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PREDICTING RIVER CONCENTRATIONS OF PESTICIDES FROM BANANA PLANTATIONS UNDER DATA-POOR CONDITIONS

VOORSPELLING VAN PESTICIDENCONCENTRATIES UIT BANANENPLANTAGES IN RIVIEREN ONDER GEGEVENSARME OMSTANDIGHEDEN

door

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CONTENTS

CHAPTER 1. INTRODUCTION

View of the Chaguana river basin, Ecuador

1.1. BACKGROUND

Banana is one of the most important products of exportations, from Ecuador. It represents more than 30% of the Ecuadorian exportations (Ecuadorian Central Bank 1998). To keep a high production level, Ecuadorian farmers are using pesticides and fertilizers on a frequent basis, and sometimes without technical advice. As a result, this chemical utilization has brought not only better crop production, but contaminants have been detected on some rivers and soils (ESPOL[1]-VUB 1998).

In 1993, a complaint was taken to the courts by the shrimp-farming sector against banana farmers and pesticide importers. This complaint was related to a disease observed in shrimps, which the producers claimed that pesticides used in banana sector were causing. Some shrimp production was lost because of this disease called "Taura's Syndrome" (Sindrome de Taura). Research, paid by shrimp farmers, was conducted to discover the origin of the disease. Traces of propiconazole and tridemorph, pesticides usually used in banana plantation were found in some shrimp's tissue samples. As a result, the Ecuadorian Shrimp Association tried to sue some pesticide manufactures outside the country because of the use of "hazardous" pesticides in Ecuador. However, the research was not sufficiently conclusive to assure that pesticides caused the disease. Other pollutants (heavy metals) were also discovered on tissue samples. In addition, the shrimp sector has not reported more cases related to this disease since 1996, although the banana farmers are still using the same pesticides.

In 1999, the Escuela Superior Politecnica del Litoral (Ecuador) began a cooperation agreement with the Council of Flemish Universities (VLIR) to develop scientific research in several areas of interest. The entire program was named VLIR-ESPOL Project, and it was divided in six components. Among them, Component 4 is doing research towards the development of Environmental Management Systems on Aquiculture and Agriculture. To a certain extent, the component's research focused on building a bridge between banana and shrimp producers by developing some tools that can explain and help to solve the interlinked environmental problems within their activities. For that reason, the component was divided in three main investigations:

[1] Escuela Superior Politécnica del Litoral

1. Determination of environmental impacts from the usage of pesticides in the Ecuadorian banana sector
2. Use of the benthos as an indicator of anthropogenic contamination in the natural shrimp populations
3. Development of an epidemiologic alert system for the shrimp farmers in the Gulf of Guayaquil.

The present thesis research deals with the first area of interest within Project 4 of the VLIR-ESPOL Programme. In 2003, the cooperation was renewed by adding a second phase to the programme. In the new phase, new research areas will take advantage of the work done in the first phase, including the present thesis. Because of the findings in the present research, the project team pointed that besides banana and shrimp sectors, other potential users in Ecuador could benefit from the research by expanding the initial project goals. Therefore, the new phase will deal with Integrated Watershed Management by assessing and developing environmental tools that could help Ecuadorian regulators in enforcing the existing law. Areas such as agriculture economics, biological monitoring of ecosystems (rivers and beaches), and use of GIS and Artificial Intelligence tools will be covered by the second phase.

In the same year 2003, the research team made an agreement with UNESCO to be part of the HELP programme (Hydrology for Environment, Law and Policy), and the study area of the present thesis was selected as a candidate HELP basin. Therefore, most of the research presented here will be used to develop more investigations within the HELP framework.

1.2. WORKING GROUPS

The promoter of this thesis was Prof. Dr. ir. Peter A. Vanrolleghem from the Department of Applied Mathematics, Biometrics and Process Control, Faculty of Agriculture and Applied Biological Sciences, Ghent University. In addition, there were other working groups inside and outside the project that collaborated in the development of this thesis:

- The Centre of Environmental Studies (CEMA – ESPOL, Ecuador) performed some environmental diagnostics in a banana farm within the study area. In addition, some social data were gathered in the selected basin.
- The Faculty of Earth Sciences (ESPOL, Ecuador) performed the soil analysis to obtain texture and soil-water contents. In addition, through two undergraduate theses, two

important topics for this research were accomplished: the hydrology and the hydraulics issues in the selected river basin (Guzman and Bonini 2003; Vivas 2004).

- The Centre of Aquiculture Services (ESPOL, Ecuador) performed the analysis in soil to obtain organic matter content, and BOD and solids content in water samples.
- The Commission of Atomic Energy (Ecuador) performed the laboratory analysis to quantify pesticides in water and sediment.

1.3. RESEARCH GOALS

This thesis research has focused on several goals and objectives within the framework of the VLIR-ESPOL project.

From the project point of view, this thesis has evaluated the fate of current pesticide contamination produced by a typical banana area in an Ecuadorian river basin by using monitoring and modelling. In addition, this research set the basis for new upcoming studies to be done in the frame of the VLIR-ESPOL project and in Ecuador in general.

From the research point of view, the thesis aimed to develop several modelling tools and some procedures to be used as part of the Environmental Tools that the VLIR-ESPOL project is planning to make available for Ecuadorian River Basin Management. In addition, this research aimed to increase the ESPOL know-how to turn ESPOL to an Ecuadorian Reference Centre for Environmental Modelling issues.

From the academic point of view, this thesis is intended to be used as a textbook at ESPOL University in courses such as Environmental Engineering, Hydrology, Modelling or GIS at the Faculties of Earth Sciences and Marine Sciences. In Ecuador, there is currently no official textbook that explains the procedures and limitations involving environmental modelling with an Ecuadorian Case Study. As it is stated in the thesis, poor developing countries such as Ecuador lack several tools that could help in evaluating a non-point pollution problem like it is done in well-developed countries such as Belgium.

From the author's personal point of view, this thesis is another step in enriching his own knowledge to become a more useful and experienced lecturer for his students. Whether the author works in research, academic or consultant areas in Ecuador, this is a contribution to improve the way scientific research is used in Ecuador.

1.4. THESIS OVERVIEW

The thesis is arranged in such a way that the reader can easily understand the scope and goals of the research. In addition, the text arrangement is intended to be used as a guiding textbook for assessing non-point pollution problems where a poor data-set is available.

Chapter 2 gives a review of available literature regarding pesticide issues. The chapter is divided in five sections: a description of the existing water quality regulations in Ecuador, the behaviour of pesticides in the environment, existing non-point pollution models, the use of GIS tools within environmental modelling, and background information regarding pesticides and banana issues in Ecuador.

Chapter 3 deals with the gathering of data to perform the pesticide assessment. It is pointed out that in poor-developing countries such as Ecuador data collection is quite difficult and sometimes impossible. Existing data could be outdated, in non-standardised formats and usually recorded frequencies lower than the models need. This chapter shows some procedures to generate secondary data from measured or existing scarce data (named as primary data) in order to run some models to predict chemical concentrations as near as possible to field data measured during this research.

Chapter 4 explains the evaluation and two screening or compartmental models, EXAMS and EQC, which helped in visualizing the way pesticides are grossly distributed in the environment. A comparison between the outcomes of both models is presented. In addition, it is also shown the the evaluation, calibration and outcome comparison between two spatially-integrated models, AGNPS and SWAT models. AGNPS model is a runoff-based model that evaluates mainly agrichemicals attached to sediment transported in a river. However, other agricultural practices such as fertilisation, irrigation and livestock management can also be evaluated. Although SWAT model is also a runoff-based model, it mainly focuses in the chemical interaction between soil and water compartment. Both models are the most used for pesticide management purposes worldwide.

Chapter 5 gives the conclusions of the research, and presents some recommendations to be considered for future researchers and Ecuadorian regulators to improve the way non-point pollution problems should be assessed.

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.

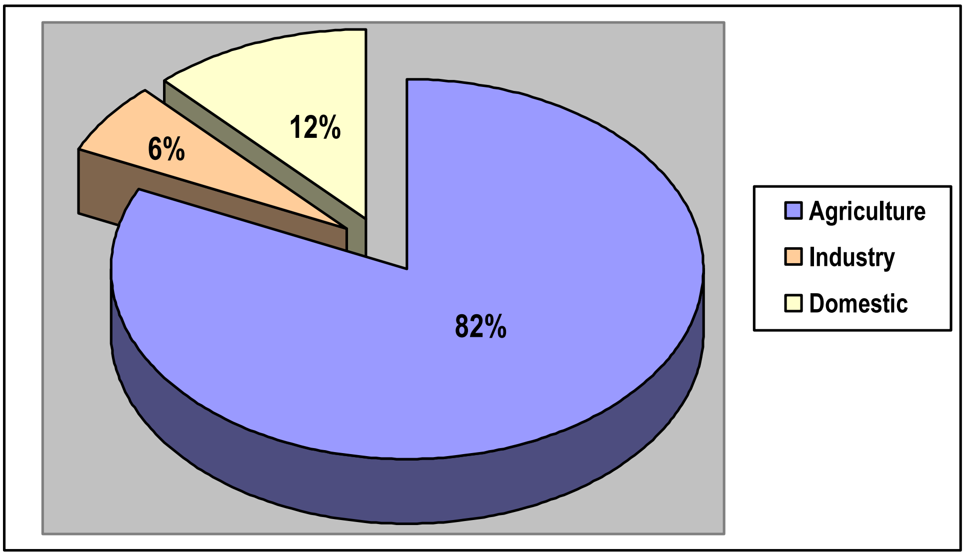

Figure 2.1. Water usage distribution in Ecuador after Herrera *et al.* (2004, *in press*)

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

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

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

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

[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.

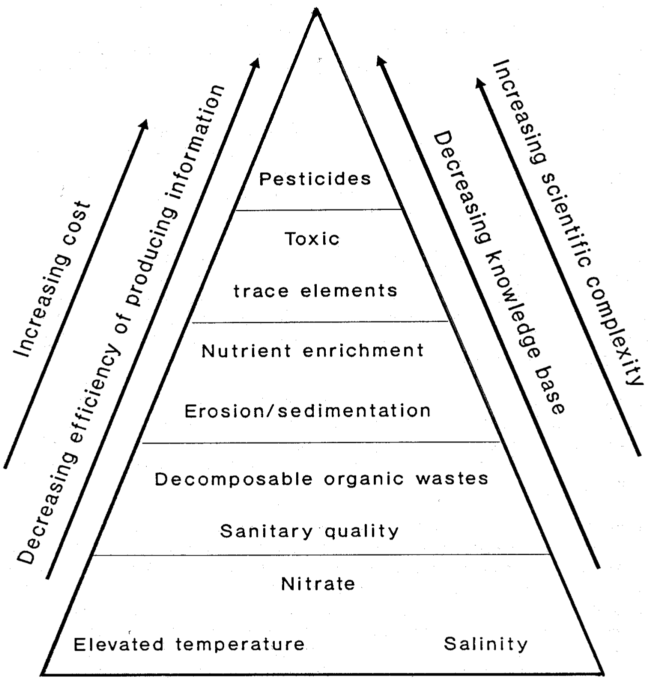

Figure 2.2. Hierarchy of pollutants from agricultural activities (Rickert 1993; Ongley 1996)

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.

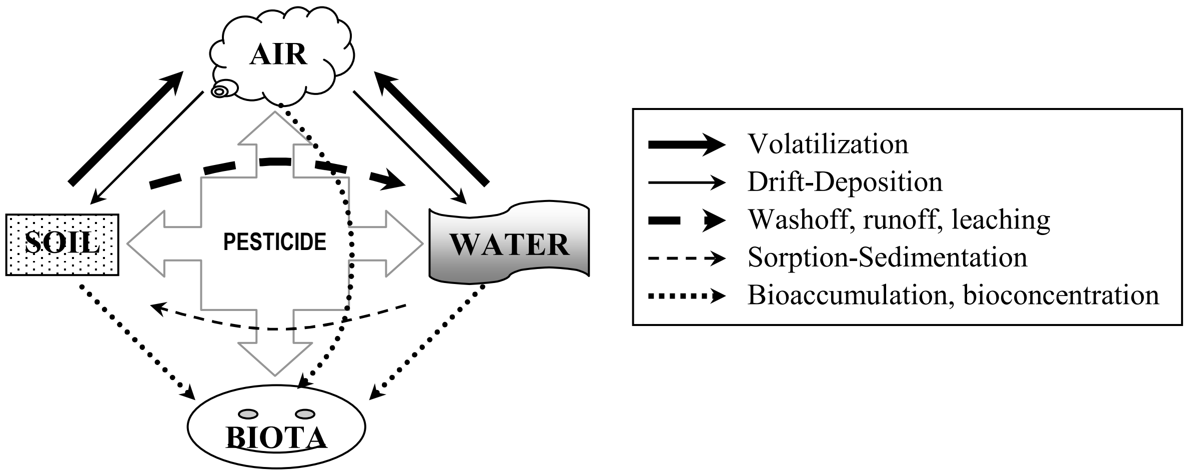

Figure 2.3. Movement of pesticides between compartments of the environment

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.

$$C_Z = \frac{2\, C_h\, h\, (h - z)}{\left(\sqrt{2\pi}\right)\sigma^2}\, e^{-\frac{h^2}{2\sigma^2}} \qquad [2.3]$$

[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.

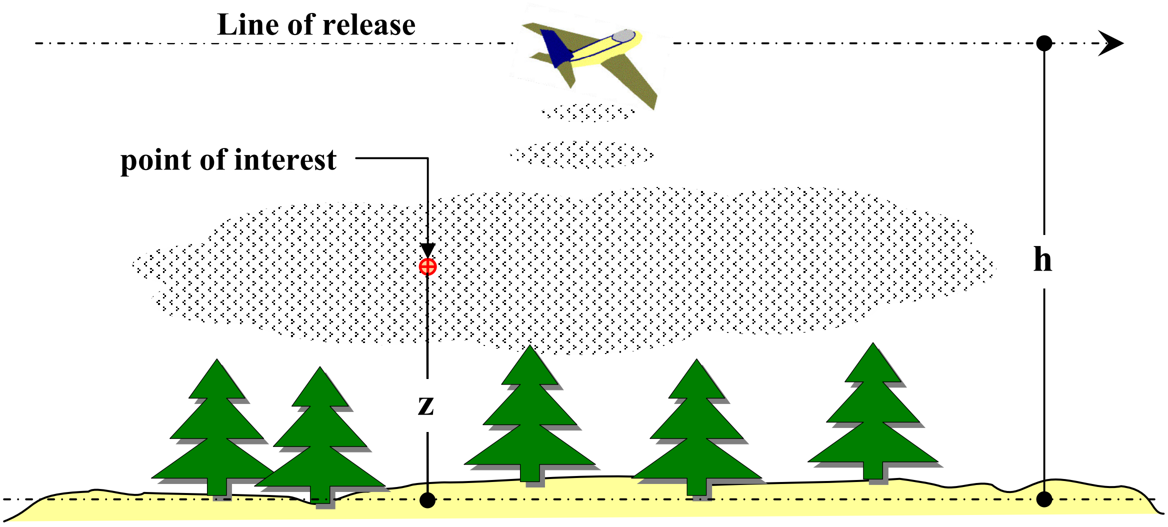

Figure 2.4. Pesticide cloud dispersion after Johnson and Sayer (1970) and Csanady (1973)

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]).

$$\frac{dM_{foliage}(t)}{dt} = \left[-k_F \ M_{foliage}(t) - W_{pesticide}(t) + A_{pesticide}(t)\right] \quad [2.4]$$

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.

$$C_S = K_d \ C_W \quad [2.5]$$

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]).

$$\frac{\partial \theta}{\partial \psi}\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial x}\left[K(\psi)\frac{\partial \psi}{\partial \theta}\frac{\partial \theta}{\partial x}\right] + \frac{\partial}{\partial y}\left[K(\psi)\frac{\partial \psi}{\partial \theta}\frac{\partial \theta}{\partial y}\right] + \frac{\partial}{\partial z}\left[K(\psi)\frac{\partial \psi}{\partial \theta}\frac{\partial \theta}{\partial z}\right] + Sink_{water} \qquad [2.7]$$

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

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.

$$R_F \frac{\partial C}{\partial t} + V\frac{\partial C}{\partial x} = D_X \frac{\partial^2 C}{\partial x^2} + D_Y \frac{\partial^2 C}{\partial y^2} + D_Z \frac{\partial^2 C}{\partial z^2} - R\, k_T\, C \qquad [2.8]$$

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].

$$\frac{\partial C}{\partial t} = \left(D_X \frac{\partial^2 C}{\partial x^2} + D_Y \frac{\partial^2 C}{\partial y^2} + D_Z \frac{\partial^2 C}{\partial z^2} \right) - \left(V_X \frac{\partial C}{\partial x} + V_Y \frac{\partial C}{\partial y} + V_Z \frac{\partial C}{\partial z} \right) \pm \text{Reactions} \qquad [2.9]$$

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)

$$R = \frac{V}{V_P} = 1 + \frac{\rho_b K_d}{n_T} \qquad [2.10]$$

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])

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

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).

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

Where

C_i , C_j	Pesticide concentration in organism *i* and *j* respectively
C_d	Pesticide concentration dissolved in the water
$F_{i\,j}$	Consumption rate of organism *i* on organism *j*
W_i	Weight of organism *i*
$\alpha_{i\,j}$	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*

[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.

[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.

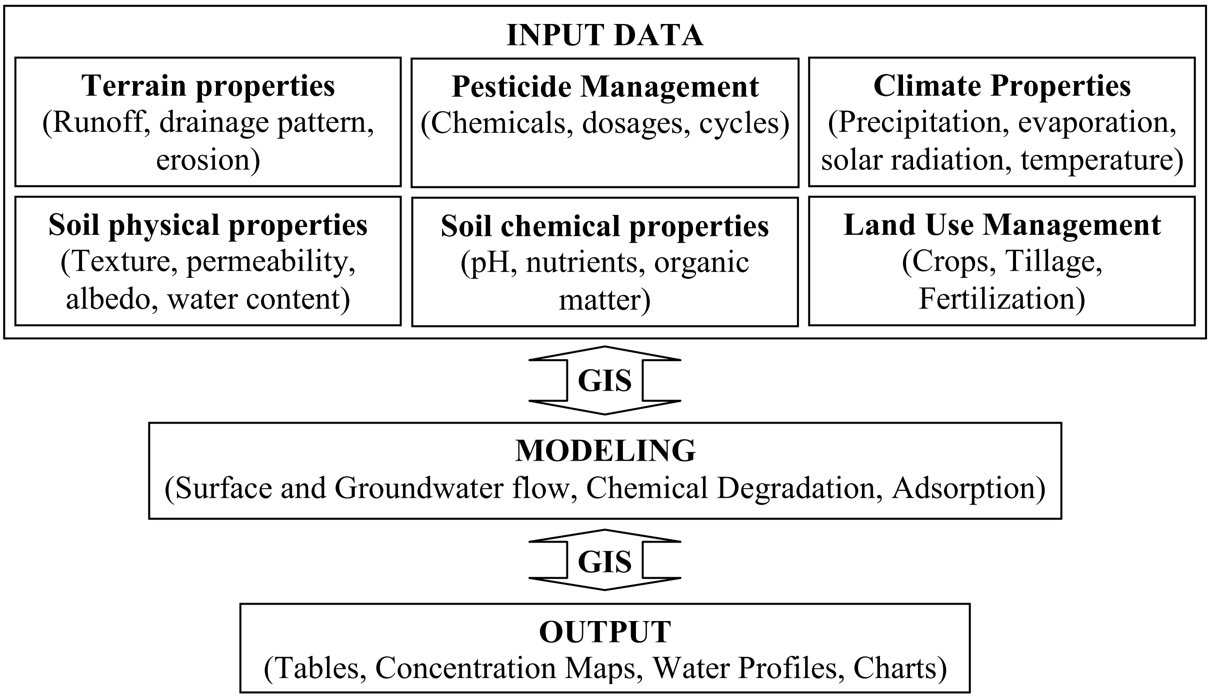


Figure 2.5. GIS-based pesticide modelling scheme

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

[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.

[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.

CHAPTER 3. DATA GATHERING PROCESS

Measurements in the Chaguana river, Ecuador

Parts of this chapter were published in

Matamoros D., Bonini J., Guzman E., Ramirez G., and Vanrolleghem P.A. (2002). Design and implementation of a measuring campaign to model pesticide impacts in an Ecuadorian watershed. Water Science and Technology, 46(9), 37-45.

Matamoros D., Van Biesen L. and Vanrolleghem P.A. (Submitted). Development of a Geographical Information System for pesticide assessment on an Ecuadorian watershed. *Submitted to:* Water Science and Technology.

3.1. INTRODUCTION

The present chapter shows the procedure followed to gather all necessary data to run the evaluated models, mainly AGNPS. When gathering information, data is not necessarily in the correct format for the model execution. Thus, this chapter also presents several processes to convert the collected data. The data structure of each model is shown in the next chapter.

As part of the research objectives, this chapter presents some guidelines for selecting, gathering and processing poor data for environmental evaluation of watersheds in developing countries based on the current experience in Ecuador. The following sections show data processing procedure followed to obtain the most reliable data to be used in the model evaluation phase.

3.2. METHODOLOGY

Before using an environmental model to determine pesticide impacts caused by banana plantations in a watershed, an important step is the collection of representative and reliable data to be used in the model. In Ecuador, like in the majority of developing countries, public and private institutions do not always maintain a good housekeeping of environmental records. In addition, available information is sometimes outdated and not easily accessible. Thus, obtaining information could be difficult to accomplish, and some extra efforts must be done to process the gathered data.

In this Ph.D. thesis, GIS procedures were used in the data evaluation process. The platform selected for GIS processing was ArcView. Most of the GIS generated data was used as input data in the model execution step. However, the majority of data representing the different phenomena are only available as scarcely and irregularly distributed data. Thus, it is necessary to convert those data to a raster format in order to consider spatial variability in the modelling work. Other data were converted to vector format[10] as an intermediate step to aggregate raster data for classification purposes. All data were grouped in two categories:

[10] Vector data in ArcView is represented by shapefiles which is a simple non-topological format for storing attributes and location of data.

- **Primary data** were collected directly from available national databases or measured in the field. These data were evaluated according to the source, year of publication and scale in order to maximise information extraction (Table 3.1). For example, edaphology data was extracted initially from printed maps (only existing soil taxonomy groups in the area); later, these data were complemented with own soil sampling campaigns (Matamoros *et al.* 2002) and lab analysis (texture, soil moisture content).

Table 3.1. Primary data obtained in the Chaguana river basin

Data	*Primary Source*	*Year*	*Scale*	*Data extraction procedure*
Topography	Printed Maps	1970	1:50000	Scan of 4 topographical sheets
Geology	Printed Maps	1970	1:250000	Scan of 1 geological sheet
Edaphology	Printed Maps	1970	1:250000	Scan of 1 edaphological sheet
Land use	Digital Data	1998	1:50000	Visualization in ArcView
Climate	Database	Depends on station	Not applicable	5 georeferenced weather stations
Soil	Field Measurement	2001	Not applicable	30 georeferenced sampling sites
Water Quality	Field Measurement	2002	Not applicable	26 georeferenced sampling sites

- **Secondary data** are more elaborated data that include spatial variability in grid format. For the current research, it was generated from primary data by using kriging interpolation, accepted equations or methodologies applied in similar situations. The majority of information was generated as raster format because the evaluated models are raster-based. The cell size for the generated raster data was 1 hectare. Multiple thematic maps were developed to extract input data for the models (Table 3.2).

Table 3.2. Thematic maps generated from primary data on the Chaguana river basin

Thematic Maps	*Geographic Feature*	*Generation procedure*	*Reference*
Elevations	Point	Digitising from scanned maps	GIS procedure
Digital Elevation Model	Grid	Interpolation procedure	GIS procedure
Slope	Grid	ArcView Avenue statement	GIS procedure
Geologic Units	Polygon	Digitising from scanned maps	GIS procedure
Taxonomic Units	Polygon	Digitising from scanned maps	GIS procedure
Weather Stations	Point	Add as an event theme in ArcView	GIS procedure
Precipitation	Grid	Interpolation procedure	GIS procedure

Thematic Maps	*Geographic Feature*	*Generation procedure*	*Reference*
Runoff Erosivity Factor	Grid	Use of RUSLE equations in Map Calculator	Renard *et al.* (1997)
Sampling Sites	Point	Add as an event theme in ArcView	GIS procedure
Clay – Silt – Sand content	Grid	Interpolation procedure	GIS procedure
USDA Soil Texture	Grid	Boolean Algebra	Benham *et al.* (2001)
Very fine sand content	Grid	Interpolation procedure	GIS procedure
Soil Moisture content	Grid	Interpolation procedure	GIS procedure
Saturation content	Grid	Use of equations in Map Calculator	Saxton *et al.* (1986)
Field capacity content	Grid	Use of equations in Map Calculator	Saxton *et al.* (1986)
Wilting point content	Grid	Use of equations in Map Calculator	Saxton *et al.* (1986)
Bulk density	Grid	Use of equations in Map Calculator	Saxton *et al.* (1986)
Saturated hydraulic conductivity	Grid	Use of equations in Map Calculator	Saxton *et al.* (1986)
Hydraulic soil group	Grid	Boolean Algebra	USDA-NRCS (1986)
Organic matter content	Grid	Interpolation procedure	GIS procedure
Soil albedo	Grid	Use of equation in Map Calculator	Baummer *et al.* (1994)
Soil Map	Polygon	Data aggregation from soil grids by using Taxonomic Map as a mask	GIS procedure

3.3. SELECTION OF THE STUDY AREA

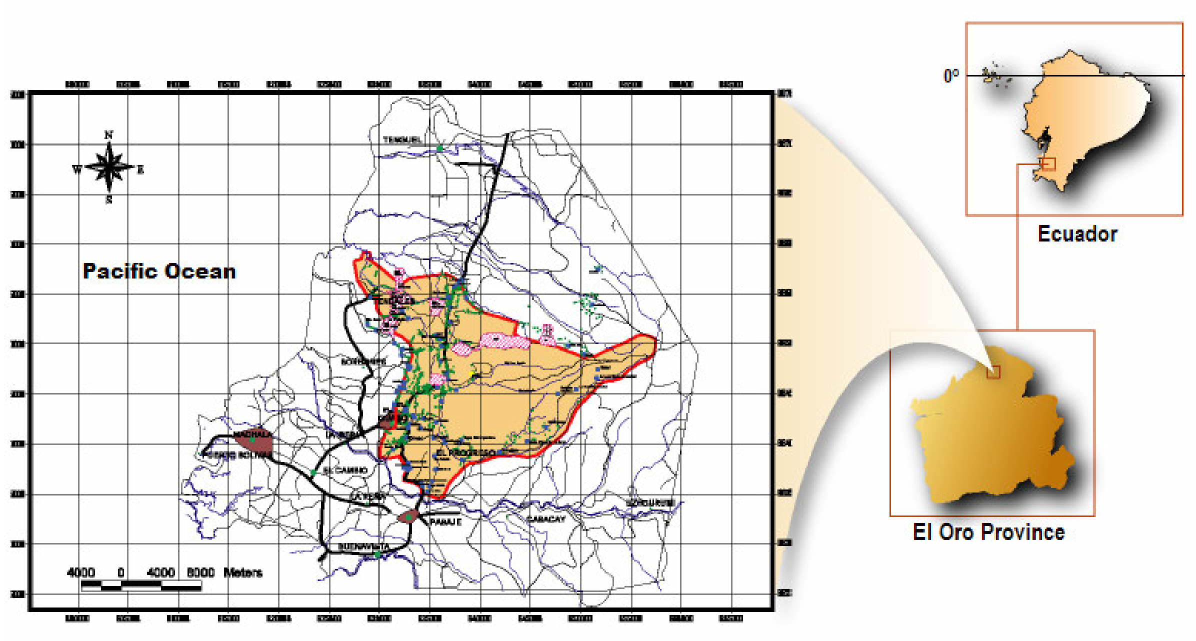
According to the Ecuadorian Central Bank, the Ecuadorian banana activity covers approximately 139000 Ha distributed over 7 coastal provinces. However, the banana activity is not always the only crop affecting a specific site. Thus, an impact assessment of pesticides only coming from banana plantations could be impossible to achieve[11]. For that reason, the current research selected a site in such a way that the main goal could be achieved by minimizing other crop interference. The criteria applied for site selection were:

- As pesticides are transported mainly through the hydrological cycle, a river basin should be the most acceptable site to perform the assessment. However, pesticide drift from adjacent basins could influence the final assessment of the selected river basin.

[11] Other crops sometimes use the same agrichemicals as banana farms do (e.g. glyphosate)

- The basin should be median or low size (less than 50000 Ha) in order to avoid multiple crop activities. The larger the basin, the bigger the chance to find more than one crop activity in the basin.
- At least some farmers should agree to collaborate with research (farm management records, pesticide usage, soil and climate records and accessibility)

After visiting some potential study sites in Ecuador, the Chaguana River Basin was selected. It is located in the El Oro Province in the South-Western part of the country (Figure 3.1). This river basin is approximately 32000 Ha, which could be considered as a hydrological system between a rural catchment and a river basin (Maidment 1996). The Chaguana system does not discharge directly to the sea, but to a bigger watershed called the Pagua River Basin. However, the sea tidal influence reaches up to 6 km upstream the Chaguana basin's outlet.



Source: Centre of Environmental Studies (CEMA) – ESPOL, 2002

Figure 3.1. Location of the Chaguana river basin

3.4. TOPOGRAPHICAL DATA

3.4.1. Available Cartographical Information

In Ecuador, the Geographical Military Institute (IGM) is the official organism to keep, publish and distribute all topographical information. Most of the available information is from 1970, and it is distributed as printed maps at 1:50000 scale. On those printed maps, elevation contours are displayed every 40 meters with scattered elevation points representing measured bench marks above sea level. Terrains between 0 and 40 meters do not show any elevation contour. Contours on printed maps were drawn based on aero-photogrammetric procedures.

Because topographical information is always used as a reference for other types of information, cartographical data were obtained from those printed maps, with geographical characteristics given in Table 3.3

Table 3.3. Cartographical characteristics used in the geo-referencing data process

Coordinate System / Projection	Universal Transverse Mercator – Zone 17 S
Datum	Provisional South American Datum 1956
Spheroid	International 1924
Horizontal and Vertical Units	Meters
Latitude of Origin	0º
Central Meridian	-81º
False Easting (meters)	500000
False Northing (meters)	10000000

The selected study site, the Chaguana River Basin, is covered by 4 printed topographical sheets: Machala, Tendales, Uzhcurrumi and Ponce Enriquez. The basin is enclosed in a rectangle whose boundary coordinates are shown in Table 3.4. The basin's centroid is located at 641000 E and 9647000 N. The maximum recorded elevation on the basin is 3267 meters and the minimum elevation is 1 meter above sea level. The banana sector in the basin is located below 60 meters and above 4 meters elevation levels.

Table 3.4. River basin boundary locations

Boundary	North	East	South	West
UTM Coordinate	9658919 N	656048 E	9634843 N	625952 E

3.4.2. GENERATION OF DIGITAL ELEVATION MODEL AND OTHER NEEDED TOPOGRAPHICAL CHARACTERISTICS FOR THE STUDY SITE

The Digital Elevation Model (DEM) is raster type data that contains spatially distributed elevation information to allow an automatic delineation of watersheds[12]. DEM for the Chaguana Basin was not available at the time of the study; thus, it was necessary to generate it based on existing topographical maps following the procedures bellow:

[12] Watershed delineation is based on the eight-direction pour point model (Jenson and Dominque 1988)

1. *Digital Conversion of Printed Maps*: Topographical information was converted into digital data by first scanning topographical sheets and then geo-referencing scanned images.
2. *Extraction of Elevation Data*: All elevation contours were digitized into a polyline coverage called *CONTOURS*. Polyline vertexes were then converted into an elevation point coverage by using the EDIT TOOL extension (Tchoukanski 2002). It was necessary to edit the elevation layer to obtain the best terrain representation, which includes manual extrapolation of additional elevation points and addition of some measured terrain levels. Scattered points were also added manually to adjust the shape of the derived river streams to the shape of existing ones[13].
3. *Cell Size Selection*: Before generating a raster image such as a DEM, it is important to define the size of the cell containing elevation data within the raster format. Dealing with watershed delineation, a rule called *thousand-million*[14] is usually applied to obtain the minimum recommended cell size for the watershed assessment (Maidment 1996). For the current watershed assessment, the regional area enclosing the basin is 750×10^6 m^2 ($\approx$ 25 km $\times$ 30 km). Therefore, the minimum recommended cell size was 750 m^2 ($\approx$ 27 m $\times$ 27 m). However, the cell size was defined as 10000 m^2 (100 m $\times$ 100 m) because the majority of agricultural practice management in Ecuador is performed on one-hectare basis. The selected cell size will be used in all generated raster maps.
4. *Data Interpolation*: Finally, the DEM is generated by using an interpolation method with all elevation point data. The selected method was the *Universal Kriging Interpolation Procedure* included in the KRIGING INTERPOLATOR 3.2 extension (Boeringa 2002). The main problem with interpolation is the potential creation of systematic errors in the generated surface. Therefore, the interpolation procedure should be repeated as many times as necessary together with the point layer editing process and river stream generation in order to obtain the best DEM for the study site. Figure 3.2 shows the generated digital elevation model (*FILLEDEM100* raster file) with a 100 m cell size.

[13] Further explanation on stream derivation from DEM will be explained in the hydrological data processing section 3.5.
[14] The rule states that the regional area enclosing the evaluated watershed can be divided down to one million cells without compromising too much effort in the assessment. Further watershed subdivision might not add more precision to the watershed assessment. In addition, the minimum watershed area that could be delineated in that region is obtained by multiplying one thousand times the cell area.

Once the DEM is obtained, other important topographical data for modelling purposes can be obtained by using accepted equations within Avenue statements and macro tools (Map Calculator) in ArcView.

