. Visits were paid to different laboratories (both public and private) in Guayaquil including ESPOL's Chromatography Lab. Other laboratories in Ecuador were contacted via e-mail, phone and fax. Some labs outside Ecuador were located via Internet for use as reference[9]. Some of these foreign labs also have information related to testing prices in their web pages.

Table 2.14. Recommended analysis to detect pesticide concentrations in water and sediments

Pesticide	Possible Lab Analysis to determine residues on soil and water	Comments
Glyphosate	HPLC + post column derivatisation	
Imazalil	GLC-ECD, HPLC	
Propiconazole	GLC-ECD, GLC-TSD, GLC-FID	Methods available from Ciba-Geigy AG
Thiabendazole	HPLC	
Tridemorph	Colorimetry of a derivative, GC-MS	Methods available from BASF

Source: Several references
Notes: HPLC: High Performance Liquid Chromatography
   GLC: Gas-Liquid Chromatography
   MS: Mass Spectrometry
   ECD: Electron Capture Detector
   TSD: Thermionic Specific Detector
   FID: Flame Ionization Detector

Table 2.15 shows a summary of the findings on laboratory availability in Ecuador up to 2001. This lab availability information will become very important to the banana sector if environmental regulations on exportation markets require monitoring pesticides in the farm environment.

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[9] Due to the events in the USA in September 2001, sample shipments to several countries including Belgium were forbidden or restricted. Therefore, the current research was forced to find and select a qualified Ecuadorian laboratory to do the pesticide analysis.

Table 2.15. Available laboratories for pesticide analysis in the current research (2001)

LAB	Lab Type	Supply Sampling Bottles	Pesticides	Comment
Chromatography Lab – ESPOL	public	NO	Imazalil, Propiconazole	It has a GC Chromatographer but it is necessary to buy some accessories and reactants to do the tests. Prices per sample are around $ 120. Some investment could be done to improve the lab capacity.
Institute of Hygiene	public	-	None right now	It has the equipment but the personnel does not have experience with pesticide detection
CEDEGE	public	-	None right now	It has the equipment but the lab was shut down due to lack of work and expertise.
GRUNTEC	private	YES	All	Actually it does not have the equipment, but it has an agreement with foreign labs to conduct the tests. However, the lab manager recommended us to contact the foreign labs directly because of the price (above $250 per sample)
Ecuadorian Service of Agriculture Sanitation (SESA)	public	-	Not known	A fax was sent to it requesting information. The lab did not answer.
Ecuadorian Commission of Atomic Energy	public	NO	Propiconazole, Imazalil, Thiabendazole	It has the equipment and personnel. Prices per sample are around $ 80
National Institute of Agriculture Research (INIAP)	public	-	Not known	Upon request, they answered that the lab can do pesticide tests, but they do not have enough personnel to accomplish the project.
NESTLE – Quito	private	NO	Glyphosate	They have currently implemented a chromatography lab to trace herbicides in their dairy products.
AQUALAB (New England, USA)	private	Not known	All	It is shown for comparison purposes. The web site is http://www.aqualab.net. The price per sample is around $575 but includes basic analysis (pH, dissolved solids, nutrient content and others), shipping and handling would be added.

Based on table 2.15, it is clear that the lab capacity for pesticide analysis in Ecuador is extremely low. The few existing labs (mainly public) can detect only some pesticides in water and soil. In contrast, Ecuador is importing pesticides grouped in more than 30 chemical families.

If different events (inside and outside the country, such as environmental restrictions to the banana market) are on the way forcing people to know more about pesticide concentrations, the field of pesticide analysis should be increased and Ecuadorian authorities and institutions such as ESPOL must improve their response to on this challenge.

Another problem, also tested in USA and Europe, is that analytical detection levels in pesticide analysis may be too high to determine the presence/absence for human health protection (Ongley 1996). Some pesticide standards and drinking water levels have reached the nanograms per liter level (1×10^{-6} mg/l). However, some labs will only produce a ND (not detectible) value which is not evidence that the chemical is not present in concentrations that might harm the biota and human beings. This analytical problem represents an extremely serious drawback for environmental monitoring in developing countries such as Ecuador.

2.6. PROBLEM DEFINITION

Once all facts were reviewed in the present chapter, a research path was devised regarding the study of environmental impact of pesticides in Ecuadorian banana plantations. Thus, two main issues will be cleared out in this Ph.D. thesis.

The first issue deals with gathering the available information in order to perform the pesticide assessment. Such data include topographical, meteorological, soil and crop data. Main sources of information are farmers and public institutions. However, as pointed out in this chapter, those sources do not have sufficient records. Therefore, it will be necessary to generate secondary information to fill the data gaps. A compilation of several procedures will be presented as future guidelines for other researchers.

Once the data set is completed, the second issue will be tackled: assessing pesticide impacts by using existing modelling techniques. As previously pointed out, available data set is poor, so the use of this kind of data becomes a challenge in modelling issues. Most of poor developing countries usually do not have very good data sets for modelling purposes or do not have the budget to generate it. Therefore, the case study presented here can help others to overcome the problem of data scarcity when modelling pesticides in the environment.