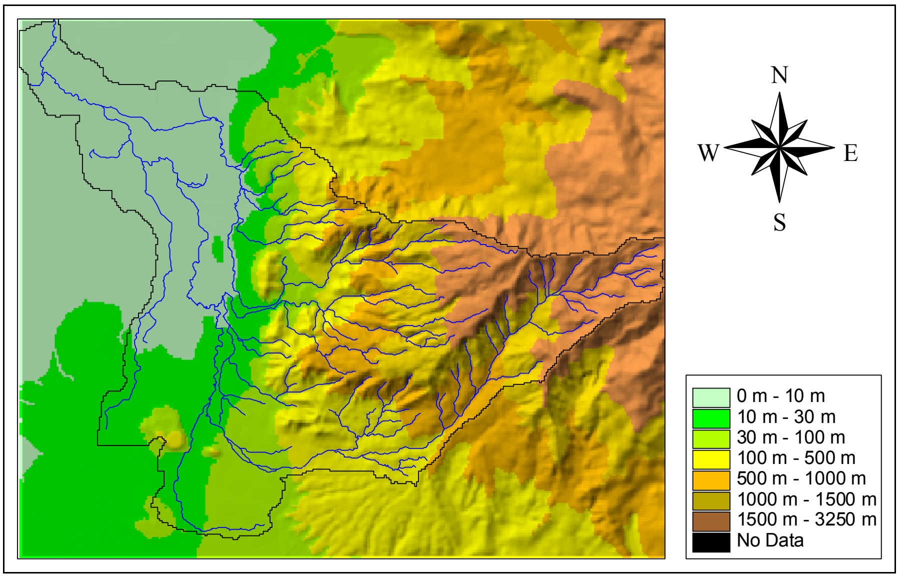


Figure 3.2. Digital Elevation Model with a 100 m cell size

<u>Terrain Slope:</u> The terrain slope angle representation (*SLOPE_PERCENT* raster file) can be generated by using AVENUE statements. The value of each cell is represented as percent rise. Figure 3.3 shows the generated slope raster image. The applied Avenue statement was

SLOPE_PERCENT = FILLEDEM100.Slope(Nil,TRUE) [3.1]

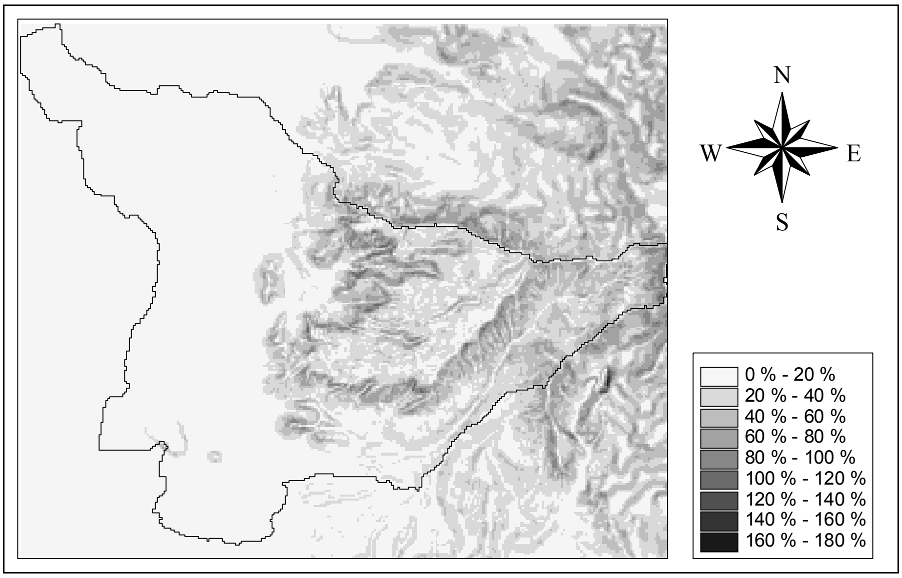


Figure 3.3. Slope percent of the Chaguana river basin

3.5. HYDROLOGICAL DATA

3.5.1. EXISTING FLOW GAUGING STATIONS

When modelling chemicals in rivers, the hydrological data is a very important piece of information to help in quantifying chemical amounts transported by the river flow. In the current research, it was possible to obtain some hydrological information (periodical water flows) in three existing gauging stations from the former National Institute of Water Resources[15]. The locations of the existing stations are shown in Figure 3.4.

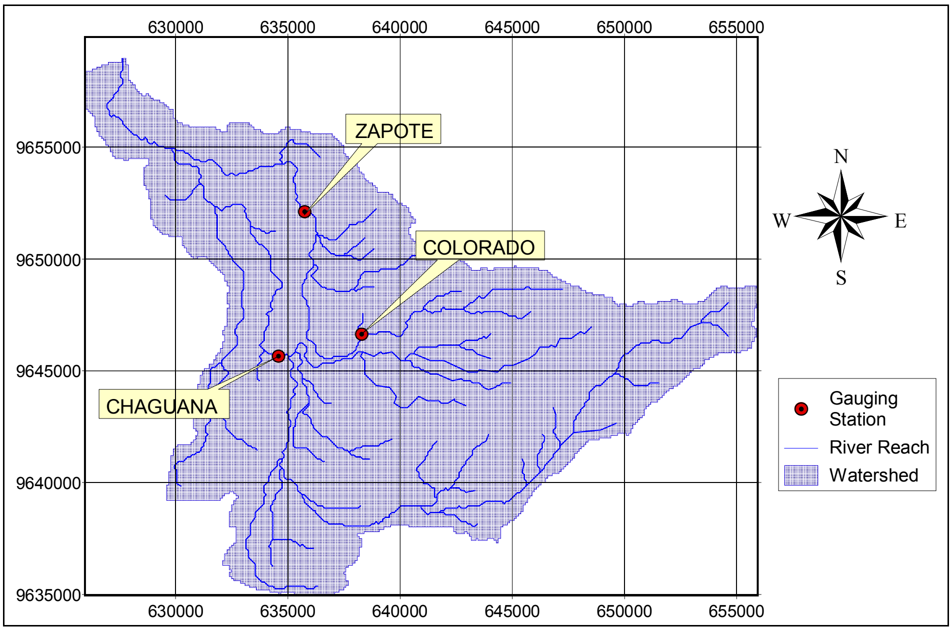


Figure 3.4. Location of existing gauging stations

However, there are some drawbacks related to these records.

- Apparently, the Water Agency is no longer measuring flow data on those stations. The supplied hydrological data only represents a 4-year non-continuous period of measurements (1978 – 1980 and 1982 – 1983).
- The data represent only average monthly flows.
- Some monthly flows are missing at all stations (probably not measured)
- There is no reliable information regarding the measurement method. However, there is a possibility that the flows have been measured by using the existing level marks attached to the bridge's piles at the gauging points (photo 3.1).

[15] INERHI (Spanish acronym) was changed by law in 1994 to the National Council of Water Resources (CNRH)

Photo 3.1. Level marker attached to a bridge's pile

For that reason, the available data was statistically processed to obtain average flow values to be used only in the hydrological calibration of the model. Table 3.5 shows median values of recorded flows within the historical period. The reason of using the median is explained later in the evaluation of meteorological records. From the table, April is the month with the highest flows recorded in the basin. This is strongly related with the rainy season in Ecuador lasting from January to May (see Section 3.6).

Table 3.5. Median flow measurements on existing gauging stations (1979 – 1982)

Gauging Station	*Drainage Area (Ha)*	*Measured monthly flows (m^3/s)*											
		JAN	*FEB*	*MAR*	*APR*	*MAY*	*JUN*	*JUL*	*AUG*	*SEP*	*OCT*	*NOV*	*DEC*
Zapote	5772	0.704	0.491	1.125	1.161	0.756	0.483	0.596	0.451	0.363	0.297	0.690	0.669
Colorado	2422	0.350	0.551	0.731	1.813	0.859	0.478	0.513	0.306	0.252	0.284	0.209	0.268
Chaguana	16199	0.762	1.440	1.646	4.453	1.621	1.121	0.619	0.571	0.346	0.481	3.470	1.173

3.5.2. Field Flow and Cross Section Measurements done in the Research

Due to limitations in the flow data, a measurement campaign was planned at some river points to obtain in-situ velocities and cross section areas. These measured data were also used as part of another research whose objective was the hydraulic characterisation of the Chaguana River by using the HEC – RAS model (Vivas 2004). The location of measured river points is shown in Figure 3.5. The monitored points were selected mainly on the basis of accessibility. The campaign was conducted in July 2002.

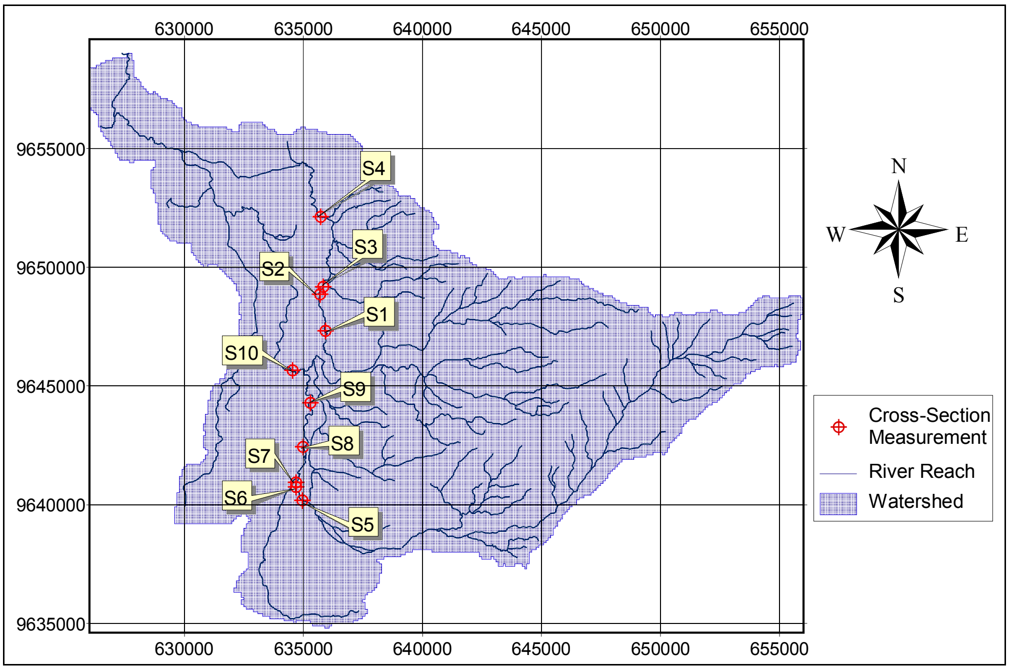


Figure 3.5. Location of measured cross-sections during July 2002

Velocities were measured with a GENERAL OCEANICS Digital Flowmeter, Model No. 2035MKIV. To obtain a representative velocity, the probe was located at one third of the river depth on several places in the same cross section. Then, an average velocity was estimated for the specific cross section. The cross section profiles were obtained by topographic measurements (photo 3.2). Measured data and calculated flows are shown in Table 3.6.

Photo 3.2. Measurement of the cross section S1 in the Zapote river

Table 3.6. Flow estimations at Chaguana river basin during July 2002

River	*Monitored Point*	*Cross Section (m^2)*	*Average Velocity (m/s)*	*Estimated Flow (m^3/s)*
Zapote	S1	1.55	0.320	0.49
	S2	2.03	0.293	0.59
	S3	3.70	0.164	0.61
	S4	3.34	0.226	0.76
Chaguana	S5	2.72	0.222	0.60
	S6	1.23	0.500	0.62
	S7	3.68	0.289	1.07
	S8	1.91	0.651	1.24
	S9	3.03	0.455	1.38
	S10	7.92	0.224	1.77

3.5.3. WATERSHED DELINEATION AND OTHER HYDROLOGICAL DATA NEEDED FOR SELECTED MODELS

Flow data is mainly represented as vector data. However, some hydrological information should be spatially distributed (raster format) for modelling purposes. The majority of those data can be generated from topographical information by using GIS techniques as shown in Figure 3.6.

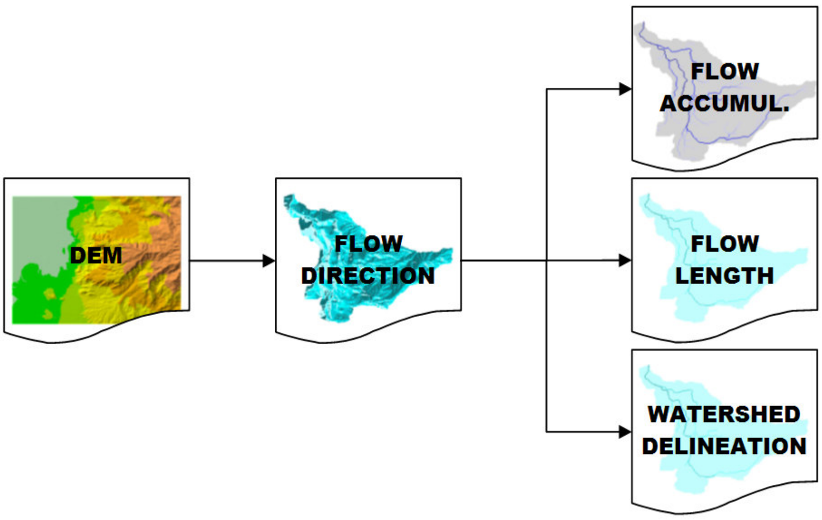


Figure 3.6. Generation of other hydrological data

In this figure, the flow accumulation map generated from the DEM actually shows the cumulative area that drains into a specific cell. By applying colour ramps to the cell values, the map could resemble a river network. However, there are some deviations from the actual river system that can be produced because of:

- **DEM resolution:** The river line in the vector format has actually no real width. The raster cell size is significantly bigger than the visual representation of that line. Thus, the bigger the size of the cell in the DEM, the greater the deviation in the generated river network. In the current research, the cell's size was fixed to 1 hectare as explained in Section 3.4.2.
- **Accurate Topography:** Actual depressions and elevations of the river area may not be well represented by the digital elevation model. Thus, the generated DEM should be adjusted to reflect actual topographical elements at specific sites. There are several methodologies to overcome this problem such as *the burn-in river* method (Maidment 1996). However, such method did not produce good results in the current research. Instead, elevation cell values were changed manually at some areas to force the generated river network to fall within the actual river line.

Figure 3.7 shows a comparison of the same basin spot between the original generated river network and the corrected one by applying the manual adjustments to the Digital Elevation Model. In the figure an extreme case is showed: a conflictive zone where two independent river streams run almost parallel for about 3 km.

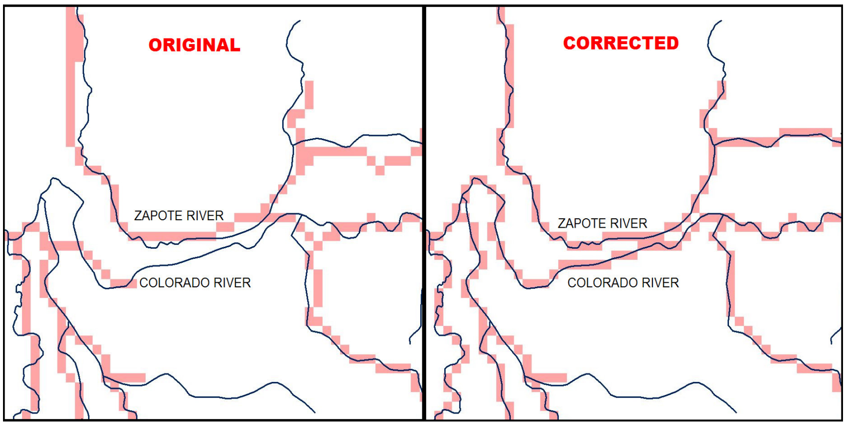


Figure 3.7. Impact of DEM adjustments over river network generation

In the figure, the darker line represents the actual river network while the connected squares represent the generated network. The flow of both rivers (Zapote and Colorado) is from right to left. The original generated network (left) represents the upper part of the Colorado River incorrectly as discharging into the Zapote River. The problem is solved by manual adjustment of the DEM as shown in the corrected river network (right). When modelling non-point sources, this problem must be solved first; otherwise, drainage areas and environmental concentrations could be under- or overestimated.

3.6. METEOROLOGICAL DATA

3.6.1. EXISTING METEOROLOGICAL STATIONS

Meteorological information was gathered among INAMHI[16] weather stations, which are located nearby the Chaguana river basin. However, none of the stations is inside the study site. Historical records on the stations are not continuous, except for one station, and even the recorded period is not the same from one station to another. Table 3.7 shows the nine meteorological stations that potentially could be considered in the river basin and Figure 3.8 depicts the location of the stations related to the watershed. In the table, the distance between each station and the centroid of the basin is also shown. The MACHALA station has the most detailed available information in the area with 27 years of continuous records and measurement of 8 meteorological parameters.

Table 3.7. General description of meteorological stations in the study area

Station	*Distance from Basin's center (Km)*	*Easting (m)*	*Northing (m)*	*Elevation (m)*	*Record Period*	*Type of Data*
Pagua	14.34	636936	9660648	13	1982 – 2000	Monthly precipitation Maximum, minimum and average temperature
Pasaje	16.06	635332	9631874	16	1982 – 1999	Monthly precipitation Maximum, minimum and average temperature
Uzhcurrumi	21.63	657402	9632796	290	1976 – 1999	
Machala - UTM	22.44	621504	9635790	5	1973 – 1999	Monthly precipitation Maximum 24h precipitation Maximum, minimum and average temperature Average relative humidity Sun hours and cloudiness Maximum wind speed and direction
Tenguel	23.25	634815	9669311	10	1965 – 1971 1973 – 1976 1979 – 1980	Monthly precipitation
Tendales	30.89	668850	9633547	750		Monthly precipitation

[16] Instituto Nacional de Meteorología e Hidrología (Ecuadorian National Institute of Meteorology and Hydrology) is the official organization in keeping meteorological records.

Station	*Distance from Basin's center (Km)*	*Easting (m)*	*Northing (m)*	*Elevation (m)*	*Record Period*	*Type of Data*
Huertas	46.49	652199	9601784	1530	1971 – 1977, 1980 1982 – 1986, 1988 1990 – 1991	Monthly precipitation
Santa Isabel	47.51	687718	9638279	1550	1965 – 1987	Monthly precipitation Maximum 24h precipitation Average temperature Average relative humidity Sun hours and cloudiness
La Cuca	49.33	603918	9614373	20	1982 – 1989	Monthly precipitation Minimum and average temperature Sun hours and cloudiness Average relative humidity

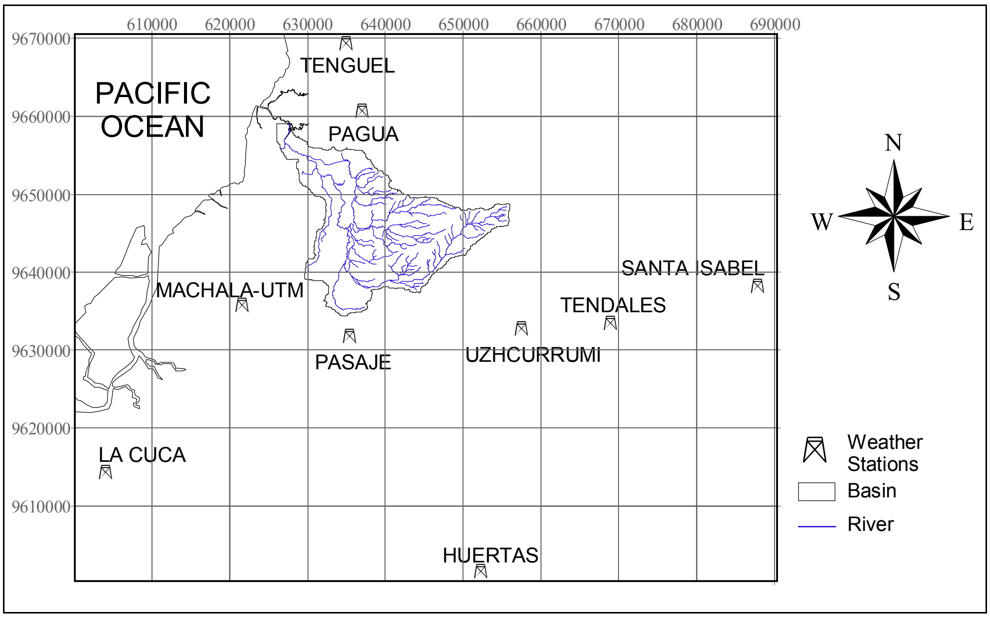


Figure 3.8. Location of available weather stations surrounding the Chaguana basin

3.6.2. MONTHLY PRECIPITATION DATA

The gathered meteorological data were used for the hydrological assessment of the river basin. However, the scope of the analysis is restricted to the average flow condition in the river system within a typical year of precipitation because the only available precipitation data are mean monthly values in all meteorological stations. The existing data is not sufficient at all, though it is the only available data to make the assessment. The actual data show no continuity, and records are not measured during the same periods from one station to another. Thus data selection is a critical step in this basin assessment.

The ideal situation to evaluate a basin's hydrology is to have meteorological stations within the evaluated basin, but that is not always the case. In such cases, some hydrological methods allow the use of data (daily, monthly or yearly data) from nearby stations only, whereas other methods use data from all stations within a certain radius of influence from the basin's centroid. The main drawback of these methods is that the resulting estimated precipitation data is assumed to be the same for the entire basin. In addition, recorded data include both normal and extreme (very high rainfall) events. In order to get a value representative from the whole data set of a station, the median value is used because it is not influenced by very high rain values as the average value is. Finally, the more the stations are geographically distributed, the more the estimated precipitation value is representative for the basin.

For the Chaguana river basin, two stations are nearest to the centroid of the basin (within a radius of 20 km), Pagua and Pasaje (Table 3.7). Their common period of data recording represents 18 years of measurements (1982-1999). Based on these two stations, Table 3.8 shows the mean (median) monthly values estimated for the entire basin. The total annual estimated precipitation is also shown.

Table 3.8. Mean monthly precipitation (mm) estimated from stations located in a radius of 20 km and data recorded between 1997 and 2000.

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
Pagua	185.3	230.9	197.5	121.3	29.0	38.9	42.8	30.9	39.7	53.2	34.4	44.7	1048.4
Pasaje	100.9	223.6	211.3	96.6	27.9	30.6	26.6	26.4	26.8	41.4	37.3	53.4	902.8
MEAN	***143.1***	***227.2***	***204.4***	***109.0***	***28.5***	***34.8***	***34.7***	***28.7***	***33.2***	***47.3***	***35.9***	***49.1***	***975.6***

Now considering a radius of influence of 31 km from the centroid of the basin, 4 additional stations could be evaluated to obtain mean monthly precipitation for the entire basin during the same record periods: Machala, Uzhcurrumi, Tenguel and Tendales. By analyzing the record periods, there are three common periods: 1973 – 1976 (Machala, Tendales and Tenguel Stations), 1976 – 1983 (Machala, Tendales and Uzhcurrumi), and 1982 – 1999 (Pagua, Pasaje, Uzchcurrumi and Machala Stations), as shown in tables 3.9, 3.10 and 3.11 respectively.

Table 3.9. Mean monthly precipitation (mm) estimated from stations located in a radius of 31 km and data recorded in 1973-1976.

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
Tenguel	110.8	352.7	319.6	102.1	75.9	37.9	43.1	24.9	41.1	54.5	43.7	35.3	1241.6
Machala	74.1	222.2	196.0	37.2	26.2	12.7	9.7	16.1	20.9	21.9	14.3	17.8	669.1
Tendales	72.3	156.0	137.9	74.0	43.6	46.2	17.6	12.8	19.9	10.9	15.9	30.4	637.3
MEAN	***85.8***	***243.6***	***217.8***	***71.1***	***48.6***	***32.3***	***23.5***	***17.9***	***27.3***	***29.1***	***24.6***	***27.8***	***849.3***

Table 3.10. Mean monthly precipitation (mm) estimated from stations located in a radius of 31 km and data recorded in 1976-1983.

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
Machala	92.4	155.9	106.6	78.2	29.8	47.5	33.9	39.3	36.9	79.3	44.6	57.5	801.8
Uzhcurrumi	87.3	98.9	149.2	76.9	33.6	17.1	14.0	10.6	14.6	17.8	21.2	52.0	593.0
Tendales	91.0	74.4	154.1	69.0	58.0	39.9	27.2	10.0	11.4	30.9	65.3	64.3	695.2
MEAN	***90.2***	***109.7***	***136.6***	***74.7***	***40.5***	***34.8***	***25.0***	***20.0***	***20.9***	***42.7***	***43.7***	***57.9***	***696.6***

Table 3.11. Mean monthly precipitation (mm) estimated from stations located in a radius of 31 km and data recorded in 1982-1999.

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
Pagua	185.3	230.9	197.5	121.3	29.0	38.9	42.8	30.9	39.7	53.2	34.4	44.7	1048.4
Pasaje	100.9	223.6	211.3	96.6	27.9	30.6	26.6	26.4	26.8	41.4	37.3	53.4	902.8
Machala	183.7	253.9	259.1	110.3	37.3	45.9	42.7	38.0	46.9	69.6	53.3	48.0	1188.5
Uzhcurrumi	117.1	117.8	135.4	99.1	34.9	24.6	15.9	11.9	12.6	23.3	26.2	71.5	689.9
MEAN	***146.7***	***206.5***	***200.8***	***106.8***	***32.3***	***35.0***	***32.0***	***26.8***	***31.5***	***46.9***	***37.8***	***54.4***	***957.4***

By considering a radius of 50 km, three additional stations are available: La Cuca, Huertas and Santa Isabel. The two last ones are located around 1500 meters above sea level; the other one is located around 20 meters. Within this influence circumference, three common periods can be analyzed, which represent more than 4 years of records: 1965 – 1971 / 1973 – 1976 / 1980 (Tenguel and Santa Isabel Stations), 1973 – 1976 / 1980 (Machala, Tenguel, Tendales, Huertas and Santa Isabel Stations), and 1982 – 1986 (Pagua, Pasaje, Machala, Uzhcurrumi, Huertas, La Cuca and Santa Isabel Stations). Tables 3.12, 3.13 and 3.14 show the mean monthly precipitation for each evaluated scenario.

Table 3.12.Mean monthly precipitation (mm) estimated from stations located in a radius of 50 km and data recorded in 1965-1971, 1973-1976 and 1980.

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
Tenguel	99.0	109.8	103.9	72.6	62.1	31.0	18.6	24.5	41.1	47.9	30.9	29.2	*670.4*
Santa Isabel	48.0	66.3	76.4	58.7	25.0	13.1	4.8	6.1	13.9	23.7	22.2	34.1	*392.2*
MEAN	***73.5***	***88.1***	***90.1***	***65.7***	***43.5***	***22.3***	***11.7***	***15.3***	***27.5***	***35.8***	***26.6***	***31.6***	***531.3***

Table 3.13.Mean monthly precipitation (mm) estimated from stations located in a radius of 50 km and data recorded in 1973-1976 and 1980.

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
Machala	91.4	182.9	171.8	53.5	40.4	18.1	14.6	16.2	27.7	27.3	18.6	19.0	*681.4*
Tenguel	94.1	291.0	211.8	107.2	60.9	37.9	35.5	23.6	42.6	54.2	43.7	35.3	*1037.8*
Tendales	74.5	145.4	144.9	68.9	62.0	60.7	24.8	13.0	20.5	17.0	21.3	33.6	*686.6*
Huertas	215.4	381.4	530.1	372.6	246.2	89.6	18.1	17.5	49.8	28.1	34.2	117.8	*2100.7*
Sta. Isabel	46.0	110.3	136.4	66.1	76.0	19.4	5.6	26.7	8.3	28.8	24.4	34.1	*582.2*
MEAN	***104.3***	***222.2***	***239.0***	***133.7***	***97.1***	***45.1***	***19.7***	***19.4***	***29.8***	***31.1***	***28.4***	***48.0***	***1017.7***

Table 3.14. Mean monthly precipitation (mm) estimated from stations located in a radius of 50 km and data recorded in 1982-1986.

Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
Pagua	208.0	182.0	276.6	136.1	15.2	103.5	180.7	28.7	54.0	54.0	39.8	38.9	1317.4
Pasaje	58.1	139.4	225.9	142.4	25.3	40.1	22.3	18.1	25.3	43.0	62.6	129.2	931.5
Machala	95.4	229.0	268.7	74.8	31.3	66.6	41.0	36.5	34.5	71.8	57.4	76.2	1083.1
Uzhcurr.	68.1	63.8	143.4	97.9	28.9	14.1	15.4	12.9	15.3	34.5	22.3	103.1	619.7
Huertas	394.8	569.2	318.5	444.0	180.3	23.5	59.8	0.0	29.8	139.9	129.5	368.5	2657.8
La Cuca	27.1	152.3	79.3	31.1	8.2	5.4	6.0	4.6	7.9	9.5	0.7	17.2	349.2
Sta. Isabel	42.6	65.1	74.3	88.2	45.1	1.2	2.2	2.0	16.5	23.7	29.3	58.9	449.1
MEAN	***125.6***	***215.8***	***176.8***	***147.2***	***58.8***	***22.2***	***24.9***	***11.2***	***20.8***	***55.9***	***47.8***	***124.8***	***1031.8***

The tables show how the mean annual precipitation for the basin could vary depending on the number of stations included in the analysis and the number of common recorded climate data. Table 3.15 shows how the estimated precipitation for the basin could vary from high to low events depending on the stations involved in the analysis and the evaluated recording period.

Therefore, the right scenario for the so called "normal" event could be selected based on a probability estimation[17] to have the same or higher annual precipitation than the one in the respective scenario (chance of 50% to have higher events).

Another important aspect of the analysis is the influence of extreme events such "El Niño" which is a period where very heavy rains occur in Ecuador. Normally this recurrent event begins at the middle of one year and ends at the middle of next year. Thus, data are normally influenced during two consecutives years by an "El Niño" event from time to time. Reported "El Niño" events were recorded in 1965-1966, 1968-1970, 1972-1973, 1976-1977, 1982-1983, 1986-1988, 1991-1992, 1994-1995, and 1997-1998 (Villacis *et al.* 2001). Therefore, this extreme event has a recurrence interval of 3 to 6 years. The table also includes some El Niño events in their data range periods for the evaluated scenarios.

Table 3.15. Evaluation of precipitation obtained in different scenarios (involved stations and recorded periods).

Scenario	*Evaluated Weather Stations*	*Period of records measured in weather stations*	*Annual Precipitation (mm/year)*	*Probability to have an event greater or equal*	*Classification of the event*
1	Pagua, Pasaje, Machala, Uzhcurrumi, Huertas, La Cuca, and Santa Isabel	1982 – 1986	1031.77	12.50%	High (humid)
2	Machala, Tenguel, Tendales, Huertas, and Santa Isabel	1973 – 1976, 1980	1017.70	25.00%	⇑
3	Pagua and Pasaje	1982 - 1999	975.58	37.50%	
4	Pagua, Pasaje, Machala, and Uzhcurrumi	1982 – 1999	957.39	50.00%	⇐ Mid (normal)
5	Machala, Tenguel, and Tendales	1973 – 1976	849.31	62.50%	⇓
6	Machala, Uzhcurrumi, and Tendales	1976 – 1983	696.64	75.00%	
7	Tenguel and Santa Isabel	1965 – 1971, 1973 – 1976, 1980	531.3	87.50%	Low (dry)

17 $$P(i) = \frac{i}{n+1} \qquad [3.2]$$
where ***i*** is the position in an ascending or descending arrangement of ***n*** values.

Based on the previous analysis, it can be concluded that scenario 4, which represents 18 years of recorded data, could resemble normal precipitation events because there is a 50% chance that the event could be higher or lower. In addition, the weather stations in this scenario are fairly distributed around the basin (Figure 3.8). For that reason, scenario 4 is the best combination of weather stations and recorded period to represent a "normal" precipitation event for the Chaguana river basin.

Map Interpolation Procedures

The monthly precipitation values estimated previously are considered as unique valid values for the entire basin allowing for spatial variability from evaluating weather stations only in an implicit form (the value changes only when another station is selected). In modelling, it is sometimes better to explicitly show spatial variability in parameters such as climatic records. This goal is achieved by interpolating data from meteorological stations. However, in this Ph.D. study, interpolation is restricted to a few methods because there are not so many available data (less than 9 stations). Based on the selected scenario, table 3.11 shows the monthly average precipitation data used for the interpolation process for obtaining a normal monthly precipitation map.

The selection of a suitable interpolation methodology for the available data is critical in order to obtain a non-distorted spatial distribution of any evaluated parameter (Mitas and Mitasova 1999). A wrong interpolation procedure could lead to false distribution patterns in the simulations (Mitasova *et al.* 1996). Based on previous works done elsewhere (Hutchinson and Bichof 1983; Hutchinson 1996; Hutchinson and Corbett 1993), the *SPLINE* interpolation method appears the most recommended for processing the climatic data. To obtain the precipitation raster maps of every month, the *SPLINE* interpolation option in ArcView[18] was applied to the stations selected to produce a normal precipitation event. Therefore, a raster precipitation map was generated for every month in a "normal" year (Figure 3.9). In addition, the total annual precipitation was generated by adding all monthly maps. Table 3.16 shows the average values for each raster map and its spatial standard deviation. From the table and figure, the wettest month in a typical year is February with 205 mm and the driest month is August with 25 mm of average rain in the whole basin.

[18] A weight of zero is selected to produce a basic Thin Plate Smoothing Spline which is the recommended interpolation for climatic events.

Table 3.16. Total monthly average and annual precipitation for Chaguana river basin

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
P_{mean}	152.9	205.2	178.6	113.4	28.2	33.0	34.1	25.2	30.4	41.9	37.0	50.9	*930.6*
Stand. Dev.	19.6	36.5	40.2	4.7	1.8	5.8	6.1	7.1	8.8	13.0	7.7	4.9	*132.3*

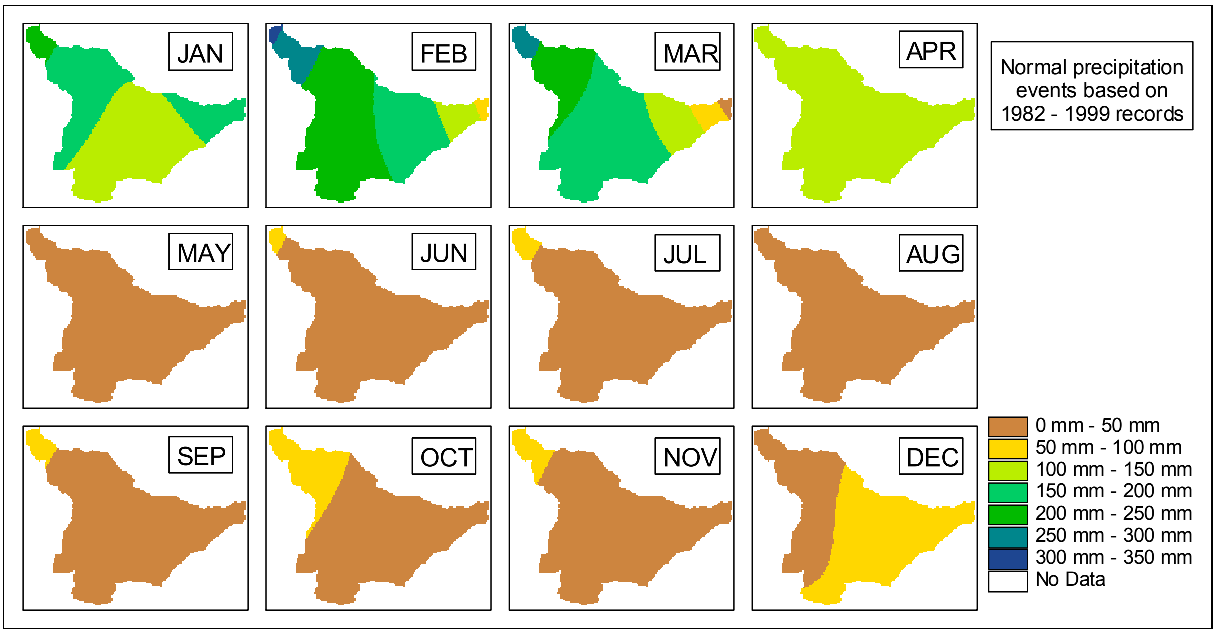


Figure 3.9. Monthly precipitation maps for Chaguana river basin

From figure 3.9, it can be seen that the maps predict more precipitation in the lowlands (west side of the basin) than in the highlands (east side) which might be considered as an uncommon behaviour in a typical precipitation pattern. However, there are two important facts that should be considered when interpreting the interpolated maps:

- The maps do not show the impact of high elevations, because the highest stations (Huertas and Santa Isabel) were not considered in the interpolation procedure. Those stations did not have enough rainfall data to support the interpolation procedure as mentioned before.
- Another important issue is that existing data in the highest stations could be biased as most of their data are influenced by the presence of an El Niño event (extremely high precipitation levels). By reviewing the rain history (interviewing local people) in the areas where the highest stations are, the southern part of Ecuador and the northern part of Peru are very dry (even in the mountain regions).

3.6.3. MAXIMUM 24-HOUR PRECIPITATION

The maximum 24-hour precipitation is a climatic parameter that is useful to obtain other parameters such as the rainfall erosivity factor, peak discharge and so on. In the Chaguana river basin, only three weather stations have records on this parameter: Machala, Pagua and Pasaje. However, these stations do not show the same recording periods for this parameter to produce a representative raster map[19] for a normal event. To overcome this problem, the Gumbel distribution (Benjamin and Cornell 1970) was applied to every monthly value in each station by assuming that these data are recorded continuously through a number N of years.

An EXCEL worksheet was used to evaluate the Gumbel distribution of 24-hour precipitation data in each station. The following equations are used in the calculations.

1. The arithmetic mean 24-hour precipitation (X_{month}) is determined for each month of the year.

$$X_{month} = \frac{\sum_{i=1}^{N} P_{month}(i)}{N} \qquad [3.3]$$

where $P_{month}(i)$ is the 24-hour precipitation for a specific month in year i.

2. The standard deviation (S_{month}) of sample data is determined for each month of the year.

$$S_{month} = \sqrt{\frac{\sum_{i=1}^{N} \left[P_{month}(i) - X_{month}\right]^2}{N-1}} \qquad [3.4]$$

3. Determination of Gumbel distribution fitting parameters: mode (μ) and dispersion (α)

$$\alpha = \frac{\pi}{S_{month}\sqrt{6}} \qquad [3.5]$$

$$\mu = X_{month} - \frac{\gamma}{\alpha} \qquad [3.6]$$

[19] For the interpolation procedure, values used in the stations should represent the same period of measurement.

4. The probability is then established to have the same or greater rain event after a recurrence interval of precipitation (T_{RETURN})[20] occurs. Then, a variate (ω) value is calculated based on this estimated probability.

$$\text{Probability} = \frac{1}{T_{RETURN}} \quad [3.7]$$

$$\omega = -\ln\left[-\ln\left(1 - Probability\right)\right] \quad [3.8]$$

Table 3.17 shows some calculated values of probability and variate for a recurrence interval of precipitation. The return period values shown in the table are the most commonly used in rain analysis.

Table 3.17. Probability – variate values based on a specific recurrence interval of precipitation

Return Period	Probability of event occurrence	Variate (ω)
2 years	0.50	0.3651
5 years	0.20	1.4994
10 years	0.10	2.2504
25 years	0.04	3.1985

5. Finally, a monthly precipitation for a specific recurrence interval is estimated based on the Gumbel fitting parameters for each month (μ,α) and the corresponding variate calculated for that interval. Based on the probability shown in table 3.17, the 2-year precipitation event could be considered as a "normal" event because there is a 50% chance to have greater or lower events.

$$P(i) = \mu + \frac{\omega(i)}{\alpha} \quad [3.9]$$

Tables 3.18, 3.19 and 3.20 show the calculated values of maximum 24-hour precipitation for each month in Machala, Pasaje and Pagua stations respectively. Those predicted values were interpolated to produce raster maps of maximum 24-hour precipitation for each month in every recurrence interval (2 years, 5 years, 10 years and 25 years) as shown in Figure 3.10.

[20] The return period (T_{RETURN}) is the average interval in years between the occurrence of an event of stated magnitude and an equal or more serious event.

Table 3.18. Estimated maximum 24-hour precipitations for each recurrence interval in Machala station

T_{RETURN}	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
2 years	57.1	70.6	60.5	37.0	19.7	14.0	8.7	7.8	8.3	8.5	12.1	25.8
5 years	106.5	114.4	94.3	75.4	41.9	40.1	15.4	16.0	15.8	11.6	29.1	60.3
10 years	139.2	143.5	116.7	100.9	56.6	57.3	19.8	21.5	20.7	13.8	40.3	83.1
25 years	180.5	180.2	145.1	133.0	75.1	79.1	25.4	28.3	27.0	16.4	54.6	111.9

Table 3.19. Estimated maximum 24-hour precipitations for each recurrence interval in Pasaje station

T_{RETURN}	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
2 years	38.1	29.8	51.3	42.7	12.8	9.6	6.1	2.8	5.9	8.1	18.9	45.4
5 years	96.1	55.6	85.1	86.0	35.8	19.7	12.3	3.8	12.2	15.8	39.3	59.6
10 years	134.5	72.7	107.5	114.7	51.0	26.3	16.4	4.5	16.4	20.9	52.8	69.0
25 years	183.0	94.3	135.7	150.9	70.2	34.7	21.5	5.4	21.8	27.3	69.9	80.9

Table 3.20. Estimated maximum 24-hour precipitations for each recurrence interval in Pagua station

T_{RETURN}	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
2 years	56.0	64.9	55.6	46.7	17.7	15.6	14.9	6.2	11.4	16.8	6.4	21.8
5 years	88.9	102.6	100.9	89.2	40.4	39.6	39.7	10.3	37.6	53.8	8.4	55.1
10 years	110.7	127.6	130.9	117.4	55.5	55.4	56.1	13.0	55.0	78.3	9.7	77.2
25 years	138.2	159.2	168.7	152.9	74.6	75.5	76.8	16.5	76.9	109.3	11.4	105.0

This precipitation data were used in the calculation of the rainfall erosivity factor for each station considered in the analysis, but only the 2-year and the 10-year return period which are used in the selected pesticide models.

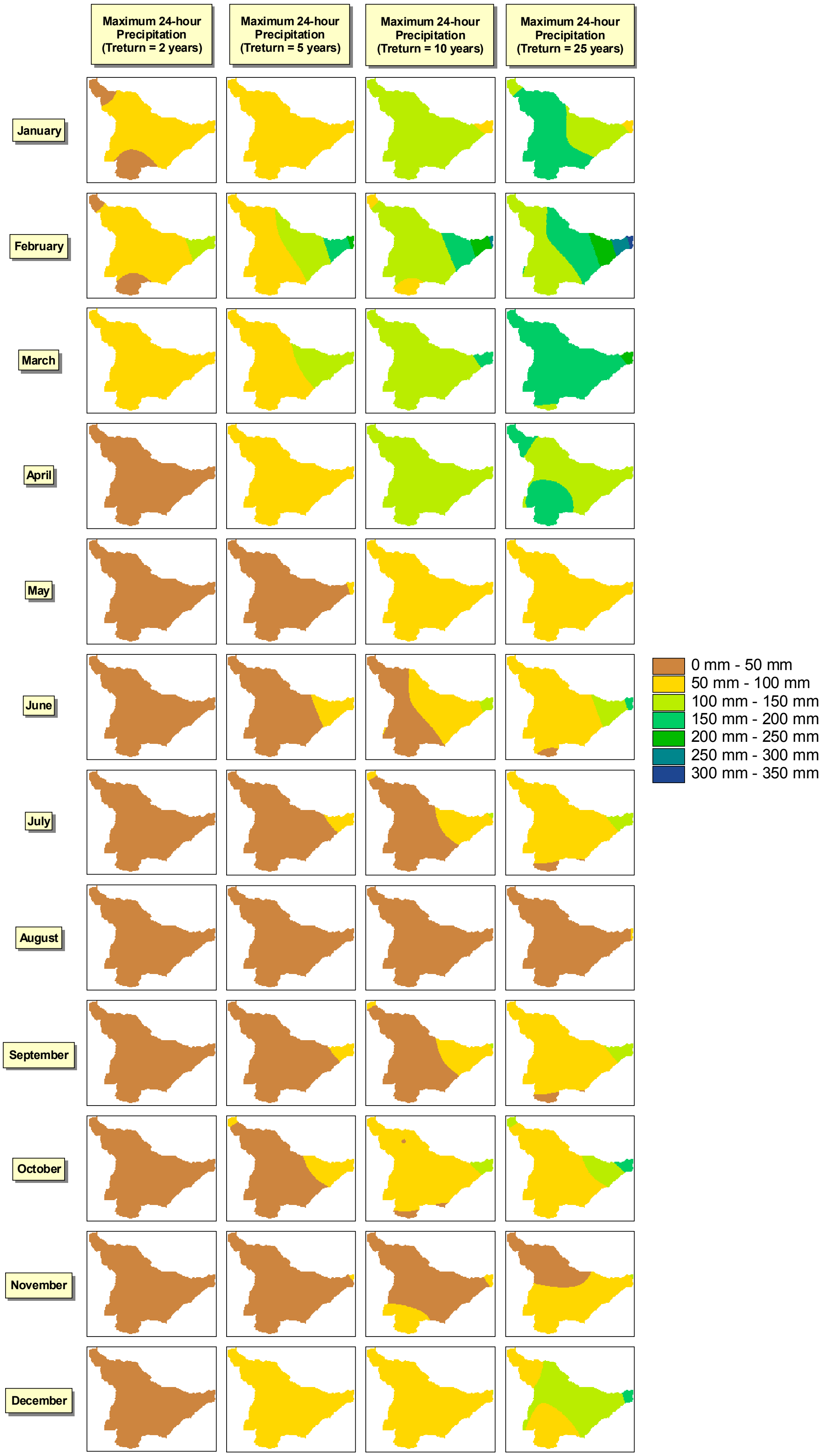


Figure 3.10. Maximum 24-hour precipitation maps for 2-, 5-, 10- and 25-years return periods

3.6.4. AIR AND DEW-POINT TEMPERATURE DATA

Air and dew-point temperature were data required for both pesticide models (SWAT and AGNPS). They can be input as monthly or daily values. Because of the restriction on data availability, only monthly values were generated. Similar to precipitation, air and dew-point temperatures generally show a tendency with topography. In the current assessment, a larger error could be expected because interpolation was done with only three stations (Machala, Pagua and Pasaje). However, this error could be within an acceptable range as explained next. The non-point source pesticide pollution (banana plantations) only affects a part of the catchment area (below 50-m terrain level). Useful stations for temperature evaluation are also located in the same area. Therefore, any error obtained above 50 m level will be irrelevant to the pesticide assessment.

Because the dew-point temperature is not usually monitored in Ecuadorian weather stations, some estimation was performed to obtain that variable. There are several approaches to estimate dew-point temperature such as

- The International Temperature Scale Procedures, established by the International Committee of Weights and Measures (ICWM 1989; Hardy 1998). Although an actual scaling method was proposed in 1990, some equipment could still have scaling methods created in 1968, 1975 or 1976. However, temperature differences between ITSP-90 and ITSP-68 are only in the range of 0.005 and 0.007 °C when the measured temperature is between 20 and 30°C. Therefore, the pesticide assessment will not be affected for the selection of any scale procedure due to this negligible difference in the current assessment context.
- An empirical relationship (Tetens 1930) that uses dry air temperature (T_{AIR}) and relative humidity (RH) to calculate dew-point temperature with ±0.1°C accuracy.
- Some software based on previous formulations such as EZAir (Parks 1998)

In the current research, the following equations based on those methodologies were applied to estimate the dew-point temperature. Those equations are

$$T_{DEW} = -\frac{\left[237.314 \ln\left(\frac{E_T}{6.1078}\right)\right]}{\left[\ln\left(\frac{E_T}{6.1078}\right)\right] - 17.26902} \qquad [3.10]$$

$$E_T = E_W - 0.63\left(T_{AIR} - T_{WET}\right) \qquad [3.11]$$

$$E_W = 6.112\, e^{\frac{(17.67\, Twet)}{(Twet)+243.5}} \qquad [3.12]$$

Where,

T_{AIR} Maximum Temperature or Dry Air Temperature

T_{WET} Minimum Temperature or Wet Bulb Temperature

T_{DEW} Dew-point Temperature

E_W Saturation Vapour Pressure over water

E_T Actual Vapour Pressure

An ArcView avenue script called Monthly DewPoint Estimation was developed to draw the corresponding raster map based on maximum (dry) and minimum (wet) temperature raster maps. The dry and wet temperature raster maps were produced with a *SPLINE WITH TENSION* interpolation performed with data from Machala, Pagua and Pasaje Stations. Table 3.21 shows the dry air (T_{AIR}) and wet-bulb (T_{WET}) temperature, as mean measurements, used in the interpolation process. The results obtained for the Chaguana basin are also shown in this table. It can be seen that temporal variation through the year on all stations and the basin estimate is quite small (less than 5ºC). In addition the spatial variation in the basin is also small for all months (less than 1.4ºC). Figure 3.11 shows temperature raster maps for a "normal" year.

Table 3.22. Measured maximum and minimum temperatures used to estimate the dew-point temperature map for the Chaguana basin

Station	*Parameter*	*JAN*	*FEB*	*MAR*	*APR*	*MAY*	*JUN*	*JUL*	*AUG*	*SEP*	*OCT*	*NOV*	*DEC*
Machala	T_{AIR} (°C)	30.5	30.6	31.2	31.2	30.2	28.6	26.9	26.6	26.8	26.0	27.2	29.4
	T_{WET} (°C)	21.9	22.3	22.7	22.4	22.1	21.1	19.9	19.9	20.1	20.5	20.5	21.4
Pagua	T_{AIR} (°C)	30.6	30.6	31.4	31.3	30.2	28.5	27.3	26.4	26.9	26.4	27.7	29.4
	T_{WET} (°C)	21.5	21.1	22.0	22.2	21.9	20.8	20.1	19.9	20.1	20.4	20.6	21.2
Pasaje	T_{AIR} (°C)	31.1	31.9	31.9	31.5	30.1	28.1	27.9	27.3	28.5	28.9	30.1	31.6
	T_{WET} (°C)	21.7	22.2	22.4	22.3	21.5	21.1	20.4	20.1	20.3	20.5	20.7	21.1
Estimated values for the basin	T_{AIR} (°C)	30.6	30.6	31.4	31.3	30.2	28.5	27.2	26.5	26.9	26.3	27.6	29.4
	T_{WET} (°C)	21.6	21.4	22.2	22.2	21.9	20.9	20.1	19.9	20.1	20.4	20.6	21.2
	T_{DEW} (°C)	17.6	17.2	18.2	18.4	18.4	17.4	16.7	16.8	16.9	17.7	17.3	17.6

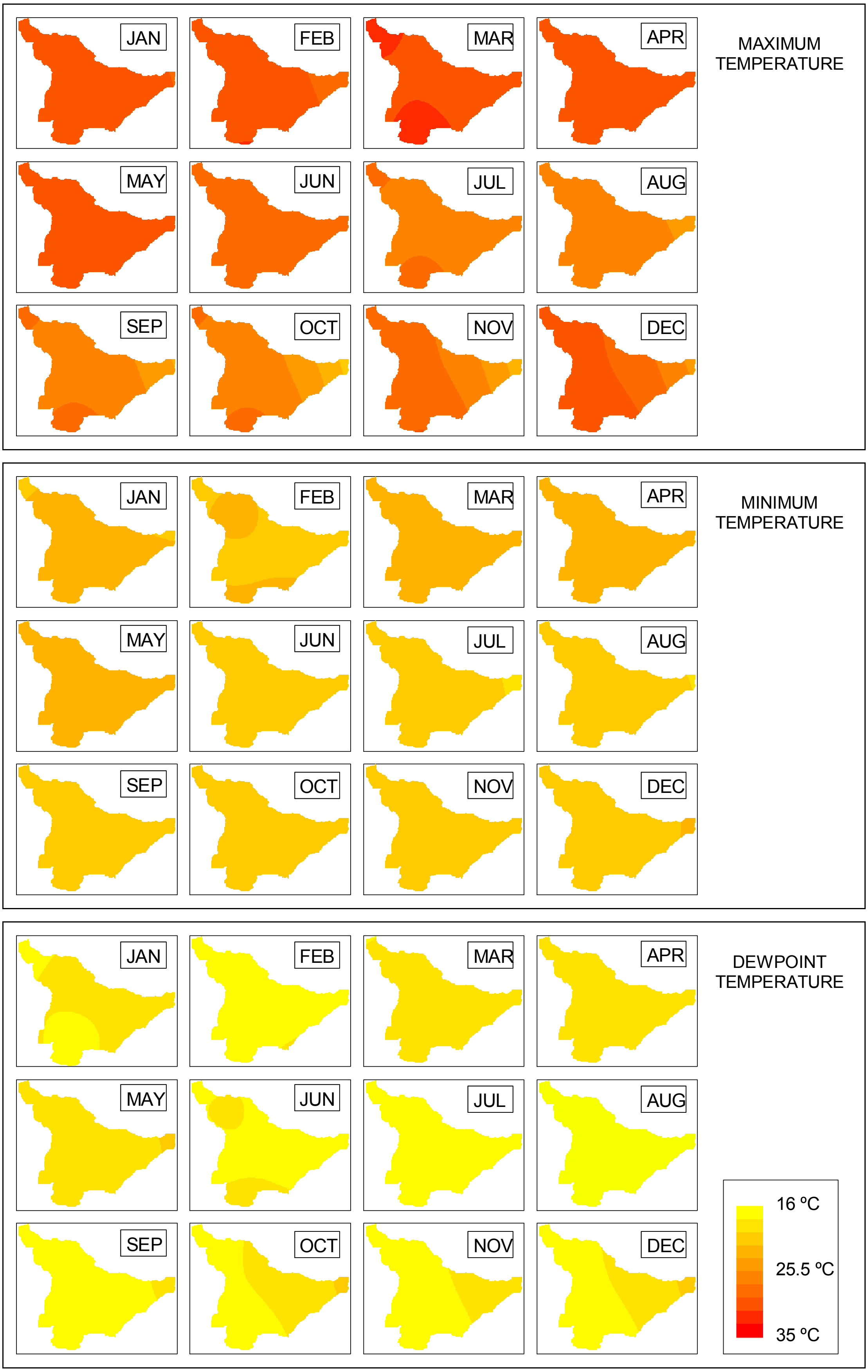


Figure 3.11. Maximum, minimum and dew-point temperature raster maps for a "normal" year

3.6.5. SOLAR RADIATION DATA

Solar radiation data are important to account for pesticide degradation due to photolysis. Only SWAT model requires solar radiation as daily or monthly information. In the present study, solar radiation data is lacking in the existing meteorological stations. Only the Machala Station has records on total effective sunshine hours for every month (Table 3.22). From this data, it can be seen that the study area is mostly covered by clouds during the entire year.

Table 3.22. Average total monthly sunshine hours for Machala station

Month	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Total Sun Hours	65.21	61.54	96.25	93.88	78.43	43.18	40.16	39.62	32.78	21.68	37.64	57.84
Average Hours/day	2.1	2.2	3.1	3.1	2.5	1.4	1.3	1.3	1.1	0.7	1.3	1.9

In order to get solar radiation data for the study area, the following procedure was used

1. ***Gathering information from an existing global on-line database at the NASA Langley Atmospheric Sciences Data Centre:*** This database gives information on solar insolation and other parameters for a 1° grid cell (around 1.2×10^6 Ha) on a 10-year average basis. These data are not necessarily representative for a specific point within the grid cell, and estimated solar data are normally higher than ground measurements (Whitlock *et al.* 2000). In the present study, the Chaguana river basin is located in the grid within 80°E, 3°S, 79°E and 4°S coordinates. Table 3.23 shows the estimated NASA solar radiation on a 10-year average basis for this grid cell.

Table 3.23. Estimated solar radiation from the NASA Langley Atmospheric Sciences Data Center

Month	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Rad ($MJ/m^2.day$)	16.02	16.85	16.96	16.52	16.09	14.54	15.19	16.60	17.68	17.24	18.14	17.28

2. ***Use of the LARS-WG software tool:*** Due to the overestimation mentioned in the previous paragraph, another procedure is needed to get more representative estimates for the study area. There is one software tool that uses sunshine hour measurements as input to get solar radiation estimates. This software was developed at the University of

Bristol, UK and it is called LARS-WG (Racsko *et al.* 1991; Semenov *et al.* 1998; Semenov and Barrow 1997). This tool is basically a stochastic weather generator and specifically can model solar radiation by using empirical distributions of wet and dry weather series. When there are no solar radiation measurements, sunshine hours are converted to global radiation by means of a regression relationship between these two variables (Rietveld 1978).

However, daily values of sunshine hours are needed to accomplish the weather generation. The input file in LARS-WG needs a daily record of precipitation, minimum and maximum temperature and sunshine hours for the entire period of analysis. In the present case study, only total monthly values for the record period are available. In order to overcome this problem, the following assumptions were made:

- Total monthly sunshine hours were converted to average daily sunshine hours for every month of each monitored year. This value was used as a daily value for every day in the current evaluated month.
- Total monthly precipitation was also converted to average daily precipitation. However, this value was only used as daily value for the total days in a month minus one. Because, the maximum precipitation value in every month was also available, this value was used for that day in the current month.
- In the existing records, temperature values represent the average value in the month, so this value was used as a daily value for every day in the current month.

Table 3.24 shows the average daily solar radiation generated from the Machala station weather data for every month. Figure 3.12 shows how the tendency of the solar radiation curve (left axis) follows the one of the sunshine hours' curve (right axis). Despite the good agreement, it is always better to have some solar radiation measurements to validate these estimations.

Table 3.24. Estimated average monthly solar radiation by using LARS-WG in the Machala station

Month	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Mean Rad (MJ/m^2.day)	9.7	10.1	12.8	12.3	10.4	7.2	7.2	7.1	7.2	5.8	7.1	8.8

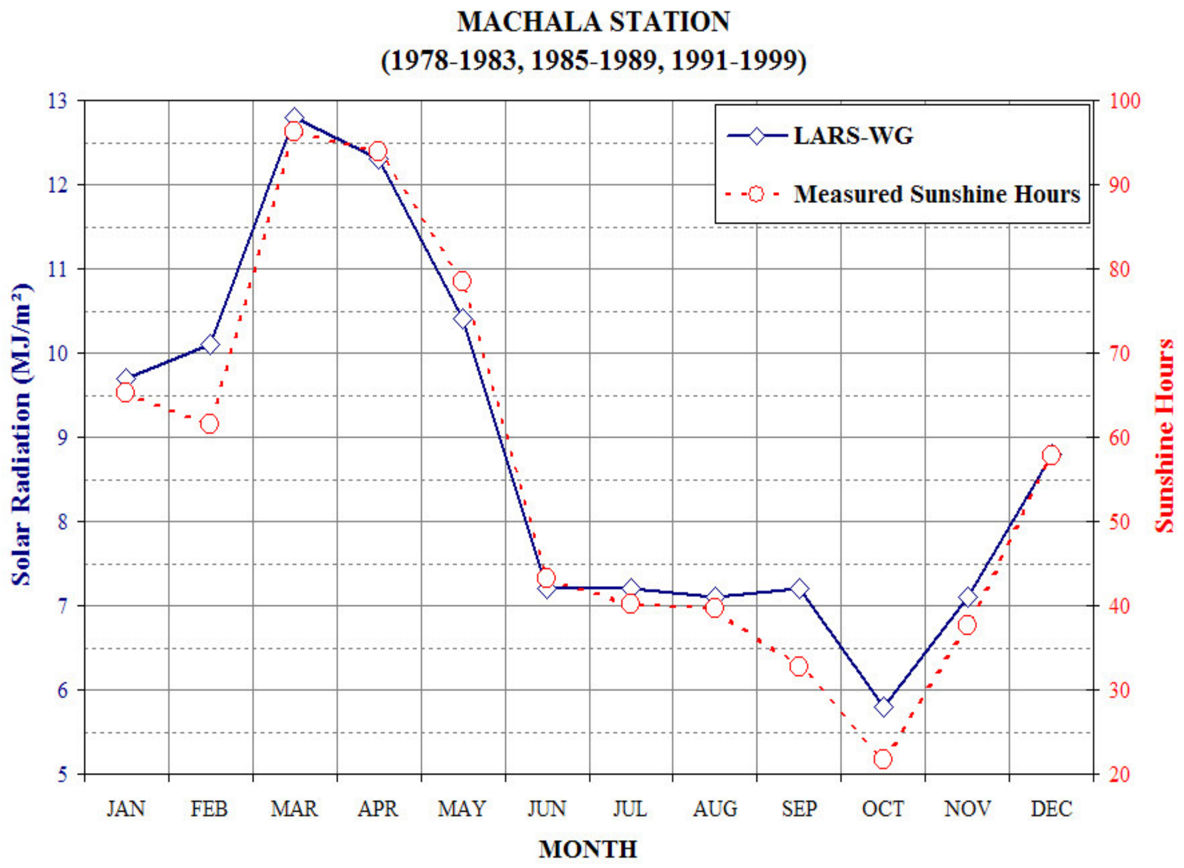


Figure 3.12. Estimated solar radiation and measured sunshine hours in the Machala station

Solar radiation is a parameter that varies not only by the weather conditions but also by the geographic latitude of a specific site. Thus, a solar radiation map would show the spatial variation of this parameter within the map. However, the current study site covers a small geographic spatial variation (less than 0.3° in latitude), which would produce only a slight variation in the parameter values. For that reason, the resulting raster map for the study area will be one with the same value in every raster cell, showing only temporal (monthly) variations and not spatial variations. Values obtained for the Machala station can be accepted as valid solar radiation values for the entire basin.

3.7. SOIL DATA

Another important group of data concerns soil information such as soil texture, permeability, and organic matter. In the Chaguana river basin, the only available information is the edaphology map which shows general information on soil taxonomic units. There is no spatial variability within each taxonomic unit. A sampling campaign was planned to overcome this lack of information.

3.7.1. SOIL SAMPLING CAMPAIGNS

The soil sampling campaign was conducted in March 2001. To plan the campaign, it was necessary to determine the extension of the survey, the parameters to be analysed and the places to be sampled. The following paragraphs will show the methodology applied in the sampling plan.

Sampling Depth and Soil Properties: As previously stated, the available soil data was too general for the selected watershed. Thus, it was necessary to generate more specific soil maps for the study site. In the context of pesticide assessment, the surface soil is more important than deeper soils (Boesten *et al.* 1999; Moorman *et al.* 1999). Thus, the first 50 cm of soil below ground level was evaluated. In addition, soil properties such as soil-water content, bulk density, organic matter and sand-silt-clay content were selected as the main objectives in the soil analysis.

Number of Sampling Sites: The second problem was to answer how many sampling sites are sufficient for the assessment. To solve this problem, the following criteria were considered:

- Both geological and edaphological maps define zones where soils can have very similar properties.
- The locations of banana farms are very important from the pesticide assessment point of view.
- The sampling sites depend on accessibility (existing main roads, consent to enter service roads in the farms). Based on this, the potential surface area to be sampled in the watershed is defined by a variable buffer area not more than 25 meters surrounding the existing and accessible roads.

- Although soil variability is a fact of nature, precision in catchment assessment is not the same as precision in farm assessment. From an agricultural point of view, the largest area representing a soil unit to be sampled is 40 hectares (Jacobsen 1999). From a landscape point of view, around 3 to 6 samples should be taken per landscape unit[21] (Manitoba Government 2000)
- It is necessary to use an adequate statistical technique to determine the minimum number of samples.
- The available budget for the sampling campaign is limited.
- The available time for the whole pesticide assessment is restricted to three years.

Thus, the most appropriate design is the stratified sampling design which has already been used in other types of assessment such as the prediction of organochlorine pesticides in sediments and animal tissues in a river basin (Black *et al.* 2000). For the present study, the sampling size was determined on the basis of statistical analysis (Gilbert 1987). Then, considering the other criteria, the recommended number of stratified sampling sites was fixed to 30 locations.

Considering only the watershed surface area (around 32000 Ha), it apparently seems that very few samples are used to evaluate an important problem in the basin (around one sample per every 1100 Ha). However, the current evaluation seems more appropriate when zoning the sampling points. These can be better seen in Figure 3.13 where sampling points are put over GEOLOGY, LANDUSE, ROAD and EDAPHOLOGY maps. In the road map (Figure 3.13d), it can be seen that a large area is difficult to be sampled due to the lack of roads.

Number of samples per site: Due to soil variability, it was necessary to have more than one soil sample per site. In every sampling site, two soil samples were obtained: a core undisturbed sample and a composite disturbed sample (cross-shaped sampling pattern). A cross-shape sampling pattern represents four sampling points at a certain distance away from the core sample (center of the cross), and separated 90° from each other with respect to the center (Figure 3.14). The radius of the cross-shaped pattern was variable depending on the topography. After collection, the sub-samples were mixed together to form a composite

[21] The landscape unit is a geographical land subdivision based on topography, vegetation, land use, regional context and built infrastructure. According to EPA, it is a designation to identify repeating patterns associated with dominant land uses in an area, and defined by the relative proportions of forest, agriculture, and developed (urban) land cover contained in that area.

sample. The core sample was used to determine the soil bulk density and the composite sample was used to determine the other soil properties.

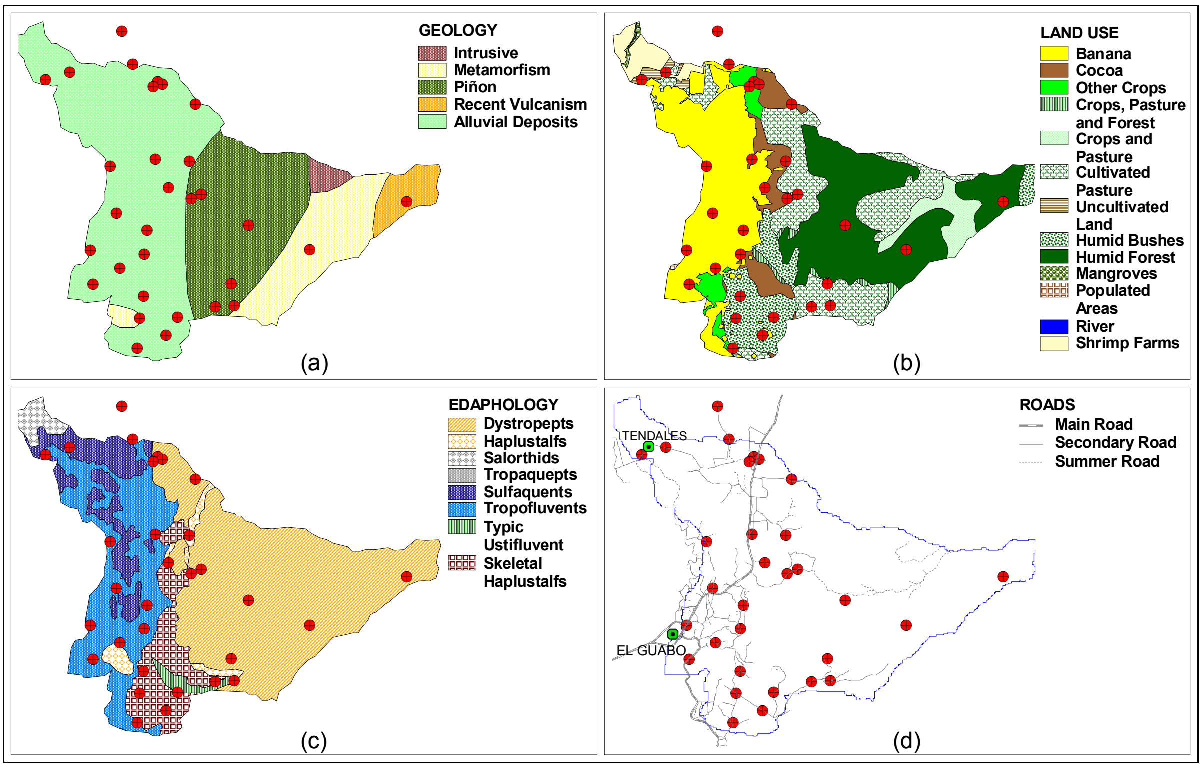


Figure 3.13. Soil sampling point locations compared to (a) Geology Map, (b) Landuse Map, (c) Edaphology Map, and (d) Road Map in the watershed.

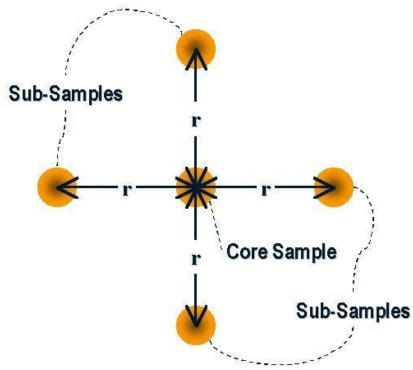


Figure 3.14. Cross-shaped sampling pattern adopted in soil exploration

Issues in sampling site determination: As written before, thirty locations were selected as sampling sites. However, during the sampling campaign, two main factors influenced the decision to obtain only 28 samples:

- Sampling sites were located using available topographical maps made in 1970. However, during the sampling campaign, it was discovered that many roads and access to sampling sites no longer existed or could be accessed only by mules, so it was impossible to get the sampling sites within the available time.
- Many farmers in the basin did not allow entering their properties to take soil samples. They claimed not to be interested in collaborating with the project.

Table 3.25 shows how the final sampling sites were distributed along the different criteria used in the sampling design (GEOLOGY, LANDUSE or EDAPHOLOGY). Zones not important from the project point of view get less sampling weight or no samples at all, mainly based on following considerations:

- Pesticides are mostly used in the banana sector.
- The banana sector is mainly located in alluvial deposits which primarily consist of silty sandy soils.
- From the point of view of edaphology, the banana sector is mainly located in Tropofluvents Soils.

Table 3.25. Zoning of soil samples based on available information for the Chaguana river basin

Information type used in sampling design		*Distribution of samples in a zone*	
Geology	Alluvial Deposits [a]	22	78.57 %
	Cretasic Formation	5	17.86 %
	Metamorphic Formation	1	3.57 %
	Intrusive rock	0	0.00 %
Land use	Banana Sector [a]	15	53.57 %
	Pasture Areas and Other Crops	5	17.86 %
	Hilly Areas	8	28.57 %
	Shrimp Farms Area	0	0.00 %
Edaphology	Tropofluvents [a]	10	35.71 %
	Skeletal Haplustalfs	6	21.43 %
	Dystropets	6	21.43 %
	Tropaquepts	3	10.71 %
	Haplustalfs	2	7.15 %
	Typic Ustifluvents	1	3.57 %
	Salorthids	0	0.00 %

(a) Zones where banana farms are located

3.7.2. LAB ANALYSIS AND RESULTS

Every sample was tested to determine parameters such as organic matter content, soil-water content, bulk density and texture. A summary of test results and some statistics are presented in Table 3.26. In the table, it is also shown the testing methods used during lab analysis. The reader should refer to those methods for further details. Each parameter can be grouped in such a way that a normal distribution can be obtained. For this type of distribution, it is expected that around 68% of the data is found within one standard deviation for the total sampling population.

Table 3.26. Statistical parameters obtained from the analysis results

	%Organic Matter	*% Water Content*	*Bulk Density (kg/m³)*	*% Sand*	*% Silt*	*% Clay*
Testing Method	ASTM-D2974-00	ASTM-D2216-98	ASTM-D2937-00e1	ASTM-D422-63	ASTM-D422-63	ASTM-D422-63
Range	0.13 – 2.01	7.53 – 53.15	1777 – 1078	6 – 99.5	0.4 – 78	0.1 – 73
Mean (X)	1.16	31.11	1409.62	41.3	40.58	18.11
Stand. deviation (s)	0.51	10.44	186.65	24.82	20.92	15.33

When evaluating the stratified sampling, it is desired that every stratum gets a representative number of samples within one standard deviation region and this for each sampling criterion. This statement should hold for every measured parameter. For every parameter data can fall in any of the following regions:

- Region S1: -1 standard deviation (s) to 1 standard deviation (s)
- Region S2: -2s to -1s, and 1s to 2s
- Region S3: -3s to -2s, and 2s to 3s

Table 3.27 shows the sampling distribution within each stratum for every sampling criterion (LANDUSE, GEOLOGY and EDAPHOLOGY). For example, for the LANDUSE Criterion (Banana farms, Hilly areas and Pasture areas; Shrimp farms do not receive any sampling weight), the standard deviation for the organic matter content is 0.51% (Table 3.26). If we consider the Banana Farm Sector in the LANDUSE criterion, it can be seen that around 73% of the 15 samples in that sector fall within the region S1, around 27% fall in region S2, and no samples in region S3. We observe that the distribution of samples fulfils the criteria specified above and that therefore the sampling locations are representative for the type of assessment this study is aimed for, i.e. pesticides in banana plantations.

Table 3.27. Sampling distribution within standard deviation regions for three sampling criteria

SAMPLING CRITERIA			*SOIL PARAMETERS*					
			Organic Matter	*Water Content*	*Bulk Density*	*% Sand*	*% Silt*	*% Clay*
LANDUSE	Banana Farms (15 Samples)	S1	73.3%	73.3%	66.7%	86.7%	86.7%	93.3%
		S2	26.7%	20.0%	33.3%	13.3%	13.3%	0.0%
		S3	0.0%	6.7%	0.0%	0.0%	0.0%	6.7%
	Hilly Areas (8 Samples)	S1	62.5%	25.0%	62.5%	50.0%	50.0%	37.5%
		S2	37.5%	62.5%	25.0%	25.0%	50.0%	62.5%
		S3	0.0%	12.5%	12.5%	25.0%	0.0%	0.0%
	Pasture Areas (5 samples)	S1	60.0%	80.0%	40.0%	60.0%	60.0%	100.0%
		S2	20.0%	20.0%	60.0%	40.0%	40.0%	0.0%
		S3	20.0%	0.0%	0.0%	0.0%	0.0%	0.0%
GEOLOGY	Alluvial Deposits (22 Samples)	S1	68.2%	72.7%	59.1%	77.3%	77.3%	90.9%
		S2	27.3%	22.7%	40.9%	22.7%	22.7%	0.0%
		S3	4.5%	4.5%	0.0%	0.0%	0.0%	9.1%
	Cretasic Formation (5 Samples)	S1	80.0%	20.0%	80.0%	40.0%	40.0%	20.0%
		S2	20.0%	60.0%	0.0%	20.0%	60.0%	80.0%
		S3	0.0%	20.0%	20.0%	40.0%	0.0%	0.0%
	Metamorphic Rock (1 samples)	S1	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%
		S2	100.0%	100.0%	100.0%	0.0%	0.0%	0.0%
		S3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
EDAPHOLOGY	Tropofluvents (10 Samples)	S1	70.0%	70.0%	60.0%	90.0%	90.0%	100.0%
		S2	30.0%	20.0%	40.0%	10.0%	10.0%	0.0%
		S3	0.0%	10.0%	0.0%	0.0%	0.0%	0.0%
	Skeletal Haplustalfs (6 Samples)	S1	50.0%	50.0%	50.0%	50.0%	66.7%	83.3%
		S2	50.0%	50.0%	33.3%	33.3%	33.3%	16.7%
		S3	0.0%	0.0%	16.7%	16.7%	0.0%	0.0%
	Dystropepts (6 Samples)	S1	100.0%	66.7%	83.3%	50.0%	66.7%	33.3%
		S2	0.0%	16.7%	16.7%	33.3%	33.3%	50.0%
		S3	0.0%	16.7%	0.0%	16.7%	0.0%	16.7%
	Tropaquepts (3 Samples)	S1	66.7%	66.7%	33.3%	100.0%	66.7%	100.0%
		S2	0.0%	33.3%	66.7%	0.0%	33.3%	0.0%
		S3	33.3%	0.0%	0.0%	0.0%	0.0%	0.0%
	Haplustalfs (2 Samples)	S1	0.0%	50.0%	50.0%	50.0%	50.0%	100.0%
		S2	100.0%	50.0%	50.0%	50.0%	50.0%	0.0%
		S3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Typic Ustifluvents (1 samples)	S1	100.0%	0.0%	100.0%	100.0%	0.0%	0.0%
		S2	0.0%	100.0%	0.0%	0.0%	100.0%	100.0%
		S3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

3.7.3. SOIL MAPS (DIGITAL DATA) GENERATION

As written before, the purpose of sampling several soil sites was to obtain enough information to develop spatially distributed soil data as raster maps (Figure 3.15). Two methods were used to produce the raster maps depending on the case:

1. Interpolation of soil point data to generate primary soil data maps, and
2. Usage of the Map Calculator macro in ArcView to generate secondary soil information by applying standard equations.

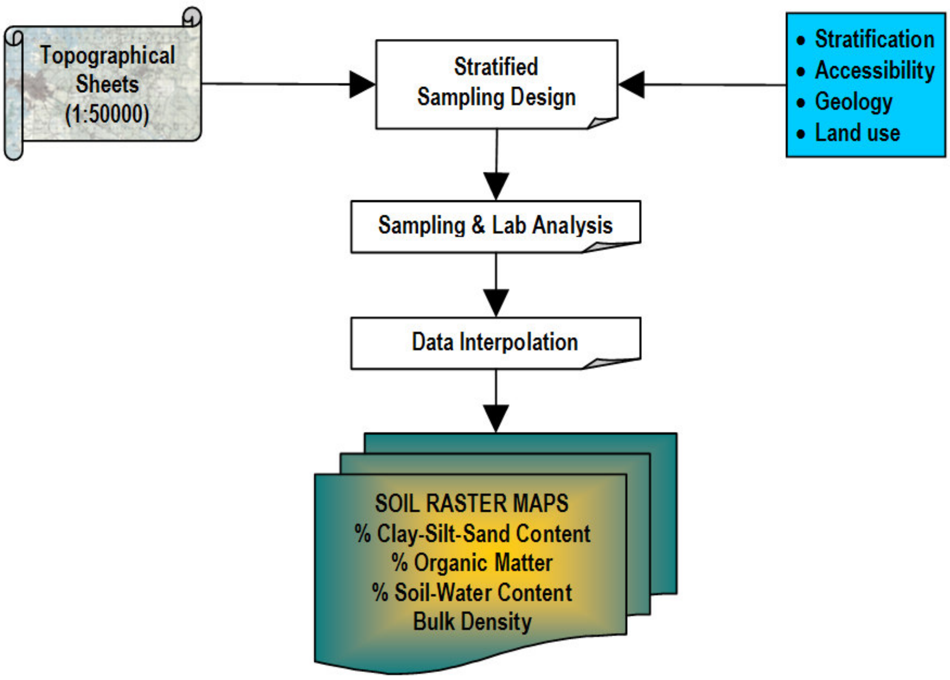


Figure 3.15. Schematic procedure to generate soil maps

<u>**Primary soil data:**</u> This type of information is related directly to the parameters obtained from lab analysis such as soil texture content (*SAND*, *SILT*, and *CLAY*), organic matter (*ORGMAT*) and water content (*WATCONT*). The soil maps were generated by applying Kriging interpolation, as shown in Figure 3.16. Soil texture maps were corrected in order to have a value of 100% in their arithmetic addition[22]. Each of three texture maps was adjusted by adding or subtracting the mean error value (MEV) to the original texture value.

$$MEV = \frac{100 - (SAND + SILT + CLAY)}{3} \quad [3.13]$$

[22] Only sand, silt and clay are considered here size fractions of the soil mass.

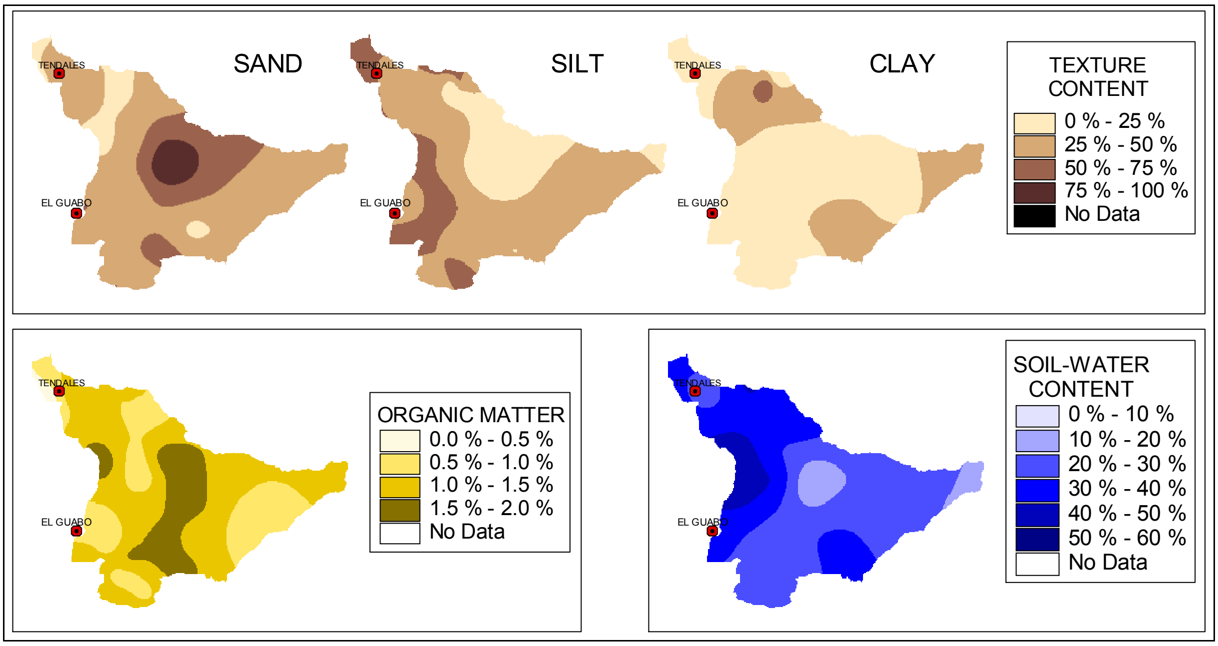


Figure 3.16. Soil primary data maps as a result of sampling interpolation

Regarding the soil water content, this soil property only reflects values obtained during an event (i.e. the sampling campaign). For that reason the generated map cannot be used for other hydrological events. In the present research, this map was used only to show the moisture pattern of the catchment: clayed and fine soils exhibit more water content than sandy soils. In addition, this information is going to be shown as a research by-product to local farmers in irrigation management issues. By showing this information, farmers can see the benefit of having and generating such data.

Regarding the bulk density map, the interpolation procedure did not consider the tillage practices. However, the majority of the crops in the basin are perennial (banana, cocoa and citrics), so tillage practices are almost not a common farming practice in the basin. The soil bulk density is required as an input data in both evaluated pesticide models.

__**Secondary soil data:**__ Data such as soil albedo, permeability, wilting point, field capacity, and soil classification can be generated with equations or Boolean algebra in the ArcView Map Calculator, as seen in table 3.28. Soil maps are shown in figures 3.17 and 3.18.

In the current research, the soil albedo was determined by using an equation that only considers soil organic matter content. This equation is not completely accurate because the albedo is also function of vegetation cover. The best way to determine soil albedo is by using remote sensing techniques, but these could not be applied in the current research because:

- The basin area is covered by clouds during almost the whole year. This climatic condition makes it impossible to have good satellite images to perform albedo estimations.
- The remote sensing techniques are very expensive and the research did not have enough budget to cover these costs.

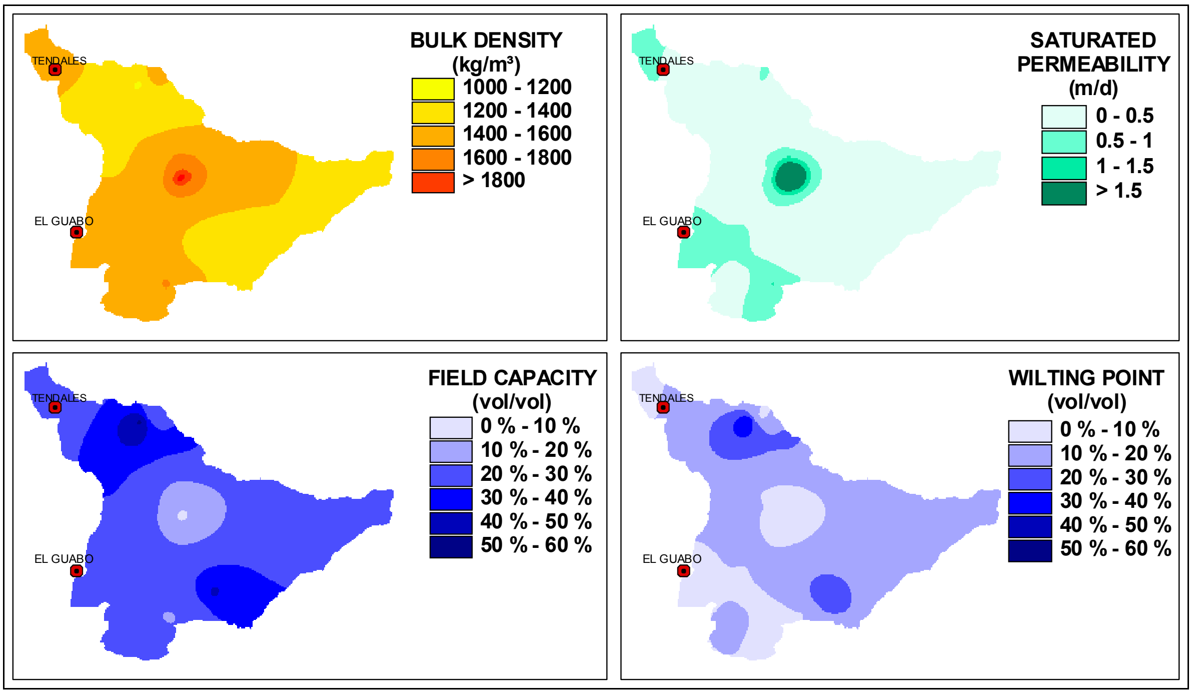


Figure 3.17. Soil properties generated with Saxton's equations

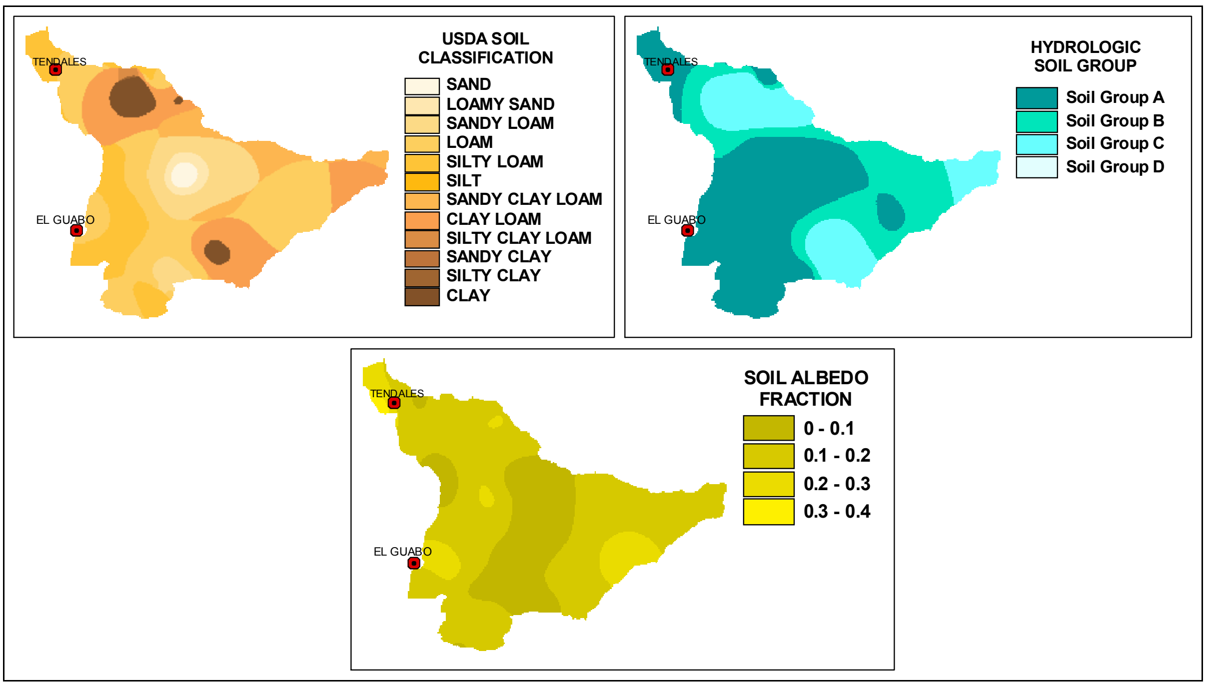


Figure 3.18. Other soil parameters generated with Map Calculator in ArcView

Table 3.28. Secondary data generated with equations and boolean algebra

Data	***Name of the map***	***Equation used***
Soil Properties (Saxton *et al.* 1986)**:** • **Permeability** • **Bulk Density** • **Wilting Point** • **Field Capacity**	*HYDCOND*	$\exp\left[12.012 - 0.0755\ Sand - \frac{3.895 - 0.03671\, Sand + 0.1103\, Clay - \left(8.7546\times10^{-4}\, Clay^2\right)}{0.332 - \left(7.25\times10^{-4}\ Sand\right) + 0.1276\log(Clay)}\right]$
	BULKDENS	$2.65\left(0.668 + 7.25\times10^{-4}\ SAND - 0.1276\log(CLAY)\right)$
	WILTPOINT	$\left[15.000\exp(4.396 + 0.0715\ CLAY + 4.88\times10^{-4}\ SAND^{2} + 4.285\times10^{-5}\ SAND^{2}\ CLAY)\right]^{B}$ *where* $B = 3.14 + 0.00222\ CLAY^2 + 0.00003484 SAND^2\ CLAY$
	FIELDCAPAC	$\left[0.3333\exp(4.396 + 0.0715\ CLAY + 4.88\times10^{-4}\ SAND^{2} + 4.285\times10^{-5}\ SAND^{2}\ CLAY)\right]^{B}$ *where* $B = 3.14 + 0.00222\ CLAY^2 + 0.00003484 SAND^2\ CLAY$
Soil Classification (Benham *et al.* 2001)	*USDAclass*	$Sand\ IF\ \left[(1.5\ CLAY + SILT) < 15\right]$ $Loamy\ Sand\ IF\ \left[(1.5\ CLAY + SILT) \geq 15\ and\ (2\ CLAY + SILT) < 30\right]$ $Sandy\ Loam\ IF \begin{cases}\left[(CLAY \geq 7)\ and\ (CLAY < 20)\ and\ (SAND > 52)\ and\ (2\ CLAY + SILT) \geq 30\right] \\ \left[(CLAY < 7)\ and\ (SILT < 50)\ and\ (2\ CLAY + SILT) \geq 30\right]\end{cases}$ $Loam\ IF\ \left[(CLAY \geq 7)\ and\ (CLAY < 27)\ and\ (SILT \geq 28)\ and\ (SILT < 50)\ and\ (SAND \leq 52)\right]$ $Silty\ Loam\ IF \begin{cases}\left[(SILT \geq 50)\ and\ (CLAY \geq 12)\ and\ (SAND < 27)\right] \\ \left[(SILT \geq 50)\ and\ (SILT < 80)\ and\ (CLAY < 12)\right]\end{cases}$ $Silt\ IF\ \left[(SILT \geq 80)\ and\ (CLAY < 12)\right]$ $Sandy\ Clay\ Loam\ IF\ \left[(CLAY \geq 20)\ and\ (CLAY < 35)\ and\ (SILT > 28)\ and\ (SAND > 45)\right]$ $Clay\ Loam\ IF\ \left[(CLAY \geq 27)\ and\ (CLAY < 40)\ and\ (SAND > 20)\ and\ (SAND \leq 45)\right]$ $Silty\ Clay\ Loam\ IF\ \left[(CLAY \geq 27)\ and\ (CLAY < 40)\ and\ (SAND \leq 20)\right]$ $Sandy\ Clay\ IF\ \left[(CLAY \geq 35)\ and\ (SAND > 45)\right]$ $Silty\ Clay\ IF\ \left[(CLAY \geq 40)\ and\ (SILT \geq 40)\right]$ $Clay\ IF\ \left[(CLAY \geq 40)\ and\ (SAND \leq 45)\ and\ (SILT < 40)\right]$
Soil Albedo (Baumer *et al.* 1994)	*ALBEDO*	$\left(0.7\ e^{-0.5596\ ORGMAT}\right)^2$
Hydrologic Soil Groups (USDA 1986)	*HSG*	Soil Type A if *HYDCOND* is greater than 0.18 m/day Soil Type B if *HYDCOND* is between 0.09 and 0.18 m/day Soil Type C if *HYDCOND* is between 0.03 and 0.09 m/day Soil Type D if *HYDCOND* is less than 0.03 m/day

3.8. LANDUSE DATA

3.8.1. EXISTING LAND USE INFORMATION

Land use data was gathered from the CLIRSEN[23] database. Information in this database is already in ArcView format (shapefiles). There are two types of information in the collected database:

- **Land Cover:** CLIRSEN compiled this data in 1994, and it was digitised from several sources of information such as aerial photographs, satellite information and printed maps at 1:250000 scale. By clipping the basin over the original landuse map, the Chaguana's land cover was obtained (Figure 3.19). Table 3.29 shows the percentage distribution of each activity in the basin. It can be seen that banana is the most important agricultural activity in the basin.

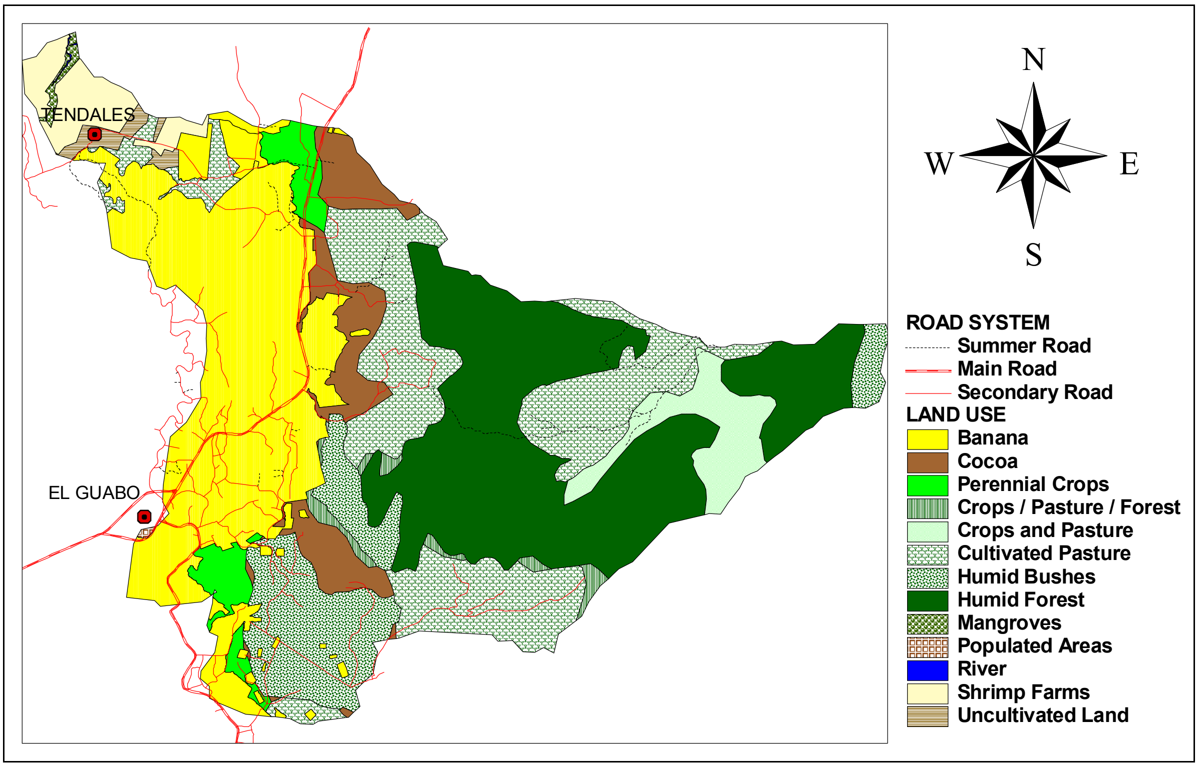


Figure 3.19. Existing land use in the Chaguana river basin

[23] Centro de Levantamiento Integrado y Sensores Remotos (Ecuadorian Centre of Integrated Survey and Remote Sensing) is the official organism to manage land cover and land use data.

Table 3.29. Land use distribution in the Chaguana river basin

Type of Activity	*Land Cover*	*Surface Area*	*Percentage*
Agricultural	Banana crops	8182 Ha	26.21%
	Cultivated Pasture	6177 Ha	19.78%
	Cocoa crops	1927 Ha	6.17%
	Other perennial crops	934 Ha	2.99%
Rangeland	Humid Forest	8142 Ha	26.08%
	Humid Brushes	2950 Ha	9.45%
	Mangroves	86 Ha	0.28%
	Uncultivated lands	261 Ha	0.84%
Mixed Activities	Mixture of crops and pasture	1264 Ha	4.05%
	Mixture of crops, pasture and forest	323 Ha	1.03%
Non-Agricultural	Shrimp Farms	944 Ha	3.02%
	Water	18 Ha	0.06%
	Populated Areas	14 Ha	0.04%

Source: Ecuadorian Centre of Integrated Survey and Remote Sensing (1999)

- **Banana Farms:** There is also information regarding the location and extension of banana farms, and each owner's name. Although this detailed information was not used in the modelling process, it was possible to display a map showing the farms by their extension (Figure 3.20). However, the database is not complete as several banana farms in the southern part of the basin have not been included. The map also shows the river network related to farm locations. It is clear that banana activity mostly affects the lower part of the river basin where other productive activities coexist. This situation can start potential conflicts between users of a river basin as was exposed in the introductory chapter of this thesis.

Based on the map, a farm distribution can be obtained for the Chaguana Basin (Table 3.30). The distribution was arranged in agreement with the classification proposed by the Ecuadorian Ministry of Agriculture for small, medium and big farms (see Chapter 2, table 2.10). By comparing both tables, it can be seen that the farm distribution in the Chaguana basin reflects very well the current situation at national scale conforming this basin as case study. The majority of banana farming comprises small lots with heterogeneous management depending mostly on economics. This situation will be analysed in the next section.

Table 3.30. Banana farm distribution per size in the Chaguana basin

Farm Size	*Percentage*	*Average Size*
Less than 30 Ha	80.2 %	10.6 Ha
30 Ha – 100 Ha	13.8 %	52.2 Ha
More than 100 Ha	6.0 %	186.5 Ha

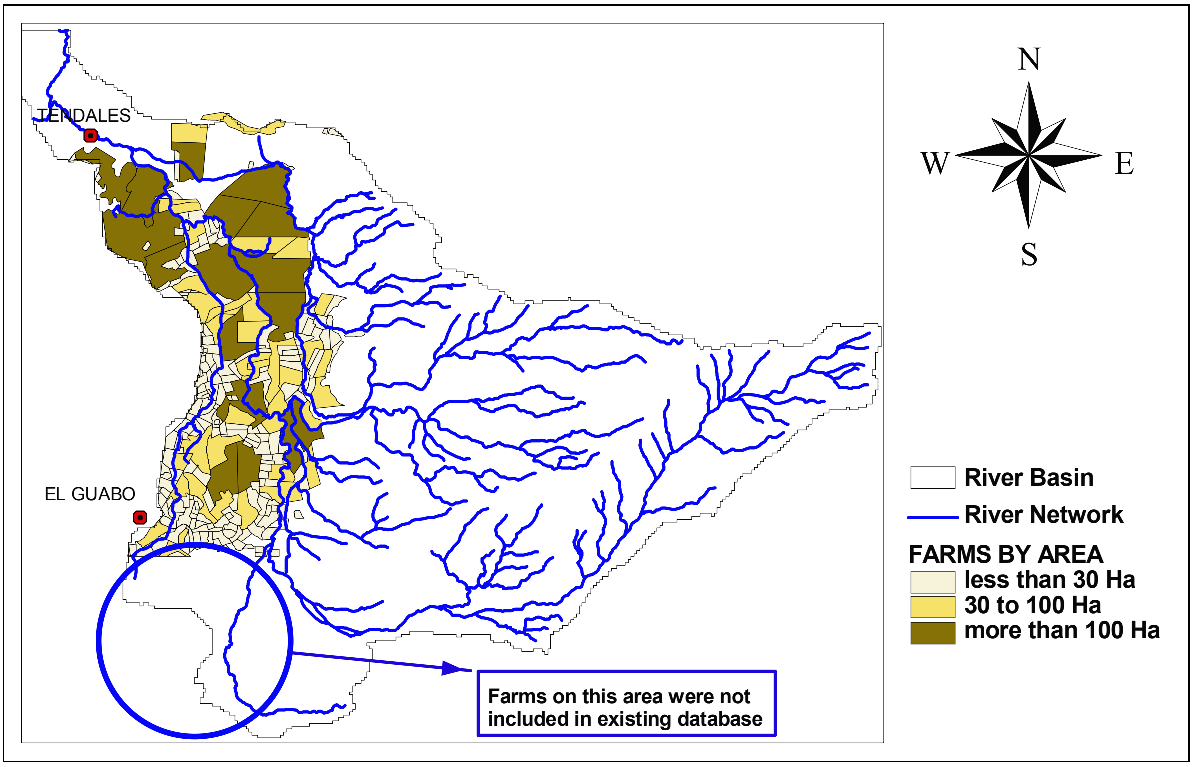


Figure 3.20. Distribution of banana farms by extension in the Chaguana river basin

3.8.2. PESTICIDE MANAGEMENT DATA

As quoted in the previous section, the majority of the banana farms in the basin can be classified as small farms which can strongly affect the way pesticides are being transported inside the basin. Although this problem analysis is out of the scope of the current research, a summary of several findings obtained during the research is presented here.

At the present time, there is a struggle between the banana farmers and the exporters about the in-situ price of a banana box. Farmers claim that prices should be increased because production costs have been increased since the change of the national currency[24]. Among the production costs, the use of agrichemicals represents the highest one after the management costs, as shown in Table 3.31.

[24] In 1999, the Ecuadorian Government decided to use the U.S. dollar as national currency.

Table 3.31. Cost distribution to produce bananas in Ecuador

Cost type	*Percentage*
Management	40.50%
Pesticides and Fertilizers	24.60%
Transport	9.08%
Planting, Caring and Replanting	8.21%
Equipment and others	7.14%
Financial Costs	4.25%
Harvest	3.72%
Irrigation and Drainage	1.57%
Packaging	0.93%

Source: National Association of Banana Producers (1999)

Some small and medium farmers have readjusted their production costs in all items, including pesticide usage, to compensate for the low price of the banana box. On the other side, big farmers can still manage the production costs because sometimes they are also exporters. Therefore, small-medium farmers are forced to use less agrichemicals than the big ones. By using that scenario on the Chaguana basin, small-medium farms are mainly located upstream the river basin while the big farms are downstream. During sampling campaigns, the downstream section of the banana sector showed pesticide concentration values higher than the ones obtained in the upstream section of banana activity (see section 3.11.2).

Thus, the pesticide modelling assessment turns to be complex because pesticides are not used homogeneously in the entire basin, and there is no available information showing the complete pesticide application planning in the watershed. During the research, it was only possible to obtain detailed information regarding the pesticide management in two banana farms: one inside the basin and the other in a different location outside the basin. These data are used together with the general information obtained during the inspections performed on seven banana farms in Ecuador (see Section 2.5). A typical pesticide application planning was structured based on the collected information (Table 3.32).

Table 3.32. Typical application plan in an Ecuadorian banana farm

Application Date	*Julian Day*	*Week*	*Type of pesticide*	*Typical pesticide*	*Application rate*
January 02	2	1	Fungicide	Propiconazole	100 g.a.i. / Ha
January 06	6		Herbicide	Glyphosate	375 g.a.i. / Ha
January 26	26	4	Fungicide	Benomyl	15 g.a.i. / Ha
				Mancozeb	800 g.a.i. / Ha
January 29	29	5	Insecticide	Bacillus Thuringiensis	1 g.a.i. / Ha
February 06	37	6	Herbicide	Glyphosate	375 g.a.i. / Ha
February 15	46	7	Fungicide	Propiconazole	100 g.a.i. / Ha
March 06	65	10	Herbicide	Glyphosate	375 g.a.i. / Ha
March 26	85	13	Insecticide	Bacillus Thuringiensis	1 g.a.i. / Ha
March 28	87		Fungicide	Propiconazole	100 g.a.i. / Ha
April 06	96	14	Herbicide	Glyphosate	375 g.a.i. / Ha
April 08	98		Fungicide	Propiconazole	100 g.a.i. / Ha
April 18	108	16	Mixture	Mancozeb	800 g.a.i. / Ha
				Propiconazole	100 g.a.i. / Ha
May 03	123	18	Fungicide	Propiconazole	100 g.a.i. / Ha
May 29	149	22	Fungicide	Propiconazole	100 g.a.i. / Ha
June 25	176	26	Mixture	Benomyl	15 g.a.i. / Ha
				Mancozeb	800 g.a.i. / Ha
August 7	219	32	Mixture	Benomyl	15 g.a.i. / Ha
				Mancozeb	800 g.a.i. / Ha
August 24	236	34	Fungicide	Propiconazole	100 g.a.i. / Ha
September 15	258	37	Fungicide	Azoxystrobine	100 g.a.i. / Ha
October 04	277	40	Fungicide	Azoxystrobine	100 g.a.i. / Ha
October 25	298	43	Fungicide	Propiconazole	100 g.a.i. / Ha
November 06	310	45	Herbicide	Glyphosate	375 g.a.i. / Ha
November 18	322	46	Fungicide	Benomyl	18 g.a.i. / Ha
November 27	331	48	Fungicide	Propiconazole	100 g.a.i. / Ha
December 06	340	49	Herbicide	Glyphosate	375 g.a.i. / Ha
December 23	357	51	Fungicide	Bitertanol	150 g.a.i / Ha

Based on the table, it is concluded that pesticides are applied on a crop field around 29 times in a year (every 13 days on average). In addition, propiconazole is the most used pesticide in the year with 10 applications through the year (at least one application each month). In the packaging facilities, two pesticides are used after the fruit washing process: thiabendazole and imazalil. Both pesticides are mixed with water and alumina, and they are sprayed over the fruit at a specific location within the packaging facility. The mixture mist is collected in ditches which are connected to the farm channels and then discharged into the river with an average travel distance of 1 km. The pesticide concentration is between 1 and 10 mg of active ingredient per litre for both pesticides. This discharge is produced at least one day per week per farm.

3.9. EROSION DATA

Because pesticide modelling also involves the movement of a chemical attached to suspended particles resulting from erosion mechanisms, it is necessary to also have data related to erosion processes. The majority of pesticide models use the Revised / Universal Soil Loss Equation (RUSLE / USLE). In this equation the following characteristics must be provided:

- The length-slope factor (LS)
- The soil erodibility factor (K_S)
- The rainfall-runoff erosivity factor (R)
- The support practice factor (P)
- The cover management factor (C_M)

These characteristics are discussed below and applied to the current case study.

3.9.1. LENGTH-SLOPE FACTOR (LS)

Basically, the length-slope factor indicates how slope length and slope steepness influence land erosion. It actually measures the relationship between case study topographic conditions to a standard plot conditions (22.12 m of slope length and 9% of slope steepness). The basic L factor equation was first proposed by Wischmeier and Smith (1978), and the first S factor equation was proposed by McCool *et al.* (1987). Combination of these two factors produces the topographic LS factor used in the RUSLE and USLE equations.

The LS factor is usually either estimated or calculated from actual field measurements of length and steepness; however at regional scale, it can be difficult to estimate them because labour-intensive field measurements are obviously not always feasible (Van Remortel *et al.* 2001). For that reason, several authors have proposed methodologies to estimate the LS factor, such as Van Remortel et al. (2001), Desmet and Govers (1996) and Mitosova *et al.* (1996). Those authors recommend not only considering depositional and ridging areas, but also flow concentrated areas in the slope length estimation. Based on those methods, the Length-Slope factor map was obtained as follows by using the ArcView Map Calculator.

Depositional Areas Determination: It has been determined that depositional areas usually begin when the steepness of the evaluated cell is less or equal to a limiting steepness defined by the "concave" area[25]. In ArcView, the concave area can be obtained by using the avenue statement *Curvature*.

CURVATURE = FILLEDEM100.Curvature (Nil, Nil, Nil, Nil)

If the curvature is negative, the cell is concave related to its neighbours; otherwise, the cell is convex. Therefore, depositional areas are the ones where cells are concave. To create the depositional area map, the curvature map is reclassified by assigning a value of 0 to all cells with a negative curvature and a value of 1 to cells with positive curvature.

Concentrated Flow Areas Determination: Another restriction in the LS factor determination is the location of areas where the flow is concentrated (streams, channels, rivers). These areas should be determined by rasterizing the actual river network. However, as explained in section 3.5.3, there are small deviations between the actual river network and the generated river network by the *FlowAccumulation* statement which is the main input for other hydrological determinations. Then, the concentrated flow areas are determined by reclassifying the Flow Accumulation raster into two classes:

- All cells with a cumulative drainage area less than 12 Ha receives a value of 1 which indicates that no water is concentrated, so the cell is susceptible to runoff erosion[26].
- When the cumulative drainage area is greater or equal to 12 Ha, the water is concentrated in the cell, and the chance of deposition is greater than the chance of runoff erosion. Thus, the assigned value is 0.

Slope Length Determination: Once depositional and concentrated flow maps were obtained, a map (named *DEPO_FLOW*) showing all areas excluded for runoff erosion was produced by multiplying both raster maps. Then, the length of slope is determined by using the avenue statement *FlowLength* considering the flow direction raster map (*FLOWDIR*) and the constrained erosion map.

LENGTH_SLOPE = FLOWDIR.FlowLength (DEPO_FLOW, True)

[25] It is the area surrounding the evaluated cell delimited by its eight neighbouring cells.

[26] Based on a digitized river network from topographical maps, it was estimated that an average drainage area of 12 Ha initiates a river stream.

Length Factor (L): The slope length factor is calculated by applying equations developed by Wischmeier and Smith (1978), Foster et al. (1977) and McCool *et al.* (1989).

$$L = \left(\frac{L_{SLOPE}}{22.12848} \right)^{\frac{\beta}{1+\beta}} \quad [3.14]$$

$$\beta = \frac{Sin\delta}{0.2688\,(Sin\delta)^{0.8} + 1.68} \quad [3.15]$$

Where

L_{SLOPE} Length of the maximum downhill slope

δ Slope angle

Steepness Factor (S): The slope steepness factor is evaluated with the equation proposed by McCool *et al.* (1987).

$$S = \begin{cases} 10.8\,Sin\delta + 0.03 & \rightarrow \quad Slope < 9\% \\ 16.8\,Sin\delta - 0.50 & \rightarrow \quad Slope \geq 9\% \end{cases} \quad [3.16]$$

Equations 3.14, 3.15 and 3.16 were used in the Map Calculator to produce the raster maps L_FACTOR and S_FACTOR, which were multiplied to obtain the LS_FACTOR map (Figure 3.21a). Table 3.33 shows the range of results obtained from the previous calculations.

Table 3.33. LS factor values for the Chaguana basin

	Length of Slope (m)	*Slope (%)*	*Length Factor*	*Steepness Factor*	*LS Factor*
Maximum value	1228	172	11.64	14.02	111.99
Minimum value	0	0	0	0.03	0.00
Mean	175	20	1.65	2.76	6.21
Standard Deviation	232	22	1.86	3.00	12.45

3.9.2. SOIL ERODIBILITY FACTOR (K_S)

The soil erodibility factor represents the soil loss due to rainfall impact on a unit plot. It is an integrated average annual value which is mainly related to the soil properties. Although it is advisable to measure this value on the field, reliable field data are not always available. However, there are several methods to estimate this value mainly based on soil properties. Based on 225 soils around the world, Shirazi and Boersma (1984) related this value to the mean geometric particle diameter.

$$K_S = 0.0034 + 0.0405 \exp\left[-\frac{1}{2}\left(\frac{1.659 + \log Dg}{0.7101}\right)^2\right] \quad [3.17]$$

$$Dg = \exp\left[0.01\left(Cl \ln\Phi_C + St \ln\Phi_{St} + Sn \ln\Phi_S\right)\right] \quad [3.18]$$

Where

K_S	Soil erodibility factor
Dg	Geometric mean particle diameter for a specific soil
Cl, St, Sn	Clay, Silt and Sand fraction respectively
Φ_C	Arithmetic mean diameter of clay size limits (0.001 mm)
Φ_{St}	Arithmetic mean diameter of silt size limits (0.00425 mm)
Φ_S	Arithmetic mean diameter of sand size limits (1.00325 mm)

By applying those equations in map calculator, the K_FACTOR raster map was obtained (Figure 3.21b). Table 3.34 shows the range of obtained values.

Table 3.34. K factor values for the Chaguana basin

	Clay (%)	*Silt (%)*	*Sand (%)*	*K factor ($Ton.Ha.h.Ha^{-1}.MJ^{-1}.mm^{-1}$)*
Maximum value	66.5	76.2	94.3	0.043900
Minimum value	0.4	4.3	8.7	0.007484
Mean	21.6	39.2	39.2	0.038658
Standard Deviation	8.6	12.8	12.1	0.007900

3.9.3. RAINFALL – RUNOFF EROSIVITY FACTOR (R)

The erosivity factor represents the soil loss produced by the influence of the energy of raindrop impacts and a 30-min rainfall intensity. Although this factor can be calculated for a single storm, it is advisable to account for all significant storms occurring through the year. Equations proposed by Brown and Foster (1987) are used in the calculation of the erosivity factor

$$E = 0.29\left(1 - 0.72\, e^{-0.05\, i}\right) \quad [3.19]$$

$$R_I = E\, I_{30} \quad [3.20]$$

Where

E	Energy produced by the impact of a typical raindrop
i	Intensity of the rain
I_{30}	Maximum 30-min intensity for a specific storm

R_I Rainfall erosivity factor for a specific storm

In the Chaguana basin, there is no information regarding this erosivity factor or 30-min rainfall information. Therefore, it was necessary to estimate the factor based on the maximum 24-h precipitation for the basin during a "normal" year (or 2-year return period as explained in Section 3.6.2). The estimated 2-year maximum precipitations were processed to obtain the annual rainfall erosivity factors for each station (Pagua, Pasaje and Machala). The TR-20[27] methodology was followed to convert the 24-h precipitation into 30-min precipitation, and to estimate the corresponding erosivity factors for each station. The rainfall erosivity map was generated by *SPLINE* Interpolation (Figure 3.21c). In table 3.35, a summary of the generated data is given.

Table 3.35. R factor values for the Chaguana basin

	Annual R factor ($MJ.mm.Ha^{-1}.h^{-1}.year^{-1}$)
Maximum value	2115.80
Minimum value	1067.50
Mean	1384.30
Standard Deviation	249.60

3.9.4. SUPPORT PRACTICE FACTOR (P)

The support practice factor represents the soil loss of a specific crop management practice related to the loss produced by upslope and downslope tillage. It is a dimensionless value ranging between 0 and 1. It is necessary to have very detailed information regarding the crop practice (contouring, stripping, tillage and so on) to estimate this factor.

In the Chaguana basin, the only information available is that bananas are cultivated in lots surrounded by drainage channels resembling terraces. Normally, when the banana plant is harvested, the plant is cut and the plant suckers are allowed to grow. Because banana plantations are permanent crops, no mechanical process affects the soil in the farm. To estimate the P factor values in the basin, equations proposed by Foster and Ferreira (1981) and Foster *et al.* (1997) can be used. Those equations are based on the terrace slope and the terrace length. In banana farms, the terrace length is normally less than 50 meters, and the slope grade is similar to the surface slope.

[27] Technical Release No.20: Computer Program for Project Formulation Hydrology, USDA (1992)

$$P = 1 - B\,(1 - P_Y) \qquad [3.21]$$

$$P_Y = \begin{cases} 0.1\exp(2.4\,s) & \rightarrow s < 0.9\% \\ 1 & \rightarrow s \geq 0.9\% \end{cases} \qquad [3.22]$$

Where

s Terrace slope grade or ground slope

B Benefit factor. It is an indicator of the probability to have deposition within the terrace. It varies from 0.5 to 1, and it depends on the terrace length. In the banana farms, this value is assumed to be 0.5.

For the non-crop areas of the basin, the same equation was applied, by considering that there are no terraces in all mountainous and rangeland areas. However, there is still a chance of deposition, so the ground slope is considered for the estimations. Table 3.36 and Figure 3.21 show the generated results for the P factor in the study area.

Table 3.36. P factor values for the Chaguana basin

	P factor
Maximum value	1.00
Minimum value	0.55
Mean	0.87
Standard Deviation	0.19

3.9.5. COVER MANAGEMENT FACTOR (C_M)

The cover management factor is also a dimensionless value ranging between 0 and 1. It represents the soil loss produced by all management activities within a period of time (usually one year). In the RUSLE estimation, this value varies every 15 days in order to cover all management activities within a farm (crop rotation, management schemes, plant growth, etc.). In the USLE estimation, on the other hand, this value is taken as a single average value representing the entire year. For areas such as rangelands or perennial crops, a single value is more appropriate to represent the soil loss rate because the actual cover changes very slowly with time.

In the Chaguana basin, this value will later be a variable to be changed in the model runs to calibrate suspended solids measurements in the river with the sediment loadings produced by the C_M factor (see Chapter 5). However, the initial values, assumed for the basin, depend on the existing land use / land cover conditions. Based on the AGNPS database, Table 3.37

shows recommended C_M factor values for the land cover conditions in the Chaguana basin. However, those values were mainly developed for USA land and crop cover. Therefore, some trial-and- error estimations should be done for banana plantations. Figure 3.21e shows the C_FACTOR map for the Chaguana basin.

Table 3.37. Recommended initial C_M factor values for the Chaguana basin

Land Cover	*Recommended C_M Factor*	
	Average	*Minimum*
Forest	0.03876	0.001
Pasture and brushes	0.06590	0.003
Crops	0.28575	0.170
Mixture of Crops and Pasture	0.17582	0.087
Mixture of Crops, Pasture and Forest	0.13014	0.058
Non crop and barren land	0.60000	0.230

Source: AGNPS model database

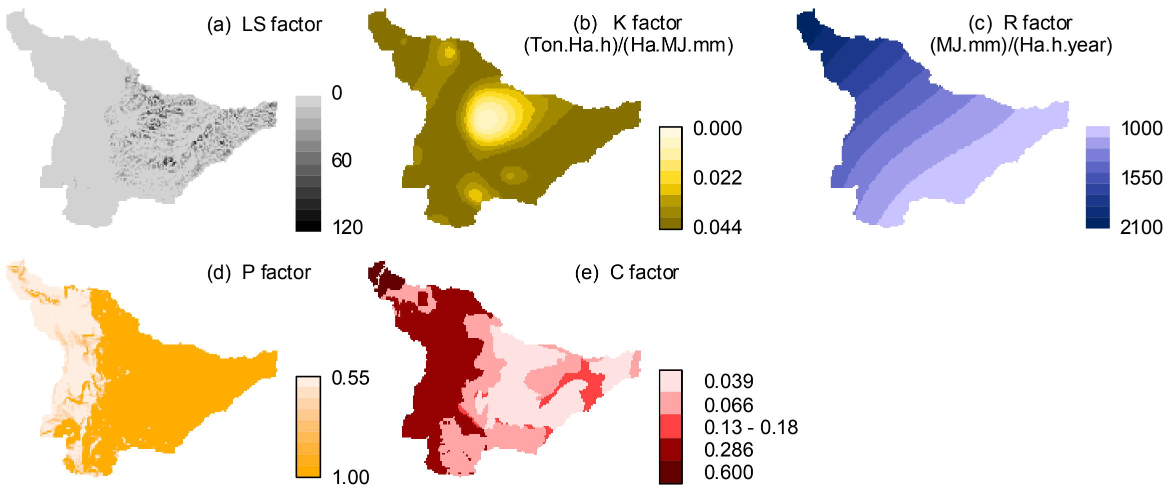


Figure 3.21. RUSLE / USLE factor raster maps for the Chaguana river basin

3.10. CROP DATA

In several pesticide models such as AGNPS and SWAT, it is also necessary to provide information regarding crops to which the pesticides are applied because plants can also affect the way pesticide is transferred to the environment. Time-changing parameters such as canopy cover, crop height and root mass are important for pesticide interception and soil detachment by erosion. Some models such as AGNPS require this information on a 15-day basis. Current models normally have a complete database showing properties of crops mostly cultivated at places where the models were developed. Unfortunately, that is not the case for banana crops.

Data from farmers

In Ecuador, farmers are usually not interested in getting this information on a continuous basis. However, some data which can be used in the evaluated models could be gathered from them:

- The average population density in a banana farm is 1478 plants per hectare which represents around 7 m^2 per plant (diameter of 3 m.)
- The average yield of a banana farm is 27 Tons per Ha.
- The final height of a banana plant differs depending on the plant variety, but the typical height observed during field visits is 3.60 meters.
- The harvest time also depends on cultivated variety ranging from 12 to 15 months. In the current research, it will be assumed that full height and harvesting is reached at the end of 12th month. Once the plant is harvested, it is half-cut so the sucker can feed on it. The farmer can distribute the planting phase in the farm to harvest bananas every week.
- The growing pattern of banana is only available as normalized height values at four growth stages: planting, development, flowering and harvesting (Table 3.38). Normal curves of plant growth show a typical sigmoid shape starting at the origin and tending to a horizontal asymptote. To obtain the height on a 15-day basis, interpolation was done to obtain the curve that fits the data best. In the current research, straight lines were used to fit the data because the height is actually not significantly affecting results in the runoff model. Banana is a perennial crop and farmers do not plant it frequently. Therefore, the plants in banana farms can be considered to be fully developed in the analysis.

Table 3.38. Average growth of banana for the main crop stages

Growth Stage	*Average Julian Day*	*Normalized Height*	*Average Height*
Planting	0	0.01 %	0.05 m
Development	101	75 %	2.70 m
Flowering	245	100 %	3.60 m
Harvesting	365	100 %	3.60 m

Source: Farmer records

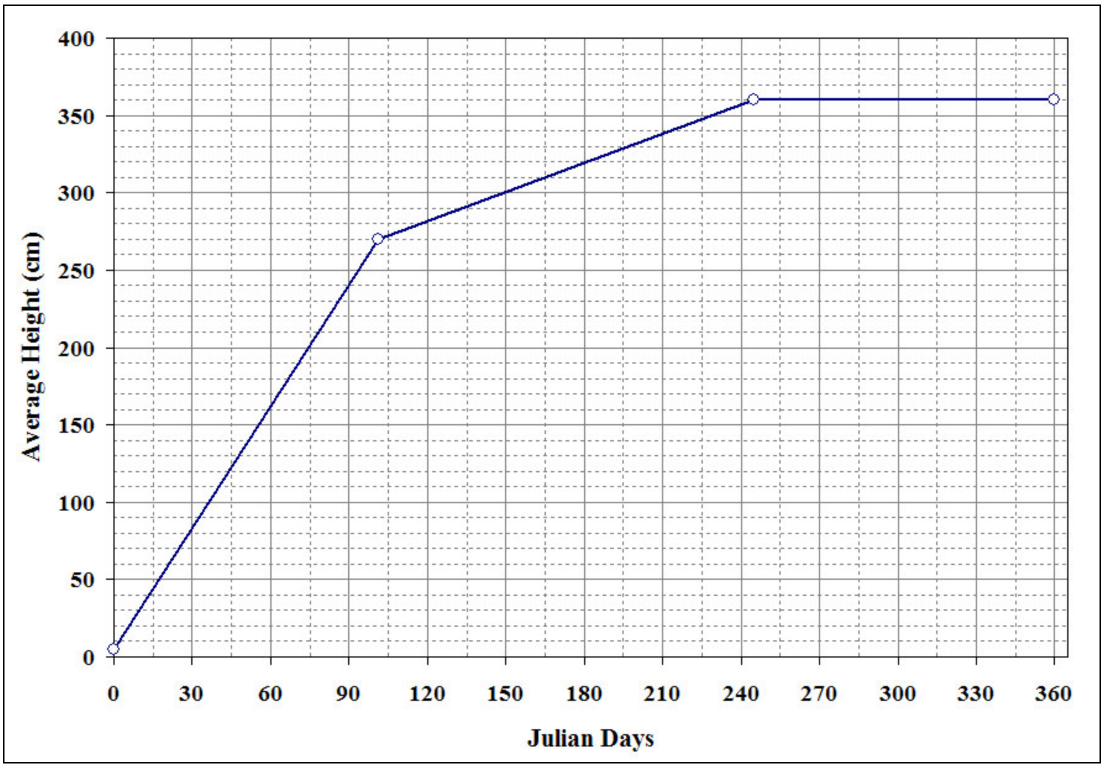


Figure 3.22. Estimated growth of a banana plant

Fresh root mass

The root mass development on a year was estimated based on the research done by Blomme *et al.* (2001a). This study states that root mass can be obtained by using the leaf area, the pseudostem circumference and the tallest sucker length of the banana plant, as shown in equation [3.23]. After searching the literature and some farmer records, values shown in table 3.39 were used to estimate the fresh root mass per hectare of harvested banana plants. For the root development on a 15-day basis, it is assumed that root mass will increase linearly up to the value obtained in the equation.

$$AM_{ROOT} = \left(\frac{0.002066\ A_{LEAF} + 0.42659\ \phi_{PSEUDO} + 0.171415\ H_{SUCKER}}{1 - w} \right) \left(\frac{Den}{1000} \right) \qquad [3.23]$$

where

AM_{ROOT}	Estimated unitary root mass
A_{LEAF}	Mean leaf area of the plant
Φ_{PSEUDO}	Pseudostem circumference
H_{SUCKER}	Height of the tallest sucker
w	Mean water content of the root system
Den	Plant population density in the farm

Table 3.39. Values used for root mass estimation for banana crops

Parameter	*Mean Value*	*Source*
Leaf Area	9900 cm^2	Kumar *et al.* (2002)
Pseudostem Circumference	130 cm	Krauss *et al.* (2001); Blomme *et al.* (2001b)
Height of tallest sucker	85 cm	Blomme *et al.* (2001b)
Root water content	75 %	Several sources

Carbon to Nitrogen Ratio

Another input parameter needed in the AGNPS model is the Carbon to Nitrogen ratio for the banana crop. A study conducted by CEMA[28] (1998), evaluated this ratio in several banana farms at two coastal provinces in Ecuador (Table 3.40). In the current research, the value from the El Oro province is used because that site is the nearest to the study area.

Table 3.40. C:N ratios for banana crops in Ecuador

Province	*Farm Site*	*Mean C:N ratio*
Los Ríos	Quevedo 1	11.75
	Quevedo 2	15.62
	La Mana	13.20
El Oro	Pasaje	17.25

Source: CEMA (1998)

3.11. CHEMICAL DATA

3.11.1. WATER AND SEDIMENT SAMPLING CAMPAIGNS

The Chaguana system has two main rivers: the Zapote and the Chaguana. The Zapote river joins the Chaguana river 5 km before the basin outlet. This basin is not discharging to the sea, but to a bigger basin named the Pagua river basin. In the assessment, the Colorado river, a tributary of the Zapote, is also considered. However, for the purposes of this analysis, it is combined with the Zapote river evaluation as “Colorado & Zapote rivers.”

The Chaguana river basin has no historical water quality records, so it was necessary to design and implement a sampling campaign to develop water quality data along the main streams in the catchment. Pesticide concentrations, BOD, TOC, pH, solids content,

[28] Centre of Environmental Studies at ESPOL, Guayaquil, Ecuador

temperature, and dissolved oxygen were measured in the samples, so the existing water conditions were established.

Four measurement campaigns were conducted between November 2001 and November 2002. Each sampling campaign was three days long in order to cover all sampling points. Only one water sample was taken in each sampling point at a certain date and time during the sampling period. Water samples were taken consecutively by following the downstream path of the river once during every sampling campaign. In addition, every certain number of sampling points, a sediment sample was taken for pesticide analysis. The sampling periods were devised in such a way that the climate of a whole year was covered:

1. Transition between dry and rainy season (November 2001)
2. Rainy season (February 2002)
3. Transition between rainy and dry season (June 2002)
4. Dry season (November 2002)

It is important to note that the fourth sampling campaign was influenced by the presence of an extreme climate event (El Niño) which began at the end of 2002 according to INAMHI, the official meteorological organism in Ecuador.

Sampling Methodology

In order to prepare the sampling campaigns optimally, an exploratory field trip was conducted to get direct data from the river system at the moment of the trip. This trip was done in June 2001 which was on the transition between the rainy and dry season. Although most of the observations done during this trip are only representative for the time of the trip (Table 3.41), other non-time dependent information was obtained to improve the future sampling campaigns such as location of banana farms, other land use activities, water discharges and so on. Figure 3.23 shows the travelled path by boat (**thicker line**) during the exploratory trip, and the location of the uppermost place where both rivers are influenced by the tidal effect **(dotted line**). It was impossible to travel by boat further upstream in both rivers because of the low river depth and river barriers[29] (Photo 3.3). Thus, the exploration was continued by following accessible roads adjacent to both rivers (**bold line**).

[29] To pump water into farms, farmers build rock barriers at the downstream side of the pump uptake

Table 3.41. Physical conditions of rivers in June 2001

River	*Average mid-stream depth*	*Average river width*	*Average water velocity*
Chaguana	0.5 m (upstream)	10 m (upstream)	0.2 – 0.6 m/s
	2.0 m (downstream)	30 m (downstream)	
Zapote	0.3 m (upstream)	6 m (upstream)	0.2 – 0.6 m/s
	1.5 m (downstream)	10 m (downstream	

Photo 3.3. Barrier built by a banana farmer to protect a pump uptake

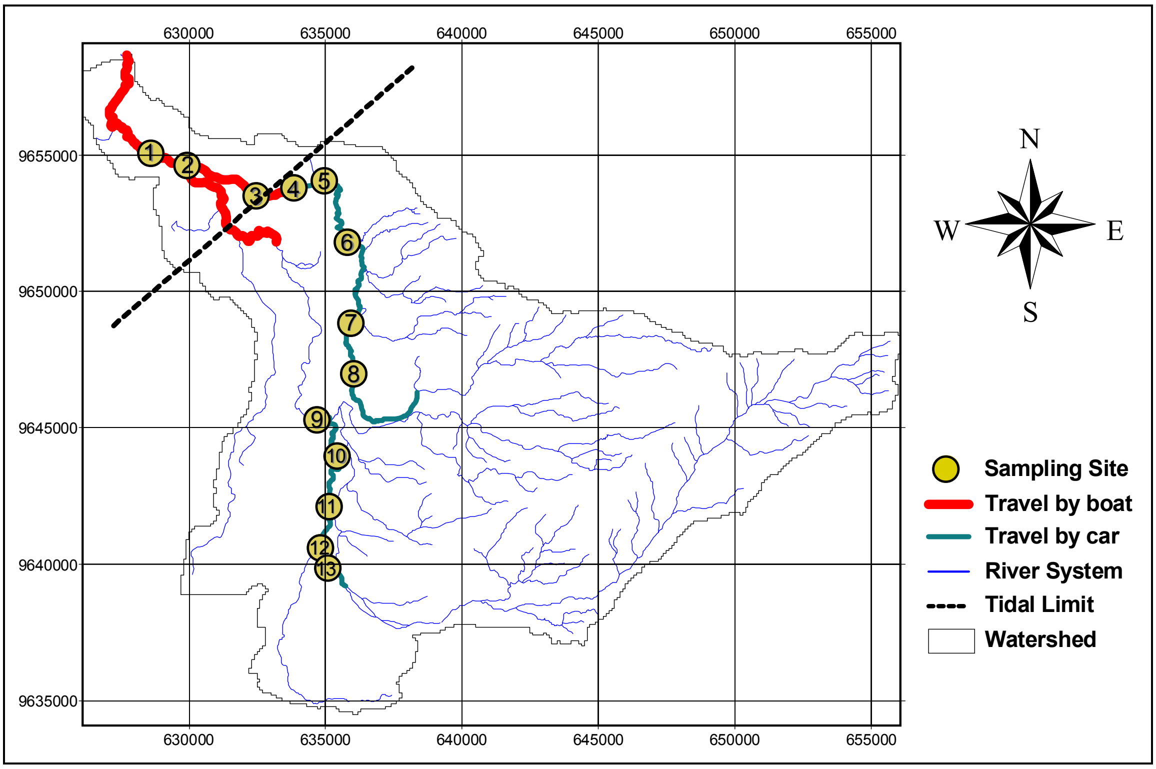


Figure 3.23. Travelling path of the survey done in June 2001 and selected sampling sites

Before the exploratory trip, a sampling procedure called follow-the-plug method[30] was opted for. However, due to the problems mentioned previously, another sampling method was selected: to sample only accessible sampling sites from the most upstream to the most downstream location.

Sampling Sites

Thirteen places which can be accessed at any time of the year were selected to take water samples and eventually sediment samples from each sampling period. From here on, these places will be known as the *Sampling Stations*. However, some other samples were taken at places only accessible by boat during the rainy season or when the river depth allowed to travel by boat. Those places will be called *Reference Sampling Sites* for river stretches not sampled during the whole campaign periods. Table 3.42 shows the location coordinates and a brief description of the sampling stations, which can be seen in Figure 3.23.

Table 3.42. Location of sampling stations in the Chaguana River Basin

Sampling Station	***UTM Coordinates***		***Monitored River***	***Site Description***
	E	***N***		
1	628475	9655363	Main River	Tendales Town near the outlet of the basin
2	629818	9654923		Confluence of both rivers
3	632343	9653798	Zapote	Pump Station at Zapote river
4	633719	9654101		Entrance to "Quirola" farm in the Zapote river
5	634849	9654362		Entrance to "Agricola Leticia" farm in the Zapote river
6	635692	9652118		Main highway bridge over Zapote river
7	635812	9649161		Service road of "Pennsylvania" farm
8	635916	9647300		The most upstream sampling point in the Zapote river
9	634582	9645601	Chaguana	Main highway bridge over the Chaguana river
10	635313	9644289		"La Flores" farm in the Chaguana river
11	635030	9642430		"Juana Fernandez" farm in the Chaguana river
12	634709	9640917		Road bridge to "Chaguana" farm
13	634963	9640170		The most upstream sampling point in the Chaguana river

Measurement Methodology

During sampling, some environmental parameters such as temperature, conductivity and salinity were measured with a YSI-30 instrument. The apparatus probe was introduced up to

[30] It considers sampling the same mass of water while travelling downstream the river.

one third of the river depth at several places across the sampling section. The average value of the measurements is reported for each sampling place.

For pesticide concentrations and other water quality parameters, a sample was obtained in each sampling point. The sample consisted of three 1000-ml bottles (1 glass bottle for pesticide analysis), which were preserved at 4ºC in coolers while they were transported to the lab. Because a sampling campaign was three days long, collected samples were sent to the lab on a daily basis.

Two bottles for each sampling place were analyzed at the Water Quality Lab of the Centre of Aquiculture Services (ESPOL) to obtain Biochemical Oxygen Demand, Total Organic Carbon and Solids Content. Samples in amber glass bottles and sediment samples were analysed in the Ecuadorian Commission of Atomic Energy to obtain pesticide concentration.

3.11.2. LAB ANALYSIS AND RESULTS

As said before, there were two groups of data measured during the sampling campaigns: digital data and data obtained from laboratory analysis. In this section, the results obtained will be evaluated and discussed. Results are displayed as colour maps on corresponding river stretches, in which the colour depends to the value assigned to each river stretch. As sampling places are points rather than lines, the following procedure was followed to assign a value to a river stretch:

- A river stretch is connected by two consecutive sampling stations.
- The value assigned to a river stretch corresponds to its upstream sampling station.
- If there are reference sampling sites in the evaluated stretch, these values will be used with the station value to obtain an average for the stretch. In case there is one reference sampling site significantly different from the others, the river stretch will be split at the location of the reference sampling site.

pH

Recorded values of pH during all sampling campaigns were between 6 and 7 which are typical for fresh water. Therefore, there is no significant discharge or no discharge at all of acids or bases that could affect the buffer capacity of the river. The Ecuadorian standard for pH in fresh water rivers is between 6 and 9.

Temperature

The behaviour of water temperature in the sampling points was a little different for all sampling periods. It is important to note that these temperatures are not measured at the same time for each point in both rivers, but they are measured consecutively with increasing time steps from point to point. Therefore, it is better to look at the temperature difference in the whole sampling period for the entire basin rather than interpreting the temperature in each sampling place.

In table 3.43, it can be seen that water temperature varies per sampling campaign. Compared with historical records for those months, the three first sampling campaigns show a normal behaviour. On the other hand, the fourth campaign exhibits a range of temperatures higher than the historical one. This could be explained due to the presence of the initial stages of the 2002 El Niño event. Figure 3.24 shows the measured temperature in the Chaguana river.

Table 3.43. Water temperature difference within the basin per sampling campaign.

Sampling Period	*Temperature Range*	*ΔT spatial*	*Comment*	*Mean $T_{HISTORIC}$*
November 2001	23.5 ºC – 24.6 ºC	1.1ºC	Abnormally dry month	23.4 ºC
March 2002	23.0 ºC – 25.8 ºC	2.8ºC	Rainy month	25.9 ºC
July 2002	22.7 ºC – 24.6 ºC	1.9ºC	Dry month	22.4 ºC
November 2002	24.4 ºC – 27.7 ºC	3.3ºC	Beginning of El Niño event	23.4 ºC

Electrical Conductivity

Conductivity measurements can help in aquatic assessments by providing an estimate of the dissolved ionic matter in the water. This value can be related to the existing environmental state of water bodies: oligotrophic, eutrophic and highly-polluted waters. The two last types of water bodies can exhibit very high values of conductivity. On the other hand, a pollution discharge can be reflected as a sudden change in conductivity. Studies of inland fresh waters indicate that streams supporting good mixed fisheries have a conductivity ranging between 150 and 500 µS/cm (EPA 1997). In the current research, conductivity was measured with digital equipment.

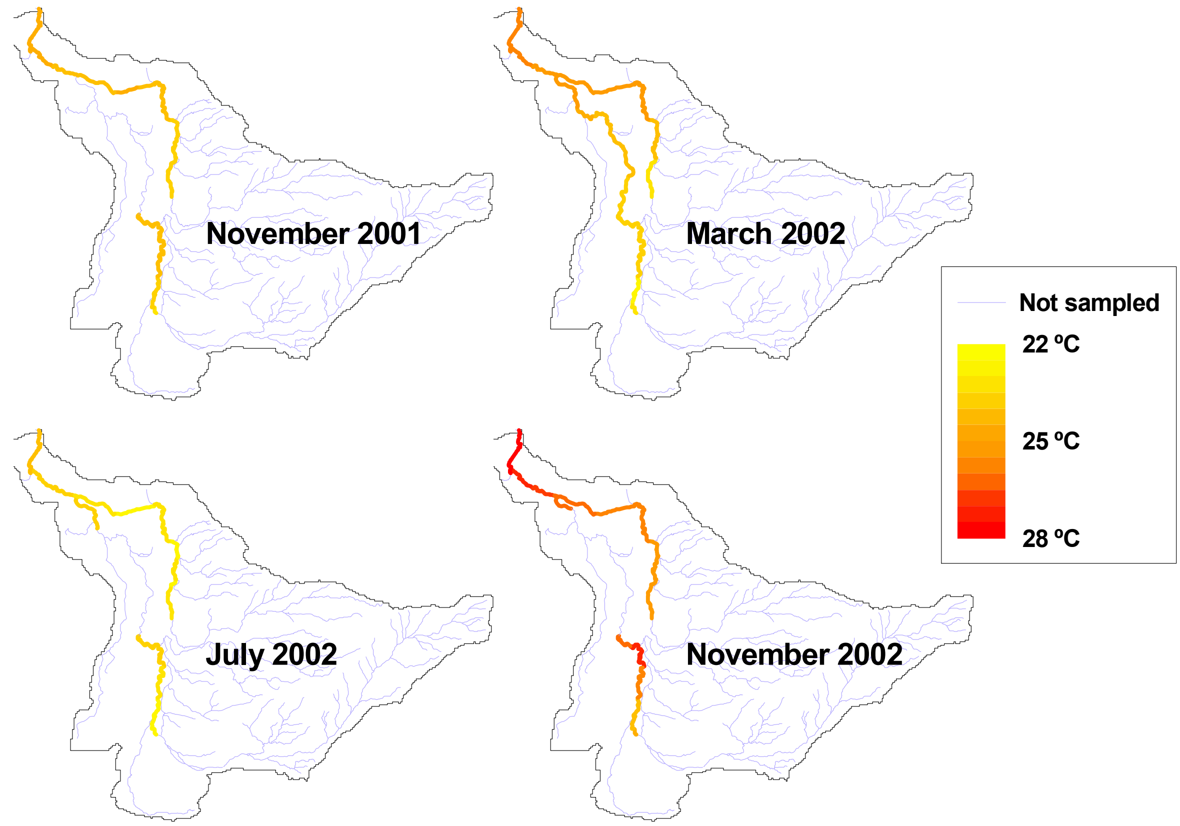


Figure 3.24. Monitored water temperature

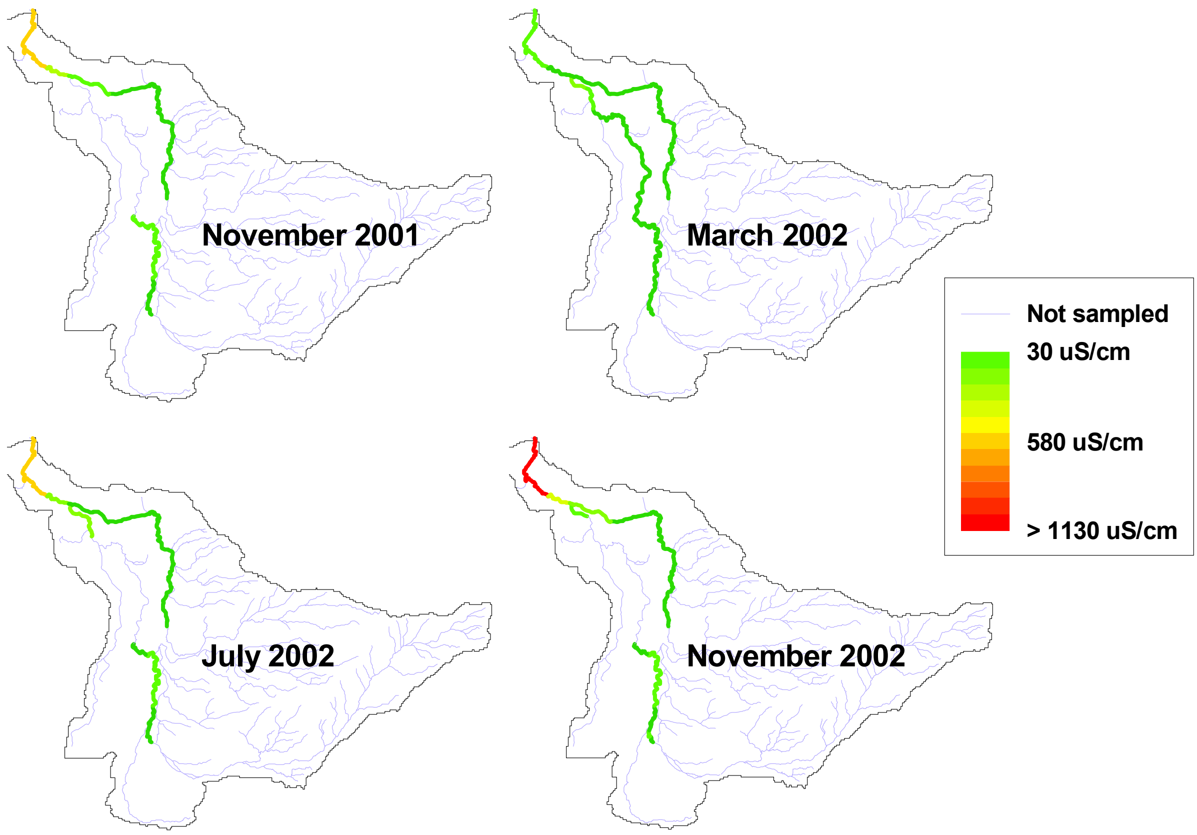


Figure 3.25. Monitored electrical conductivity

In the Chaguana river basin, the majority of the measured conductivity values are below 500 µS/cm, which means that they do not indicate pollution at the sampling dates. However, conductivity values greater than 500 µS/cm were found near the outlet of the basin (Figure 3.25); and this is explained by the potential saline intrusion into the basin. In addition, a town called Tendales (less than 2000 people) is located 5 km upstream from the outlet, and it discharges its wastewater directly to the river.

Solids Content

Suspended and dissolved solids were measured in the laboratory by using STANDARD METHODS AWWA 2540. Results are given in figure 3.26 (Suspended solids) and figure 3.27 (dissolved solids).

The suspended solids content in a river is directly related to the resulting erosion through the basin. Although the Chaguana and the Zapote rivers run through erosive soils (sands and silts), the Chaguana river (left stream) showed more suspended sediments than the Zapote river (right stream) during sampling campaigns, mainly in November 2001 and March 2002. During that period, both river sides of the Chaguana River were under civil works maintenance done by the farms adjacent to the river. Thus, some resulting river erosion was produced at that time. Farmers perform these maintenance works at least once a year.

In river waters, dissolved solids content consist of calcium, chlorides, nitrate, phosphorus, and other ions particles that will pass through a filter with pores of around 2 microns (0.0002 cm) in size. There are many sources where those ions come from; however, pesticides and fertilizers are the main suppliers of dissolved solids in basins where agriculture is the main activity.

Figure 3.27 shows the dissolved solids content measured during each sampling campaign. It is seen that both rivers exhibit very low dissolved solids content (less than 100 mg/l). However, high values (larger than 500 mg/l) were recorded near the basin's outlet. This behaviour correlates very well with the conductivity measurement done at the same places (figure 3.25). As explained before, this last river stretch is influenced by marine intrusion as flood tide enters the basin.

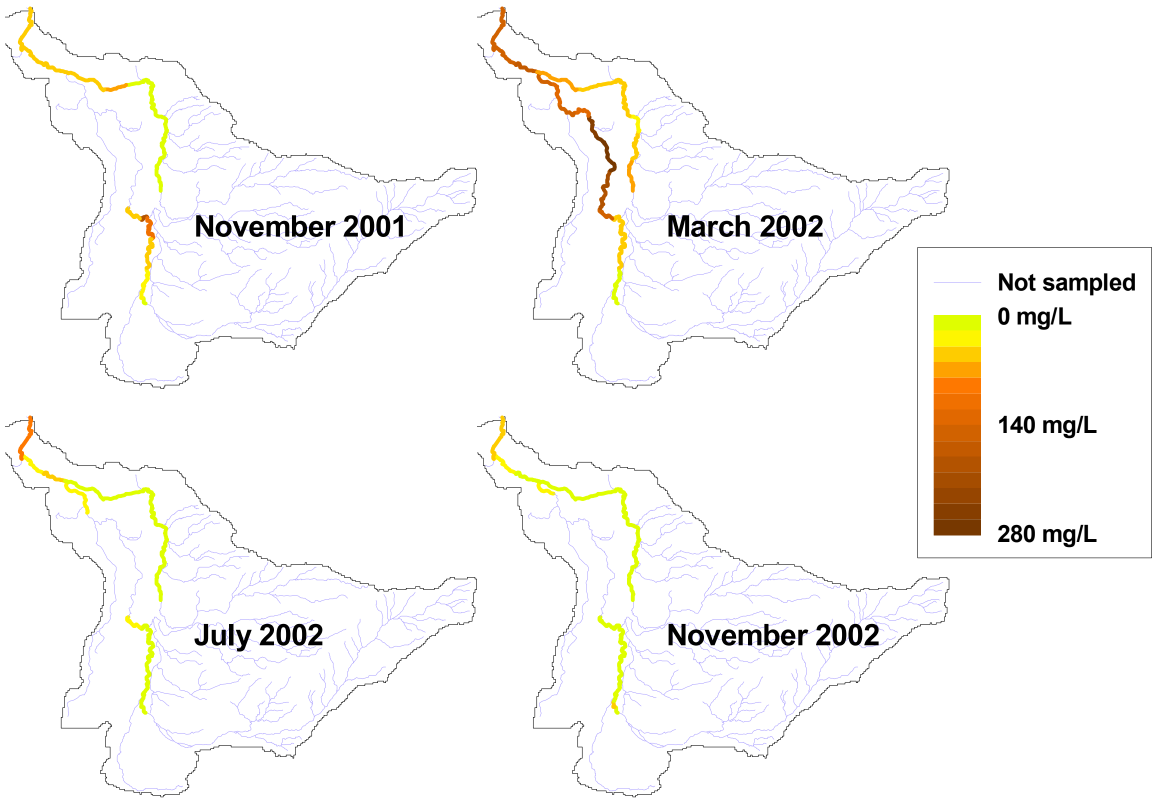


Figure 3.26. Monitored Suspended Solids

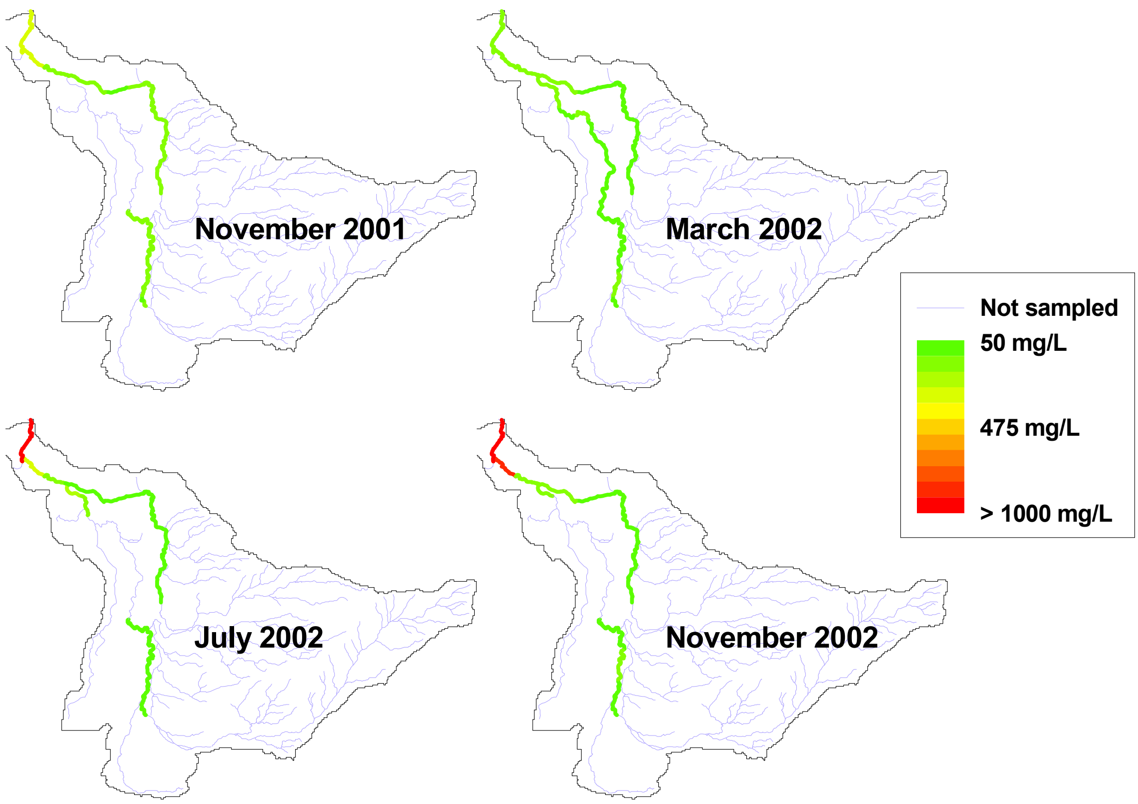


Figure 3.27. Monitored Dissolved Solids

Biochemical Oxygen Demand

BOD measurements are indirect indicators of the amount of organic matter present in water bodies, mainly produced by domestic wastewater discharges. For the case of the Chaguana river basin, the recorded BOD values were between 1 to 4 mg/l which indicates that organic matter discharges into the river were not the main concern for the ecosystem at the moment of sampling. These values are within the acceptable range for fresh-water bodies.

In the evaluated watershed, there are only two main residential areas located at the most western parts of the basin: Tendales and El Guabo (Figure 3.19). In addition, there are some sparse settlements within the farms. Most of the residential areas do not have wastewater treatment systems.

The total amount of people living in the basin is less than 20000, which represents around 23 litres of wastewater per second; and a BOD loading of 500 kg/day or 10 kg BOD per day per kilometre of the monitored stream[31].

[31] The equations used to calculate these values are

$$Q_{sewage} = \frac{N\,q_u}{86400} \quad [3.24]$$

$$Load_{daily} = \frac{54}{625}\,BOD_{domestic}\,Q_{sewage} \quad [3.25]$$

$$l_{daily} = \frac{Load_{daily}}{L_{river}} \quad [3.26]$$

Where

Q_{sewage}	Domestic wastewater flow
q_u	Unitary sewage production which is assumed to be 100 l/p/day in Ecuadorian rural areas.
$BOD_{domestic}$	BOD concentration for domestic wastewater which has an average value of 250 mg/l in Ecuadorian rural areas
$Load_{daily}$	BOD loading on daily basis
l_{daily}	Average linear distribution of BOD loading along the river length
L_{river}	Length of monitored river stream, which in the current research is around 50 km.
N	Number of inhabitants

Pesticides

Water and sediment samples were analysed to obtain pesticide concentrations. As explained in previous sections, propiconazole, imazalil, thiabendazole, glyphosate and tridemorph are the pesticides most used in Ecuadorian banana farms. However, glyphosate and tridemorph could not be traced due to existing lab restrictions in Ecuador (see section 2.5.3); and the others were detected up to 0.01 ppb (minimum detection limit). As expected, a sampling campaign can only detect pesticide concentrations when the spraying is performed within a period of time before the campaign takes place. This is mainly because the river travel time in the basin is less than 24 hours.

Propiconazole is a pesticide applied by air spraying, and it is used mainly for Sigatoka control. During the sampling campaigns some river stretches showed propiconazole concentrations while others did not show any at all (Figure 3.29). From the figure, it is clear that most of the farmers in the basin sprayed their plantations during the March campaign because Sigatoka tends to be present on banana leaves during the rainy season (extreme humid conditions). During the other campaigns, propiconazole is only detected near the basin outlet which is mainly a shrimp area; however, this pesticide could have come from the most downstream banana farm which is located around 7 km upstream the outlet.

Imazalil and thiabendazole are pesticides used during the packaging process of banana mainly as a pesticide mixture. As explained in the *Pesticide Management Data* section 3.8.2, farmers harvest banana at least one day every week. However, the packaging process is performed independently, depending on each farm's operational plan. Detected concentrations of both pesticides can be seen in figures 3.30 and 3.31. The presence of both pesticides in the river is very similar, which is very logical in view of their similar application.

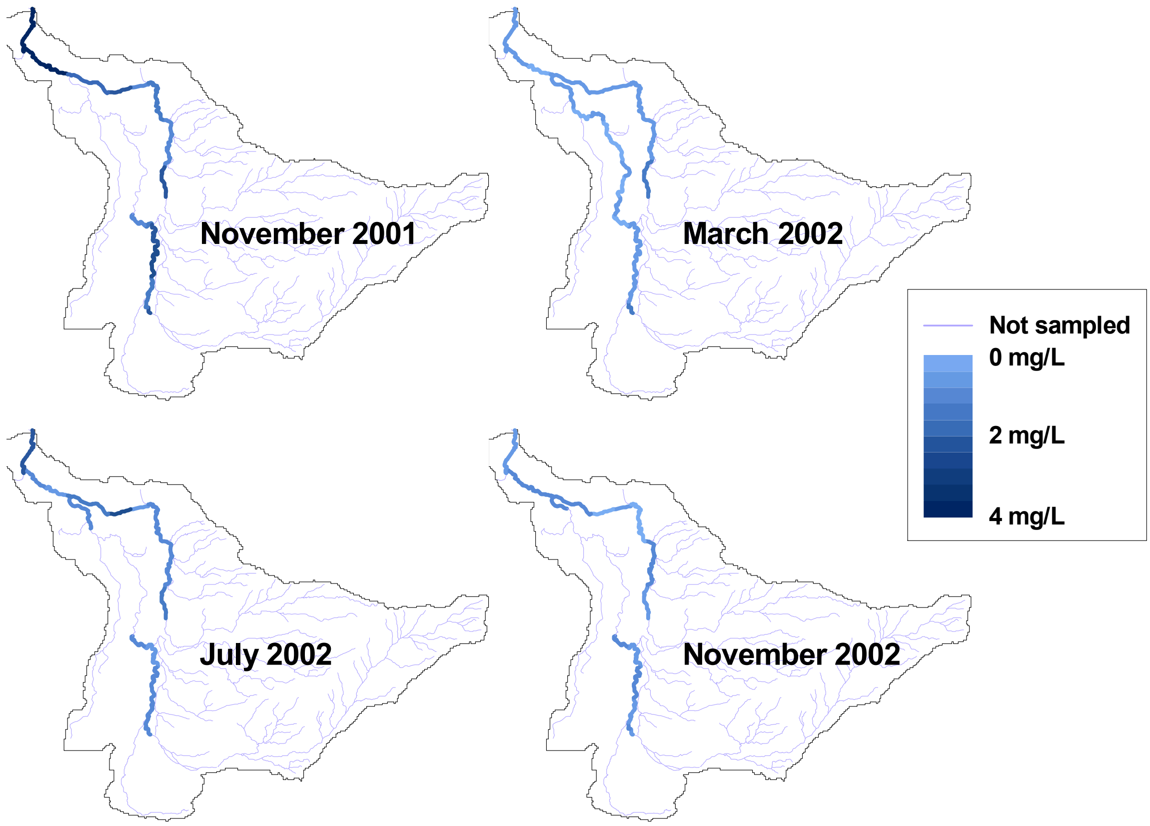


Figure 3.28. Monitored Biochemical Oxygen Demand

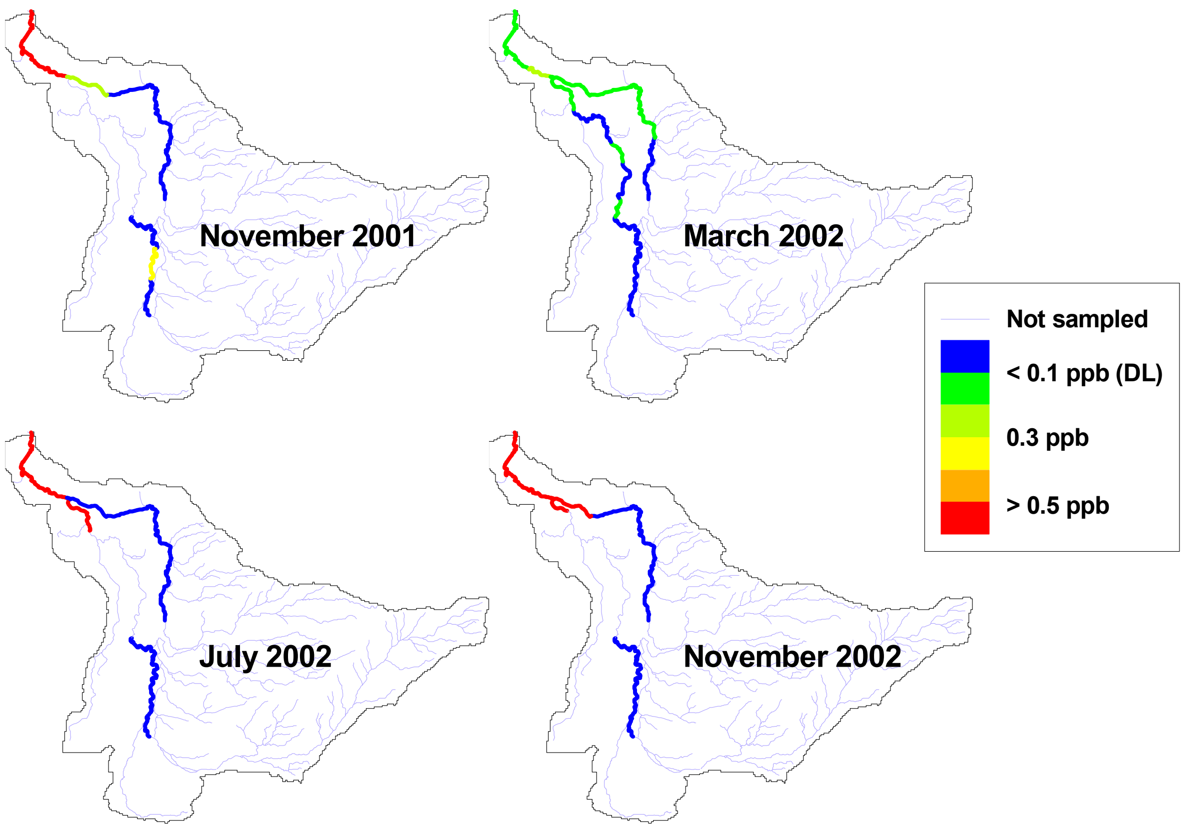


Figure 3.29. Monitored Propiconazole concentrations

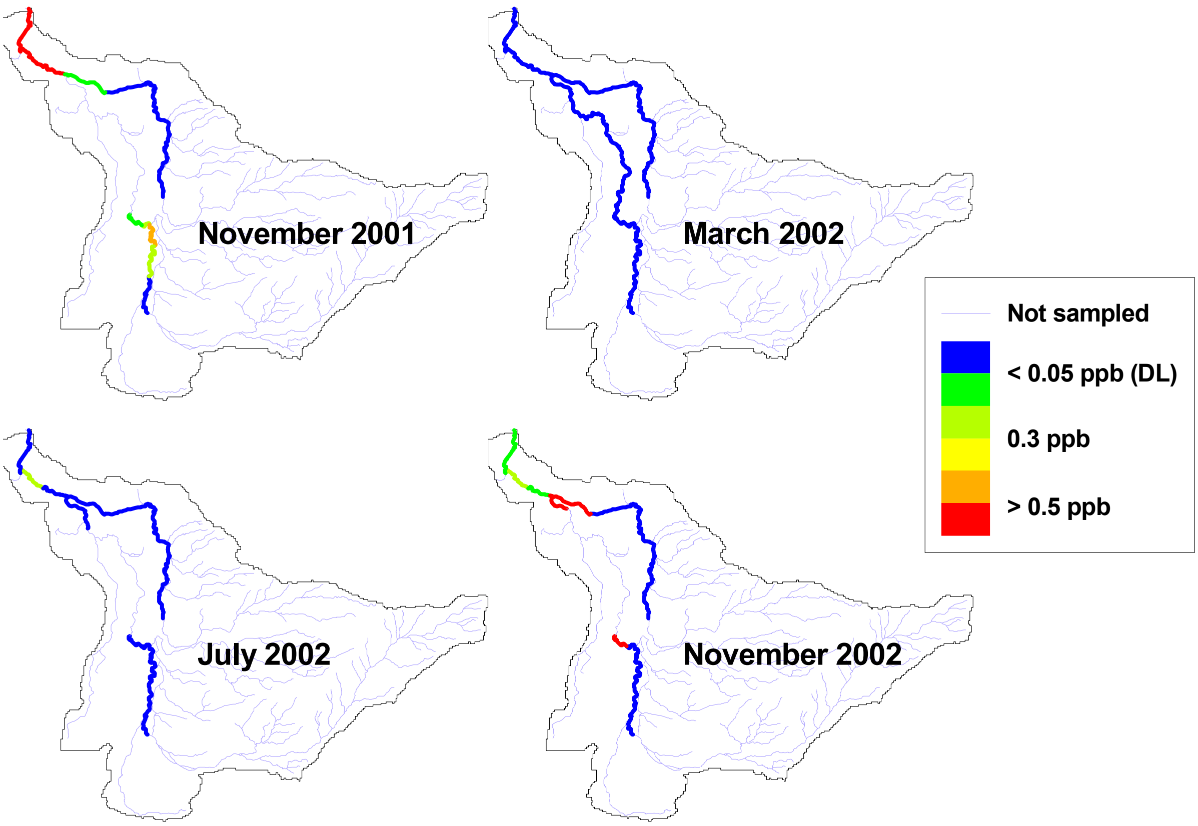


Figure 3.30. Monitored Imazalil concentrations

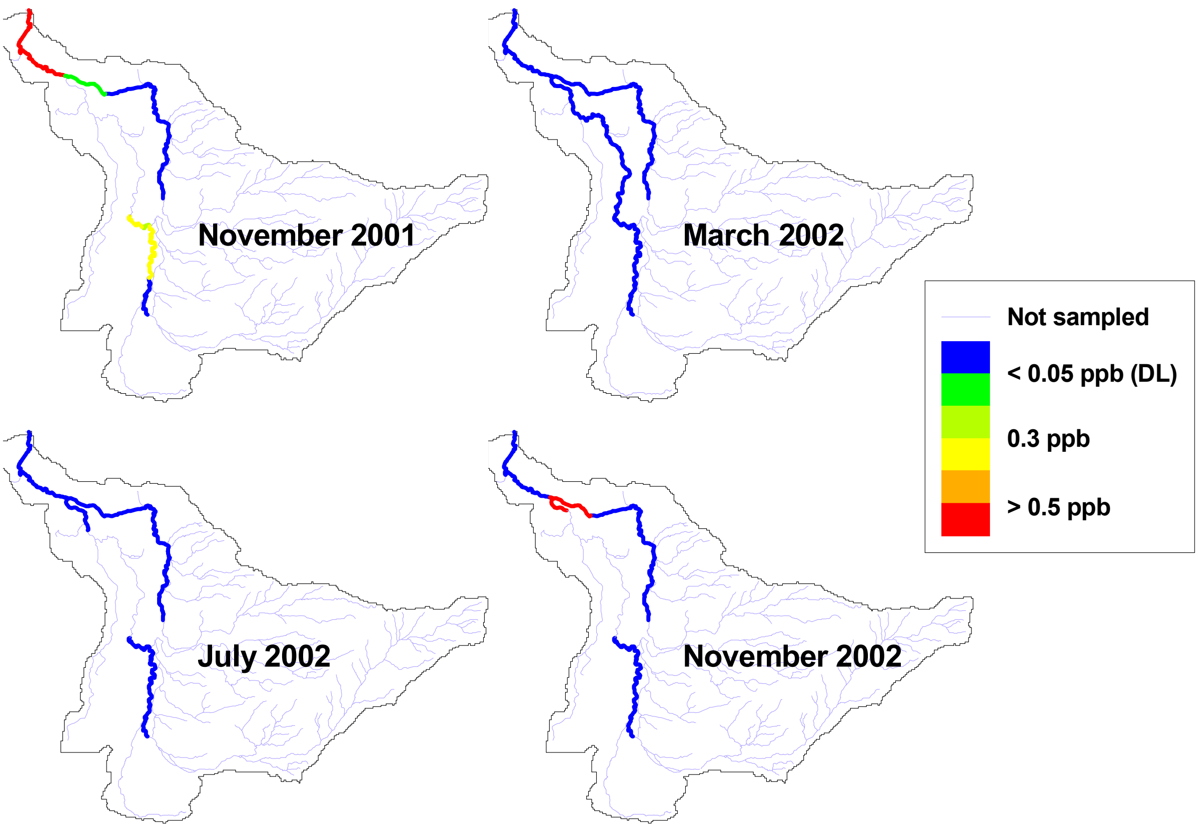


Figure 3.31. Monitored Thiabendazole concentrations

The pesticide analysis performed by the laboratory could detect other pesticides than the requested ones. Organophosphorus and Organochlorine pesticides were also detected by the chromatography analysis. Those detected pesticides represent mostly insecticides, which seem to be used in the majority of the basin's farms throughout the year, as shown in figure 3.32. In the figure, the total amount of detected pesticide concentration in every sampled stretch is displayed.

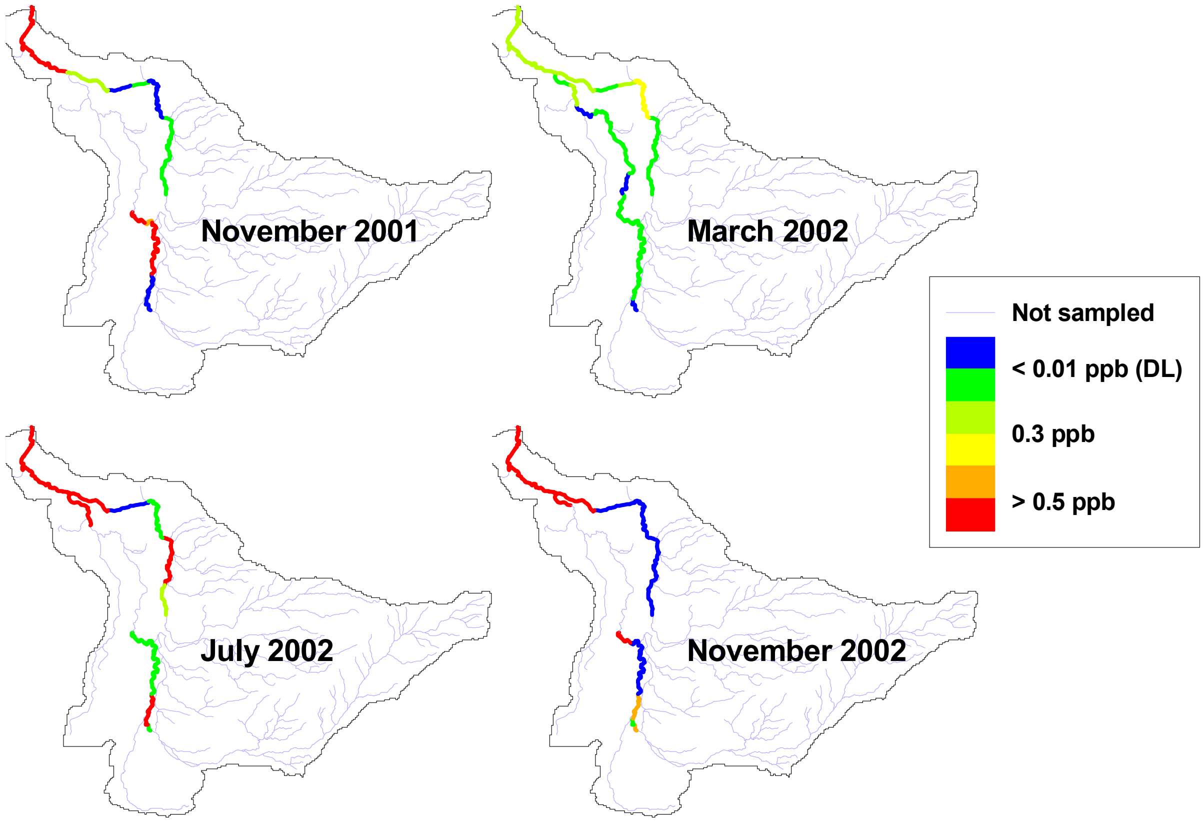


Figure 3.32. Total monitored pesticide concentrations

In the previous figure, maximum detected values were around 6 ppb (July and November 2002), which is significantly below the reported toxicity values for aquatic organisms. Based on that, the pesticide impact on the Chaguana basin on the aquatic biota is relatively low. However, detected pesticide values are exceeding the European maximum residue levels in water for human consumption (0.5 ppb for total amount of pesticides, and 0.1 ppb for one pesticide). Therefore, human health must be the main concern related to the pesticide usage in the Chaguana Basin.

3.12. CONCLUDING REMARKS

The data necessary to run a model sometimes is overwhelming, and are usually not so easily available. This chapter has gone through different methodologies to obtain reliable data to assess environmental problems in a case study: the Chaguana river basin. During the data evaluation, it was found that the existing state of the art in Ecuador regarding data housekeeping is still low. Although the procedures presented here can help to overcome that problem in other "data-poor" basins, they can not replace field measurements because uncertainties can be introduced in the model, and outcomes can differ from reality. All collected data has been organized and structured within a Geographical Information System. Thus, it can be available for future research or the basin stakeholders.

Another important finding in this chapter is the determination of the environmental baseline of the Chaguana river basin. There was no information regarding the environmental quality of the basin before this research began. Based on the sampling campaigns, it can be concluded that the basin is still not heavily polluted. However, data presented here should only be considered as a starting point to begin a monitoring programme on a frequent basis to develop a reliable historical data of several environmental parameters.

In the next chapter, a detailed description of the model evaluation is given. Selected models were executed with all data presented in Chapter 3. GIS was used to input some data into the models.

CHAPTER 4. PREDICTIVE MODELLING OF PESTICIDE FATE IN RIVERS

Tendales Town located at the lower course of the Chaguana river, 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.

Matamoros D., Guzmán E., Bonini J. and Vanrolleghem P.A. (*Submitted*). AGNPS and SWAT Model Calibration for Hydrologic Modelling of an Ecuadorian River Basin under Data Scarcity. *Submitted to:* Water Science and Technology.

Matamoros D., Van Biesen L. and Vanrolleghem P.A. (*Submitted*). Development of a Geographical Information System for pesticide assessment on an Ecuadorian watershed. *Submitted to:* Water Science and Technology.

4.1. INTRODUCTION

The first step in the study reported in this chapter was to estimate a gross distribution of the environmental concentrations caused by the pesticides most used in the Ecuadorian banana sector. Two screening models were evaluated to get an overall environmental distribution of the evaluated pesticides. This gross distribution helped to take decisions regarding the sampling campaigns and the use of more complex models to determine the impacts in the surrounding environment. The screening models used were:

- Environmental Quality Criteria Model - EQC, version 2.02 (after Mackay *et al.* 1997)
- Exposure Assessment Modelling System - EXAMS, version 2.98.01 (Burns 2000)

Chapter 2 contained a brief description of both models, explaining the characteristics and requirements of each model. However, it will be necessary to expand a little bit further regarding other aspects to assess the Chaguana basin. After estimating the gross environmental distribution of pesticides with screening models, the research pointed its analysis towards more complex models such as the integrated models that use GIS techniques to handle input data. Within the VLIR-ESPOL Project, the main goal was to establish the potential environmental impacts that could occur in a river basin with intensive banana production. In the present research, two models able to simulate the impact of pesticide usage in a basin were applied: AGNPS and SWAT. They use the same type of data whose accuracy varies depending on user's choice.

Regarding temporal resolution, both models can work with daily and monthly information. On the other hand, spatial resolution depends on the way the basin is divided. Basically, these models are semi-distributed and lumped models where all data are aggregated into each unitary subdivision of the basin.

In the current research, two independent studies were conducted on the same watershed. This Ph.D. thesis mainly focused on the use of the AGNPS model by dividing the watershed in 192 AGNPS cells on the basis of sub-basin divisions (left-, right- and upstream drainage areas). Another team, under the author's guidance, used the SWAT model and divided the watershed in 44 sub-basins with their corresponding Hydrological Response Units (HRU) on the basis of land use and soil data.

4.2. SCREENING MODELS AS TOOLS FOR PLANNING SAMPLING CAMPAINGS

4.2.1. MODELS STRUCTURE

Although the EXAMS and EQC models consider the environment as compartments, they actually do not perform calculation processes in the same way, i.e. EXAMS runs only in an aquatic system and EQC is used in a multi-compartment environment. Table 4.1 shows a summary of differences and similarities between the models. However, both models can lead to similar results when only the aquatic portion of the environment is considered as shown in the next sections.

Table 4.1. Comparison between EXAMS and EQC characteristics

Characteristic	*EQC*	*EXAMS*
Computer Environment	Windows interface	DOS
Type of Model	Deterministic (steady-state)	Deterministic (steady-state)
Compartment layout	Air, soil, water and sediment (Unique compartments)	Water and sediment (multiple linked compartments)
Compartment geometry	Constant	Can be changed
Chemical data	• All asked data is necessary to run the model • Only one chemical at a time	• The model can estimate some lacking data • Until 5 chemicals + 6 ion species for each chemical
Transport Processes	Advection	Advection + Dispersion
Environmental data	Not site-specific at all	Site-specific

In addition, the way the environment is subdivided in compartments differs from one model to another. While EQC uses one big unitary world with unique compartments representing every component of the environment, EXAMS can use more than one compartment representing the same environmental component (water or sediment). Figures 4.1 and 4.2 shows how the environment is subdivided in both models.

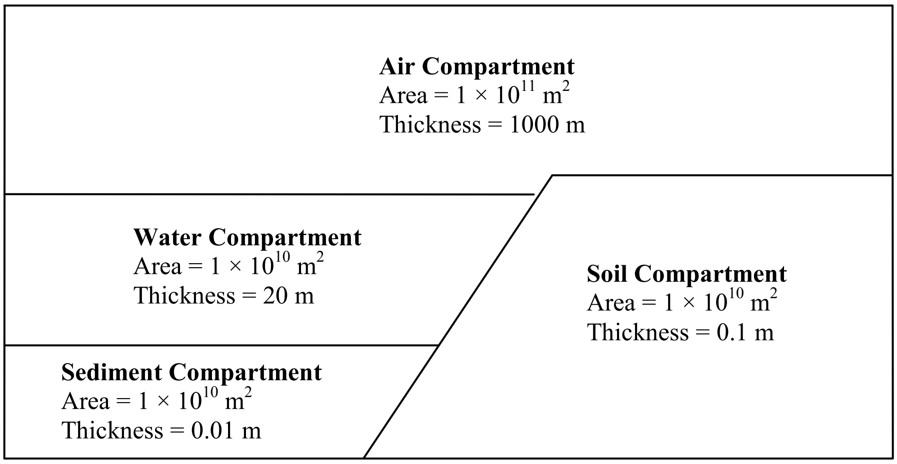


Figure 4.1. Environmental division performed by the EQC model

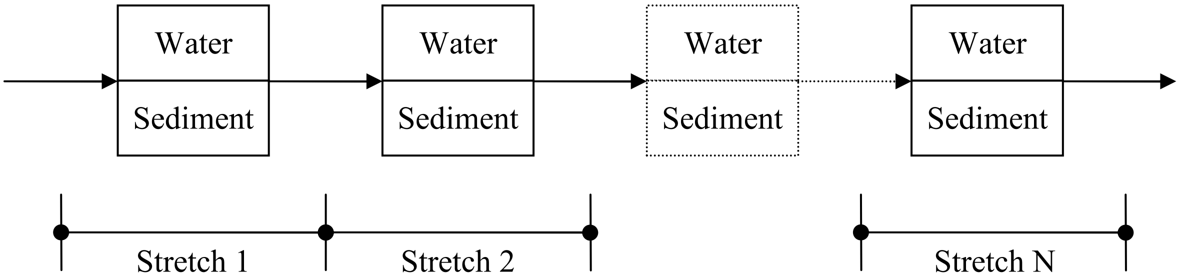


Figure 4.2. River subdivision performed by the EXAMS model

4.2.2. ANALYSIS OF RESULTS

Based on the information collected in the previous chapters, imazalil, thiabendazole and propiconazole can be considered to represent the most used pesticides in the Ecuadorian banana sector. The chemical data needed for running the models were obtained based on the average of several data found in the literature (Linders *et al.* 1994; Tomlin 1997). Table 4.2 shows the values used in the assessment for each chemical. Figures 4.3 and 4.4 show the results as charts obtained from the EQC and EXAMS runs respectively.

Table 4.2. Physico-chemical data for evaluated pesticides

Pesticide	*Imazalil*	*Thiabendazole*	*Propiconazole*
CAS Number	35554 – 44 – 0	148 – 79 – 8	60207 – 90 – 1
Molecular Mass (g/mol)	297.2 (Tomlin 1997)	201.3 (Tomlin 1997)	342.2 (Tomlin 1997)
Solubility (mg/l)	180 (Tomlin 1997)	< 50 (Montgomery 1993)	100 (Tomlin 1997)
Vapour Pressure (Pa)	1.6×10^{-4} (Tomlin 1997)	2.7×10^{-8} (Tomlin, 1997)	5.6×10^{-5} (Tomlin 1997)
Melting Point (ºC)	52.7 (Tomlin 1997)	297 (Tomlin 1997)	$< T_{ambient}$ (Tomlin 1997)
Log K_{OW}	3.82 (Tomlin 1997)	2.69 (Montgomery 1993)	3.72 (Tomlin 1997)
K_{OC} (l/kg)	2081 – 6918 (Van Leemput *et al.* 1986)	512 at pH 5 – 12 (Montgomery 1993)	650 – 720 (Tomlin 1997)
Half-life in air (h)	2400 (Tomlin, 1997)	-	288 (Tomlin 1997)
Half-life in water (h)	1350 (Tomlin 1997)	Stable in aqu. suspens. (Tomlin 1997)	600 – 2040 (Linders *et al.* 1994)
Half-life in soil (h)	2880 – 4560 (Van Leemput *et al.* 1984)	792 – 9672 (Tomlin 1997; Wauchope *et al.* 1992)	2304 – 5496 (Tomlin 1997)
Half-life in sediment (h)	3240 (Tomlin, 1997)	-	5064 (Tomlin, 1997)
Photolysis rate (h^{-1})	1.9×10^{-2} (Van Leemput *et al.* 1988)	Stable to light (Tomlin 1997)	7.77×10^{-3} (Tomlin 1997)

To perform the comparison between both models, some assumptions had to be made accounting for model differences:

1. ***EQC Assumptions:*** The assessment was conducted in the Level III mode (explained in Chapter 2) with a hypothetical loading rate of 1000 kg/h applied to specific compartments depending on the way pesticide is handled on the farm. For imazalil and thiabendazole, the loading was applied to the water compartment. The Propiconazole loading was applied to the air compartment. There is no possibility to change the dimensions of the unique environmental compartments.
2. ***EXAMS Assumptions:*** The assessment was conducted in Mode 2 (explained in Chapter 2) with the same hypothetical loading rate as the EQC model. Due to the different subdivision process, the loading can be applied only to the water and sediment compartments. For comparison purposes, the water compartment was selected as the one receiving the loading. EXAMS also differentiates the type of loads entering the compartment. For imazalil and thiabendazole, a stream load type was selected (direct discharge). On the other hand propiconazole represents a drift load type (aero-fumigation). For comparison purposes, only one water and sediment compartments were defined with the same dimensions as the EQC model.

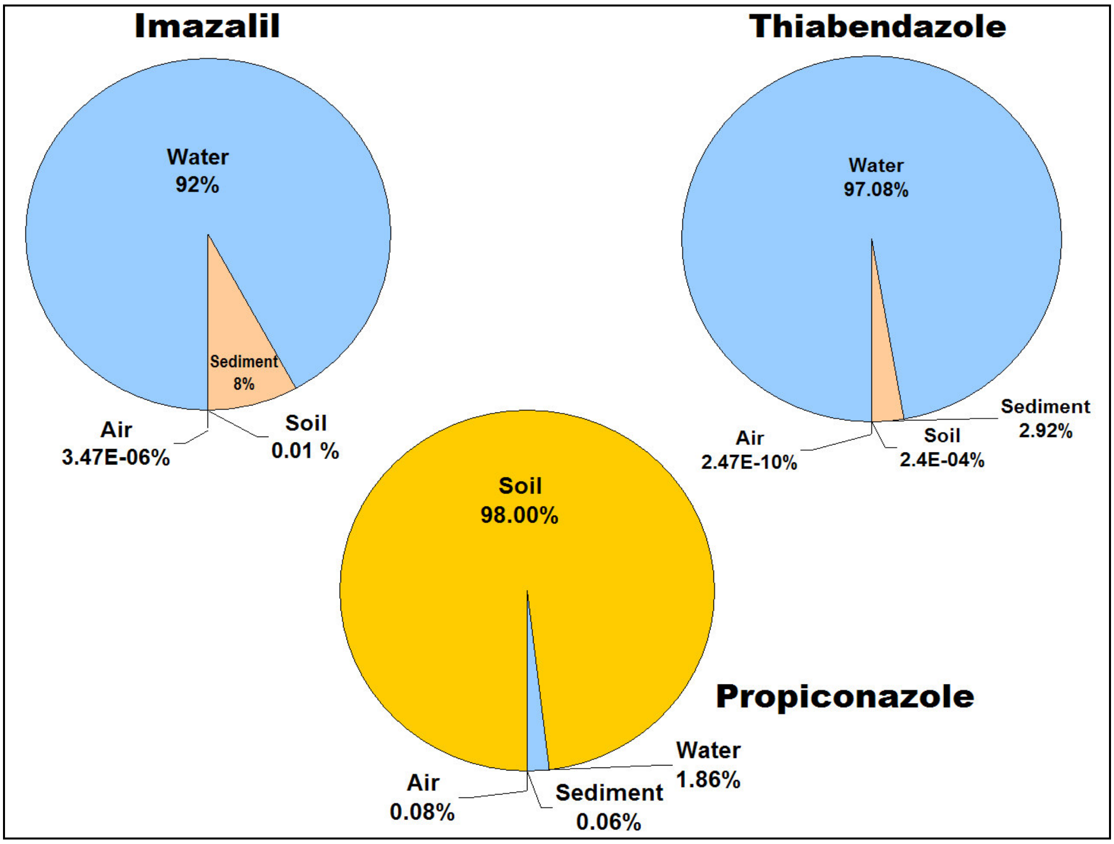


Figure 4.3. Results from EQC running

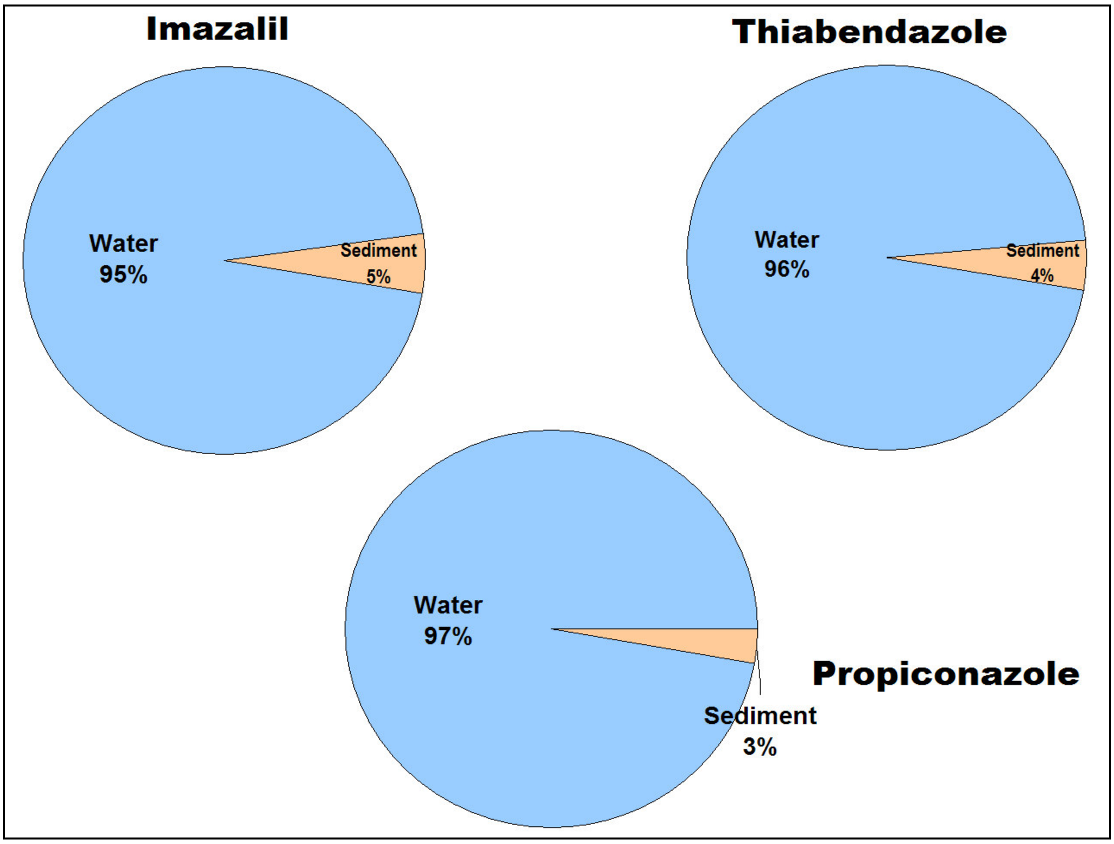


Figure 4.4. Results from EXAMS running

Based on the EQC results, propiconazole tends to distribute more in the soil compartment (around 98% of applied pesticide). Imazalil and Thiabendazole tend to distribute more likely in the water compartment (around 95%). On the other hand, EXAMS results show a significant distribution of these 3 pesticides in the water compartment. Propiconazole, Thiabendazole and Imazalil present a similar distribution between water (around 95%) and sediment (around 5%).

Due to the different approaches considered in both models, the overall results cannot be compared directly. EXAMS only performs the assessment in the aquatic portion of the environment (sediment + water). On the other hand, EQC analyses all environmental compartments (air, sediment, water and soil). Therefore, only results from the aquatic portion can be compared between both models. For example, consider the results obtained for propiconazole (figure 4.3 and 4.4):

- The EQC's aquatic (sediment – water) distribution would be 1.923% (0.064% for sediment and 1.859% for water) or 1.923 kg of propiconazole per 100 kg of aquatic mass (sediment + water).

- This total amount of propiconazole entering the aquatic portion could be divided according to the EXAMS results (3% for sediment and 97% for water), and a corrected value for the EXAMS results can be obtained.

$$\text{Sediment}_{\text{EXAMS corrected}} = (1.923\text{ kg} / 100\text{ kg}) \times 2.9\ \% = 0.056\text{ kg} / 100\text{ kg}$$

$$\text{Water}_{\text{EXAMS corrected}} = (1.923\text{ kg} / 100\text{ kg}) \times 97.1\ \% = 1.867\text{ kg} / 100\text{ kg}$$

- Those distributions now can be compared to the EQC results:

$$\text{Sediment}_{\text{EQC}} = 0.064\text{ kg} / 100\text{ kg}$$

$$\text{Water}_{\text{EQC}} = 1.859\text{ kg} / 100\text{ kg}$$

- A comparison ratio can be obtained by dividing the corrected EXAM result by the EQC result

Sediment $_{\text{EXAMS corrected}}$ / Sediment $_{\text{EQC}}$	=	0.875
Water $_{\text{EXAMS corrected}}$ / Water $_{\text{EQC}}$	=	1.004

By applying the same procedure to the other pesticides, all comparison ratios are obtained as shown in Table 4.3. In the same table, a comparison for the sediment compartment is also given.

Table 4.3. Comparison between EQC and EXAMS results

Pesticide	$W_{\text{EXAMS corrected}} / W_{\text{EQC}}$	$S_{\text{EXAMS corrected}} / S_{\text{EQC}}$
Imazalil	1.032	0.627
Thiabendazole	0.988	1.389
Propiconazole	1.004	0.875

Note: ***W*** stands for Water Compartment, and ***S*** stands for Sediment Compartment

4.2.3. DISCUSSION OF RESULTS

It is observed in table 4.3 that both models give almost equal predictions for the water compartment. However, the prediction values for the sediment compartment show significant differences for both models. The table shows only the pesticides that were analyzed in the Ecuadorian lab, but other banana pesticides not analyzed at this moment in Ecuador were also evaluated to see the behaviour of both models (glyphosate and tridemorph). Based on the comparison ratio, the differences in sediment predictions are more significant on those pesticides: around 121 for glyphosate and 3 for tridemorph. However, the predictions for the water compartment are still similar (comparison ratio of 0.87 for glyphosate and 0.88 for tridemorph). The main reason that accounts for this difference is the number of processes involved in the calculations for both models. EXAMS considers ionization, complexation and sorption processes of the compound with sediments and biota; while EQC only uses transport, transfer and basic degradation processes in the sediment compartment.

In this case study, the water compartment predictions with EXAMS represents between 0.87 to 1.03 times the predictions for the same compartment using the EQC model. As a preliminary conclusion, both models can be used independently when screening pollution in the water compartment. On the other hand, the sediment compartment is better evaluated by EXAMS than by the EQC model because more interaction processes are considered in the first one.

4.3. SPATIALLY INTEGRATED MODELS

4.3.1. AGNPS STRUCTURE

The AGNPS model is basically a runoff model that needs several types of data to be supplied. In the present research, the model structure was identified in order to optimise the available data sources in the basin. The model needs around 160 input variables to evaluate pesticides in a watershed (USDA-ARS 2002). Input data are distributed in 28 data sections as shown in Figure 4.5. They could be alphanumeric or numeric values, which could be handled with GIS. In the figure, the coloured boxes represent the minimum data sections needed for pesticide evaluation. All necessary information was grouped in primary and secondary data as shown in Chapter 3.

The input data have to be spatially distributed because the model works on a sub-basin basis. All sub-basins in the basin are divided in three zones, as shown in Figure 4.6: upstream, left and right drainage area. In the figure, the dark line represents three river stretches with their corresponding drainage basins (dotted line). Each shaded area in the upper left sub-basin represents what it is called "the cell" in the model.

AGNPS cells are different than raster cells, although many raster cells could be included within an AGNPS cell. The cell division depends on the drainage pattern and a threshold value to form a cell. Therefore, a watershed could be divided as many times as possible in order to capture the data spatial variability. By using GIS techniques, a thematic map can be created showing all generated AGNPS cells. These techniques are based on methodologies mainly developed by Garbrecht and Martz (1993, 1996 and 1999), and later included in AGNPS as a GIS interface. A detailed description of the generation procedure can be found in the TOPAGNPS module manual within the AGNPS documentation.

By overlaying the secondary data with the "*AGNPS cell*" thematic map, the input data for the model was obtained. However, in some cases a data aggregation of many raster maps into a single thematic map had to be done. Aggregation is performed by overlaying the "*AGNPS cell*" thematic map with the corresponding raster map for data extraction. For example, the complete soil information was attached to the general soil taxonomic map (polygons) in order to have a more detailed soil map for AGNPS usage.

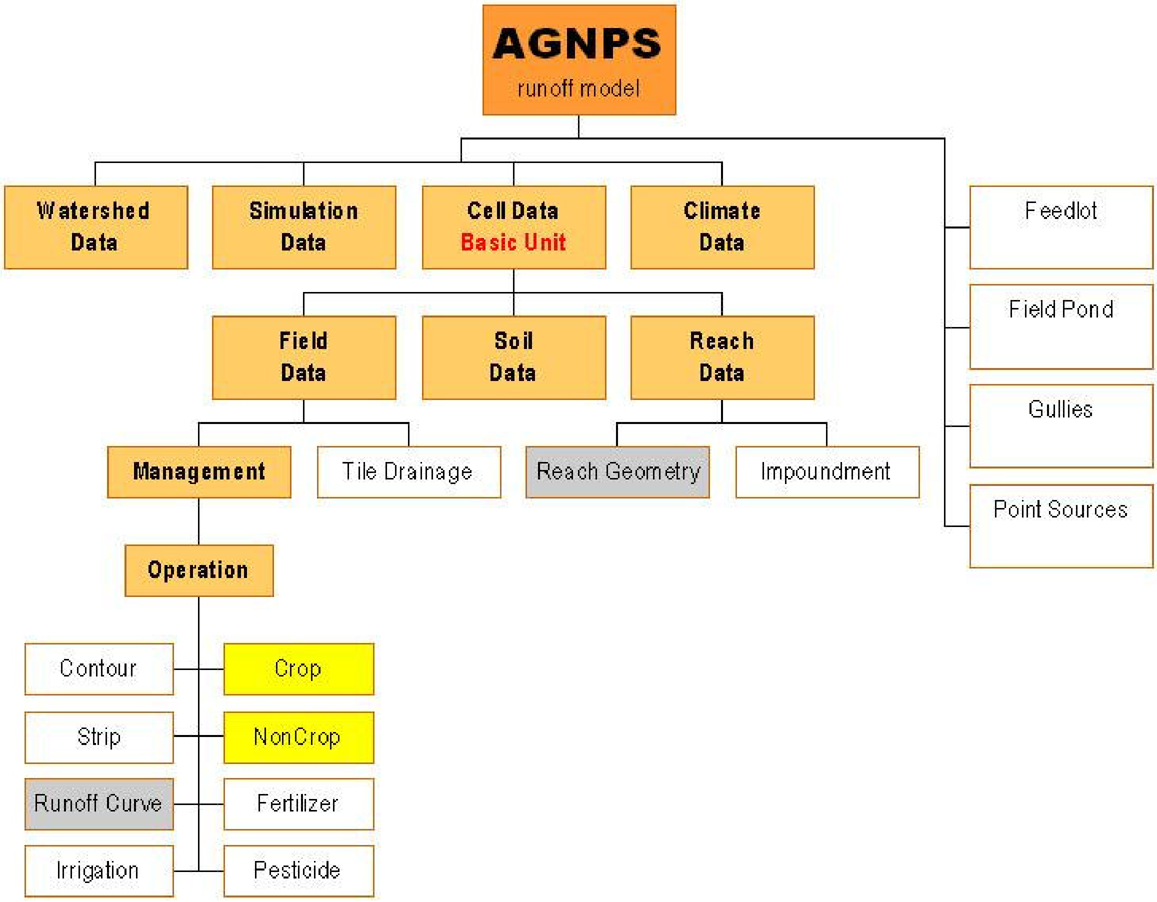


Figure 4.5. AGNPS model structure after Bosch *et al.* (1998)

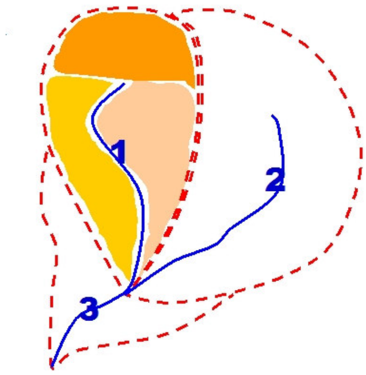


Figure 4.6. AGNPS cells created from watershed subdivision

When performing the overlying procedure, a limitation was observed: an AGNPS cell can only have one soil type and one land use type. However, most of the time more than one soil/land use type can fall into one AGNPS cell. The ArcView interface that comes with the model performs a joint spatial analysis to solve this problem by assigning the soil/land use ID with more surface area to the entire cell. The main drawback of this procedure is the loss of information across the basin. Table 4.4 shows maximum information loss percentages depending on the number of characteristic types falling in a single AGNPS cell.

Table 4.4 Maximum information loss by assigning the object ID with the largest area in a cell

# of ID's falling in a single AGNPS cell	*Maximum information loss based on area*
1	0 %
2	50 %
3	66.67%
4	75 %
n	(n – 1)100/n %

For the analysis, the Chaguana river basin was divided in 192 AGNPS cells which drain into 78 river's reaches (see figure 4.7). The resulting cell areas vary between 1 and 829 Ha. When overlaying the soil thematic map, 80 AGNPS cells presented more than one soil type (table 4.5). Due to the joint spatial analysis, soil information for around 15% of the basin surface area was not included as input data. The same assessment was done with land use as shown in table 4.6. Land use information for around 18% of the basin surface area was not included as input data.

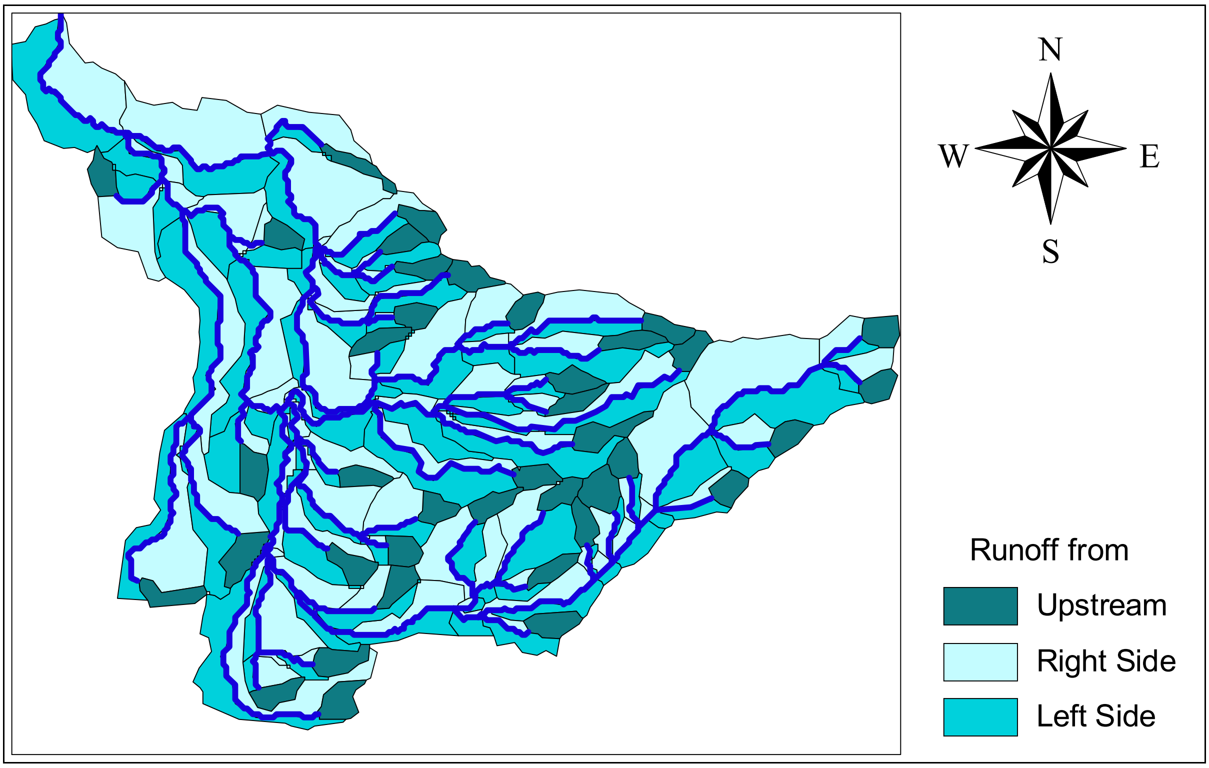


Figure 4.7. AGNPS cell division of Chaguana river basin

Table 4.5. Spatial Joint Analysis done on soil information

# soil types per AGNPS cell	*Number of occurrences out of 192 cells*	*Total area not considered after joint spatial analysis*	*% of total basin area*
2	51 cells	1951 Ha.	6.25 %
3	22 cells	1953 Ha.	6.56 %
4	7 cells	759 Ha.	2.44 %
Total	***80 cells***	***4663 Ha.***	***14.95 %***

Table 4.6. Spatial Joint Analysis done on land use information

# land use types per AGNPS cell	*Number of occurrences out of 192 cells*	*Total area not considered after joint spatial analysis*	*% of total basin area*
2	74 cells	2199 Ha.	7.05 %
3	34 cells	2839 Ha.	9.10 %
4	7 cells	377 Ha.	1.21 %
5	1 cell	123 Ha.	0.39 %
Total	***80 cells***	***5538 Ha.***	***17.75 %***

From the tables, there is more chance to have two types of characteristics falling in one cell than more types. Although it seems that the soil information loss is quite significant (around 15%), the regional soil characteristics are pretty similar in the region (silty sandy soils) and so the loss percentage is acceptable for the assessment. In the case of land use, the loss percentage also could be significant, but only 2% of the not considered area corresponds to cropland. Therefore, also the land use loss is considered acceptable for the assessment. A more detailed watershed subdivision could decrease the information loss. However, the extra effort probably could not be cost-effective. In addition, more data should be needed to get to the more detailed analysis.

4.3.2. CALIBRATION PROCEDURE

The whole calibration procedure was done with the data collected from three available gauging stations and the measurements of suspended sediments and pesticide concentrations along the river. Three statistical parameters were used to determine the goodness of fit of the predicted values related to the measured values:

- The Coefficient of Determination (r^2) is the square of the Pearson's Product Moment Correlation Coefficient, and it varies from 0.0 (poor model) to 1.0 (good model).

$$r^2 = \frac{\sum_{i=1}^{N}(O_i - O_{avg})(P_i - P_{avg})}{\left(\sqrt{\sum_{i=1}^{N}(O_i - O_{avg})^2}\right)\left(\sqrt{\sum_{i=1}^{N}(P_i - P_{avg})^2}\right)} \quad [5.1]$$

Where

O_i, P_i Observed and Predicted value for each modelled event

O_{avg}, P_{avg} Observed and Predicted average value for the evaluated range of data

- The Coefficient of Efficiency (***E***), developed by Nash and Sutcliffe (1970), ranges from minus infinity (poor model) to 1.0 (good model).

$$E = \frac{\left(\sum_{i=1}^{N}(O_i - O_{avg})^2\right) - \left(\sum_{i=1}^{N}(O_i - P_i)^2\right)}{\left(\sum_{i=1}^{N}(O_i - O_{avg})^2\right)} \quad [5.2]$$

- The Index of Agreement (***d***) developed by Willmott (1981) presents the same range of values as the coefficient of determination.

$$d = \frac{\left(\sum_{i=1}^{N}\left(\left|P_i - O_{avg}\right| + \left|O_i - O_{avg}\right|\right)^2\right) - \left(\sum_{i=1}^{N}(O_i - P_i)^2\right)}{\left(\sum_{i=1}^{N}\left(\left|P_i - O_{avg}\right| + \left|O_i - O_{avg}\right|\right)^2\right)} \quad [5.3]$$

For further information, Legates and McCabe (1999) have written a complete discussion on these three statistical coefficients normally used in hydrological and climatic model evaluations. In addition, a relative bias was estimated for every pair of measured and predicted values. Then, an average was estimated for all the sampled values based on equation [5.4].

$$Bias_{AVERAGE} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{O_i - P_i}{O_i} \times 100\right) \quad [5.4]$$

The criterion used to calibrate the model was the trial and error procedure by changing the most sensitive parameters and also the most uncertain values in the model: the curve number (CN), the cover factor (C_M) and the practice management factor (P). Those values influence the model depending on the process to be modelled.

The developers of both models (Arnold *et al.* – SWAT, and Bigner *et al.* – AGNPS) recommend following a step wise procedure in the calibration process. Because both models are mainly runoff-based, flow calibration is the most important step by adjusting the curve number. There are other sensitive parameters affecting the flow such as the snow related parameters, but those can not be applied to Ecuador (a tropical country).

After calibrating the flow, the logical step is to calibrate the sediment yield in the model. This again is done by trial and error procedures. Both models estimate sediment yields based on the USLE, RUSLE or MUSLE approaches. In this approach, all factors (R, K_S, LS, C_M and P) significantly affect the sediment yield estimations. However, only two factors showed to be more uncertain when getting data from the study site: cover and practice management factors. The reason is simple: this approach is not commonly used in Ecuador. Therefore, farmers and engineers do not keep enough records to estimate those values. Even in literature, no information was found regarding tropical crops such as banana, cocoa and citrus. Although there is some degree of uncertainty in the other values, they can be estimated more easily from the gathered information than the C_M and P factors. That was the main reason to use those parameters in the calibration procedure.

The last step in the calibration procedure concerned the pesticides. Again, trial and error was used based on the most uncertain characteristic of the pesticide application in the study area: where was the pesticide applied? and when?

There was no information from the farmers (the degree of collaboration in the project was extremely low). Therefore, a trial and error procedure was implemented to devise the period and location of application. The procedure was to select a cell or basin with banana activity, use the recommended application rate and compared the predicted results with the observed values.

4.3.2.1. Flow Calibration

The first calibration step adjusted the flow predictions as close as possible to the flow measurements. As written before, three gauging stations, known as Chaguana, Zapote and Colorado gauging stations (see Figure 3.4), were used, and mainly located in the middle course of the river basin. The recorded period on these stations is limited to only 4 years of measurements (1979, 1980, 1982 and 1983). There is no available measurement after 1983. The flow data represent average monthly values.

The AGNPS model is basically a runoff model that estimates flows based on SCS Runoff Curve Numbers, which are indicators of how much water is running off from the soil surface. The higher the Curve Number, the higher the estimated runoff. In addition, the model can be run in a "warm-up" state which is the possibility to run the model during a certain period of years without giving any result. This process is useful for reaching an appropriate wetness state as similar as the real state of the basin before the predicition phase occurs. The process is mainly done by analysing the variation of water holding capacity during a continuous time-series.

Flow calibration was conducted by adjusting the Curve Number for each land use type involved in the basin assessment. As written before, the basin was subdivided in 192 cells (or 78 sub-basins) with their own runoff characteristic. A way to make the procedure easier is to group the sub-basins in areas with similar characteristics as land use, soil type or geographic region. In table 4.7, the grouped areas for each gauging stations with their own land use distribution are shown. Also the Curve Numbers adopted before and after the calibration procedure are given.

Basically, the Colorado gauging station was calibrated first because it has a smaller drainage area and only two land cover types. The Zapote gauging station was calibrated second because it is located immediately downstream the Colorado station. And finally, the Chaguana station was calibrated by adjusting the curve number for each of its drainage basins. Unfortunately, there was no gauging station at the outlet of the basin.

Table 4.7. Curve Number adjustment based on land use distribution in drainage basin per gauging station.

Gauging Station	*Drainage Basin*	*Land Use distribution*	*Main Soil Group*	*CN before calibration*	*CN after calibration*
Colorado	Colorado	Pasture (713 Ha / 30%)	B	79	61
		Forest (1665 Ha / 70%)	B	66	55
Zapote	Zapote ([a])	Forest (379 Ha / 9.6%)	B	66	55
		Cocoa (459 Ha / 11.6%)	B	83	70
		Other Crop (683 Ha / 17.2%)	B	83	70
		Banana (1082 Ha / 27.3%)	A	74	67
		Pasture (1357 Ha / 34.3%)	B	79	69
Chaguana	San Jacinto	C and P [(b)] (398 Ha / 3.9%)	B	47	47
		Banana (501 Ha / 4.9%)	B	83	83
		Pasture (1913 Ha / 18.9%)	B	79	69
		Brushes (2645 Ha / 26.1%)	A	68	68
		Forest (4676 Ha / 46.1%)	B	66	55
	Charengue	C and P and F [(c)] (99 Ha / 4.9%)	A	65	65
		Banana (110 Ha / 5.4%)	B	83	83
		Cocoa (555 Ha / 27.4%)	A	74	74
		Brushes (607 Ha / 29.9%)	A	68	68
		Forest (656 Ha / 32.4%)	B	66	55
	La Polvora	Banana (77 Ha / 2.1%)	A	74	74
		Pasture (1591 Ha / 43.8%)	B	79	79
		Forest (1963 Ha / 54.1%)	B	55	55
	Middle Chaguana	Banana (1662 Ha)	B	83	83

Notes:
(a) It does not include the drainage basin that is discharged from the Colorado river gauging station.
(b) C and P = Mixture of crops and pasture
(c) C and P and F = Mixture of crops, pasture and forest

The AGNPS model estimates flows based on single or continuous daily events (rainfall), so it is necessary to have daily data to calibrate the model. In the present research, the gauging stations only had average monthly flows. In addition, weather data were also limited to total monthly values, the number of rain events and the maximum 24-hour precipitation fallen during every month. Therefore, it was necessary to generate daily precipitation data for the recorded period of the gauging stations (1979, 1980, 1982 and 1983) by considering the following assumptions:

1. There is only one maximum precipitation event in every month corresponding to the recorded 24-hour precipitation at a specific reported day.

2. As a first approach, the rest of the monthly precipitation is equally distributed among the recorded number of rainy days in a month.
3. AGNPS model is run for every estimated daily event for that month. A mean monthly flow is obtained by averaging the resulting daily flows. That average monthly flow is compared with the reported flow in the corresponding gauging station.
4. If the statistics parameters are still showing "poor" fit, then the daily events in the month are rearranged by keeping always in mind the maximum monthly precipitation and the number of rainy days. This process is repeated until flow predictions fit the measured values.

Figures 4.8, 4.9 and 4.10 show the comparison between predicted and measured flows for Colorado, Zapote and Chaguana gauging stations respectively. Table 4.8 shows the estimated statistics coefficients of fit for all three gauging stations. The model could predict the flows in Chaguana gauging station well (r^2 = 0.87, E = 0.73, and d = 0.93). For the Colorado and Zapote stations, the model showed lower values of goodness of fit (E = 0.53 for Zapote and 0.37 for Colorado). Based on the model execution it is concluded, the AGNPS model usually fails to predict flows that occur in very small drainage areas with very low precipitation events, and this is mainly because the output results are restricted to three decimal place positions. Therefore, any predicted flow below 0.001 m^3/s (1 litre per second) is reported as zero. In addition, the lack of more data for flow validation is critical; the data mainly represent extreme events (an "El Niño" event occurred during 1982 and 1983).

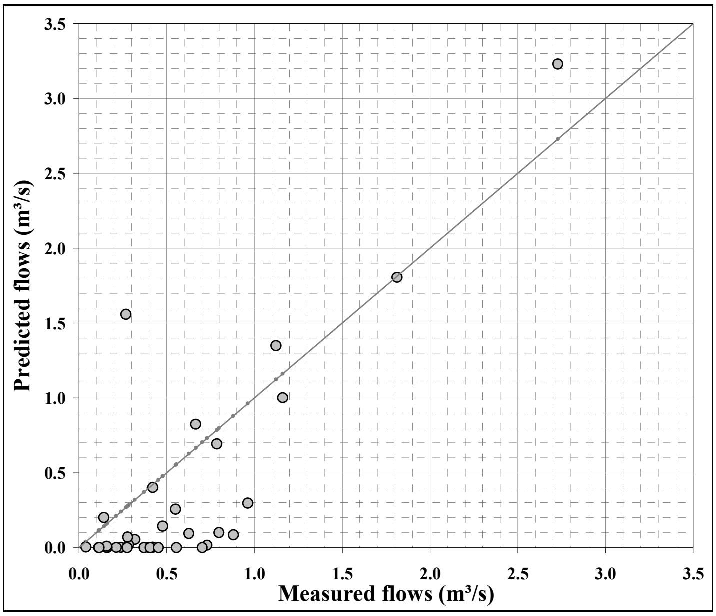


Figure 4.8. Predicted vs. observed values in Colorado river gauging station

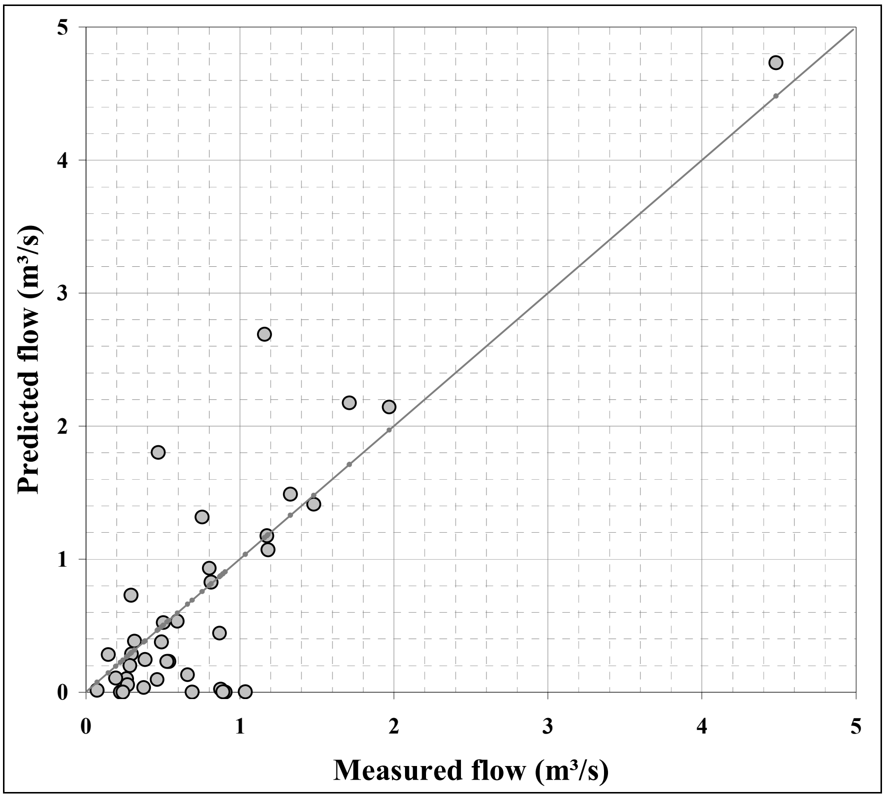


Figure 4.9. Predicted vs. observed values in Zapote river gauging station

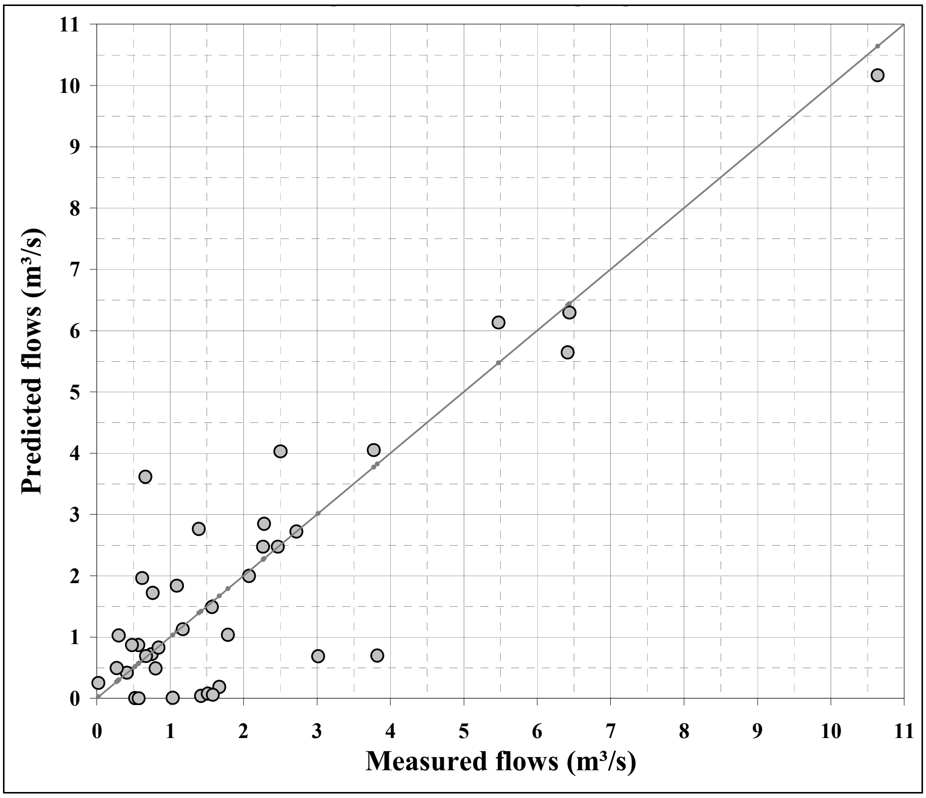


Figure 4.10. Predicted vs. observed values in Chaguana river gauging station

Table 4.8. Summary of measured and predicted (AGNPS flows) statistics for Colorado, Zapote and Chaguana gauging stations

Statistics		*Colorado*	*Zapote*	*Chaguana*
Predicted	**Mean**	0.020 m^3/s	0.284 m^3/s	1.031 m^3/s
	Standard Deviation	0.691 m^3/s	0.977 m^3/s	2.198 m^3/s
	Number of events	35	38	38
Measured	**Mean**	0.421 m^3/s	0.567 m^3/s	1.407 m^3/s
	Standard Deviation	0.527 m^3/s	0.762 m^3/s	2.147 m^3/s
	Number of events	35	38	36
Coefficient of Determination (r^2)		0.83	0.85	0.87
Coefficient of Efficiency (E)		0.37	0.53	0.73
Index of Agreement (d)		0.88	0.91	0.93
Mean relative bias (%)		90.31	26.79	0.83

Based on the previous flow calibration, a relationship between the estimated flow rate and the average precipitation that fell in the basin was developed at three points of interest: the basin outlet, the crossroad over the Chaguana river and the crossroad over the Zapote River (Figure 4.11). The graph can be useful to determine flow rates, and it was used in the sediment calibration step as explained in the next section.

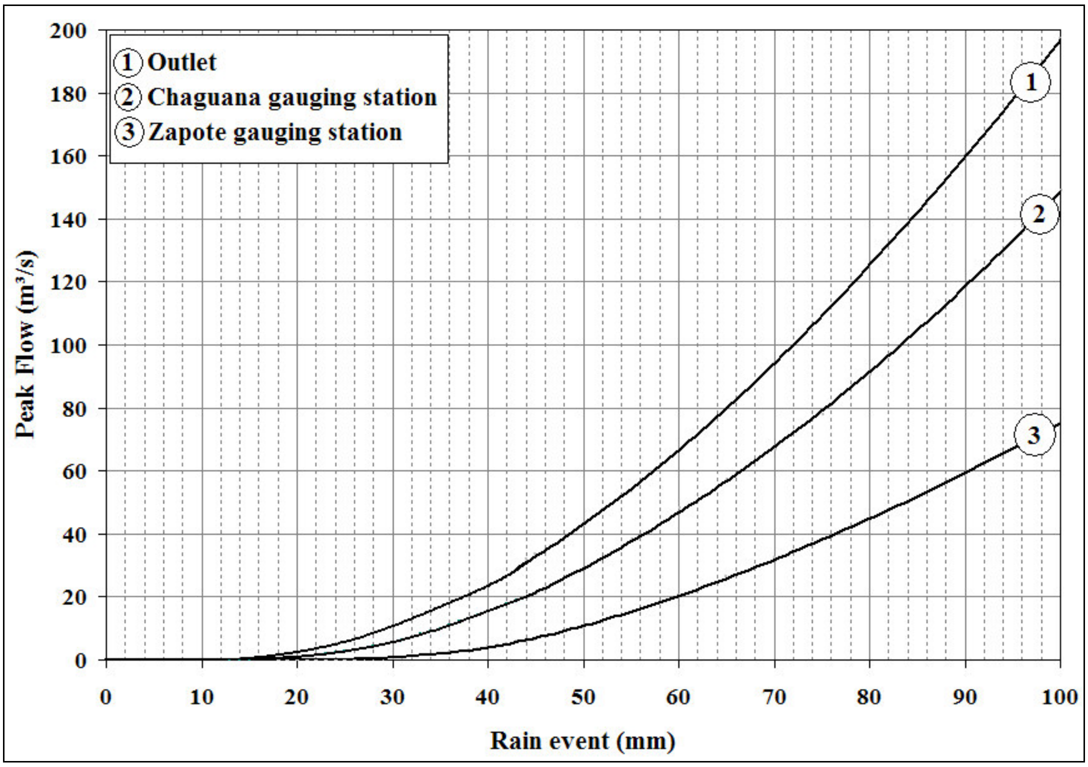


Figure 4.11. Estimated peak flow for three points for an average daily rain event in the Chaguana basin

4.3.2.2. Suspended Sediment Calibration

The official database, where the flow data were obtained, did not contain measurements of suspended sediments to perform the model calibration. Therefore, during four sampling campaigns between 2001 and 2002, several monitoring points were set along the river to determine suspended sediments and flow measurements (see chapter 3).

To perform the suspended sediment calibration, it was necessary to use the outputs of the flow prediction to assess the unknown inputs (rain events) which were used in the suspended sediment predictions of those inputs. This method is known as Inverse Modelling, and it has been used in several applications. Basically, Inverse Modelling is the use of a model output to estimate a model input.

In the Chaguana basin case study, the AGNPS model required the precipitation on the campaign dates to predict the sediment yield. Due to the lack of precipitation data for the sampling days, it was necessary to perform an interpolation on the calibrated flow graph obtained from the flow calibration step (figure 4.11). The estimated rain events were obtained by introducing the monitored flow values in figure 4.11. The obtained values represent an average rain event as falling at the same time in the entire catchment area[32]. Table 4.9 gives the estimated rain event for the four sampling campaigns, which are the values used in the model execution.

Table 4.9. Estimated daily rain event for sampling days based on flow calibration

Campaign	*Date*	*Estimated Daily Rain Event*
First	14 November 2001	4 mm
Second	30 March 2002	58 mm
Third	5 July 2002	3 mm
Fourth	11 November 2002	5 mm

The AGNPS model was only run in the river reaches that showed measurements of suspended sediments. As shown in table 4.10, the sediment calibration was performed by adjusting the two parameters that contribute to sediment yield and do have more uncertainty in their estimated values: the cover management factor (C) and the practice management factor (P).

32 In the real world, different rainfall amounts can be measured at the same time in the watershed because precipitation is a spatially distributed variable. However, models sometimes consider only a single rainfall value for a specific runoff assessment (for the whole watershed or for smaller subdivisions)

Table 4.10. C and P factor adjustment based on land use per sampled river.

River	*Sub-basin*	*Land Use*	*C before*	*C after*	*P before*	*P after*
Zapote	Colorado	Pasture	0.066	0.041	0.990	0.200
		Forest	0.039	0.016	1.000	1.000
	Zapote	Forest	0.039	0.039	1.000	1.000
		Cocoa	0.286	0.170	0.850	0.600
		Other Crop	0.286	0.170	0.900	0.650
		Banana	0.286	0.013	0.400	0.100
		Pasture	0.066	0.003	1.000	0.200
Chaguana	San Jacinto	Crop and Pasture	0.176	0.176	1.000	1.000
		Banana	0.286	0.286	0.250	0.690
		Pasture	0.066	0.003	0.960	0.900
		Brushes	0.066	0.321	1.000	1.000
		Forest	0.039	0.003	1.000	0.900
	Charengue	Crop-Pasture-Forest	0.130	0.130	0.949	0.995
		Banana	0.286	0.286	0.500	0.690
		Cocoa	0.286	0.286	0.750	0.910
		Brushes	0.066	0.039	0.890	0.925
		Forest	0.039	0.100	1.000	1.000
	La Polvora	Banana	0.286	0.286	0.370	0.690
		Pasture	0.066	0.041	0.800	0.861
		Forest	0.039	0.62	1.000	1.000
	Las Juntas	Banana	0.286	1.000	0.300	0.100
		Other Crop	0.286	0.010	0.600	0.100
	Chaguana	Banana	0.286	0.286	0.250	0.690
		Shrimp Farms	0.600	1.000	0.100	1.000

The three statistical parameters used in the flow calibration step were also applied to compare the predicted and the observed suspended sediment values. The comparison was done in two different ways. First, the Zapote and Chaguana rivers were compared separately to determine in which basin the model shows more agreement. Then, an overall comparison was done with all evaluated sampling reaches. Figure 4.12 shows the overall comparison. Table 4.11 gives the statistical values of the performed comparisons.

Table 4.11. Summary of measured and predicted (SS concentrations) statistics for the sampled reaches in Zapote, Chaguana and the whole river system

Statistics		*Zapote*	*Chaguana*	*Basin*
Predicted	**Mean**	36.45 mg/l	31.00 mg/l	34.37 mg/l
	Standard Deviation	13.35 mg/l	57.09 mg/l	48.58 mg/l
	Number of samples	13	28	41
Measured	**Mean**	14.24 mg/l	29.58 mg/l	28.50 mg/l
	Standard Deviation	19.02 mg/l	62.14 mg/l	54.23 mg/l
	Number of samples	13	28	41
Coefficient of Determination (r^2)		0.60	0.94	0.93
Coefficient of Efficiency (E)		0.00	0.88	0.86
Index of Agreement (d)		0.70	0.97	0.93
Mean relative bias (%)		-30.37	-3.64	-6.70

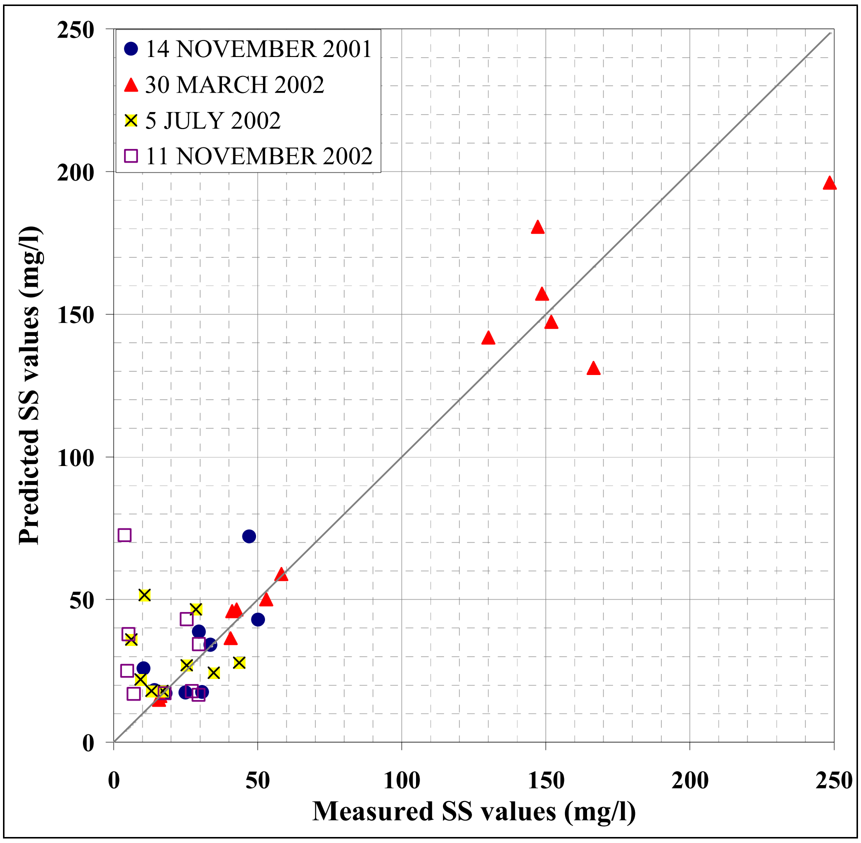


Figure 4.12. Predicted vs. observed SS values in all sampled reaches of the basin

Discussion

The use of inverse modelling techniques represents a useful approach to overcome problems regarding input data. However, this technique also represents a risk because the outcome could not represent the phenomena to be modelled. For that reason, it is always better to use real data in the modelling process. In the case study, the lack of daily rainfall data to run the model for the sampling events represented an opportunity to apply inverse modelling techniques. The obtained outputs were within the expected range values.

After running the model, it is clear that the predictions for the Zapote River are not good enough as the coefficient of efficiency (E) is equal to zero. However the model can predict the sediment behaviour in the Chaguana river fairly well. There could be many reasons for this difference:

- The Zapote river has less reaches sampled than the Chaguana river during sampling campaigns. Thus the characterization of this river is quite low.
- As said in the flow calibration, the model has a lower prediction efficiency in cells with small drainage areas. The Zapote river does not have as long a course (drainage area) as the Chaguana river, so the predictions are affected by this difference.
- Another reason is that information loss occurred during spatial data aggregation.

In the Chaguana river, there were also significant differences between predicted and measured values at specific sampling points only for the March sampling period (rainy season) while the rest of the sampling dates showed a good agreement. There was some dredging activity at certain points along the Chaguana river between Reaches 45 and 22. This civil work affected the sediment yield by increasing the suspended solid concentrations on those reaches as seen in Figure 4.13. For that reason, the model failed to predict the suspended sediment concentrations as the model calculates sediment yield based mainly on soil erosion from runoff. Figure 4.13 shows the predicted and measured concentrations for around 28 km of monitored Chaguana river during the sampling campaign conducted on March 2002.

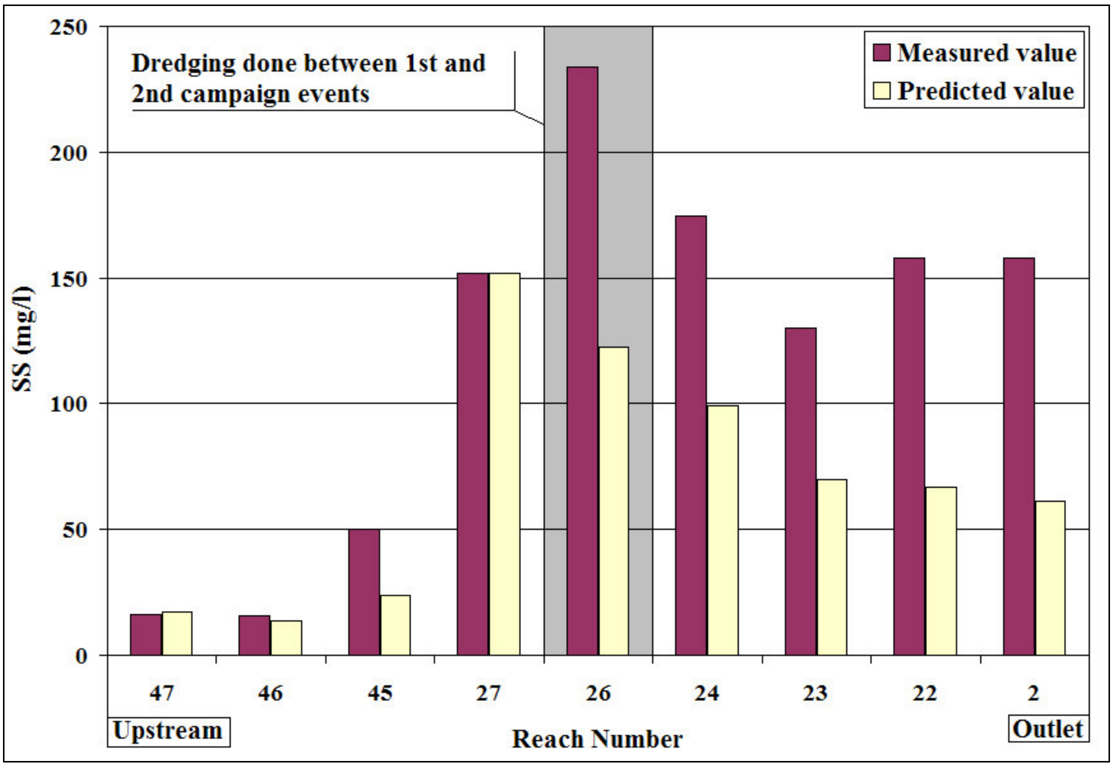


Figure 4.13. Sediment yield impacted due to unexpected changes (dredging) in March 2002

In addition, the last reach, Number 2, still shows values lower than the actual ones. That is because that reach was influenced by the tidal push at the moment of the sampling. When the tide is entering the basin, some sediment is pushed back into the basin. This additional sediment load cannot be predicted by the runoff model. Therefore, the model is no longer applicable for those situations.

4.3.2.3. Pesticide Concentration Calibration

The pesticide calibration was performed based on the sampling dates, the amount of pesticide applied per farm and the number of days from the sampling date up to the last pesticide application in the field. On this step, inverse modelling techniques were also applied due to lack of information.

There were four sampling dates, as written in chapter 3, which roughly represent the climate conditions throughout the year (14 November 2001, 30 March 2002, 5 July 2002 and 11 November 2002). Due to the lack of daily rainfall data, precipitation on those dates were estimated in the previous section.

Regarding the pesticide application rate, the model was initially run with the recommended dose of 100 grams of propiconazole active ingredient per hectare. However, this amount was adjusted based on the following reflections:

- Farms do not apply pesticides on the same date. There was no information regarding application days for all existing farms in the Chaguana basin, but from only one farm outside the basin (used as a reference in the current research)
- The pesticide application rate varies from farm to farm depending on several conditions (degree of sigatoka presence, economic condition, planting dates, etc.)

For simplicity of the assessment, all AGNPS cells with the banana landuse were considered as a banana plantation. Forty out of 192 cells were considered as banana plantations representing around 8128 Ha (16 % of surface area in the Zapote basin and 84% in the Middle-Chaguana basin). First, a unique pesticide management was assigned to each of these cells (dose and application day through the year).

Because the sampling campaigns usually did not coincide with pesticide application, the detected pesticides in the river system were assumed to be the result of previous applications performed during certain days previous to the campaign on certain farms in the basin. By a trial and error procedure, the span of days since the last application of propiconazole in the banana sectors of the basin was determined (see figure 4.14).

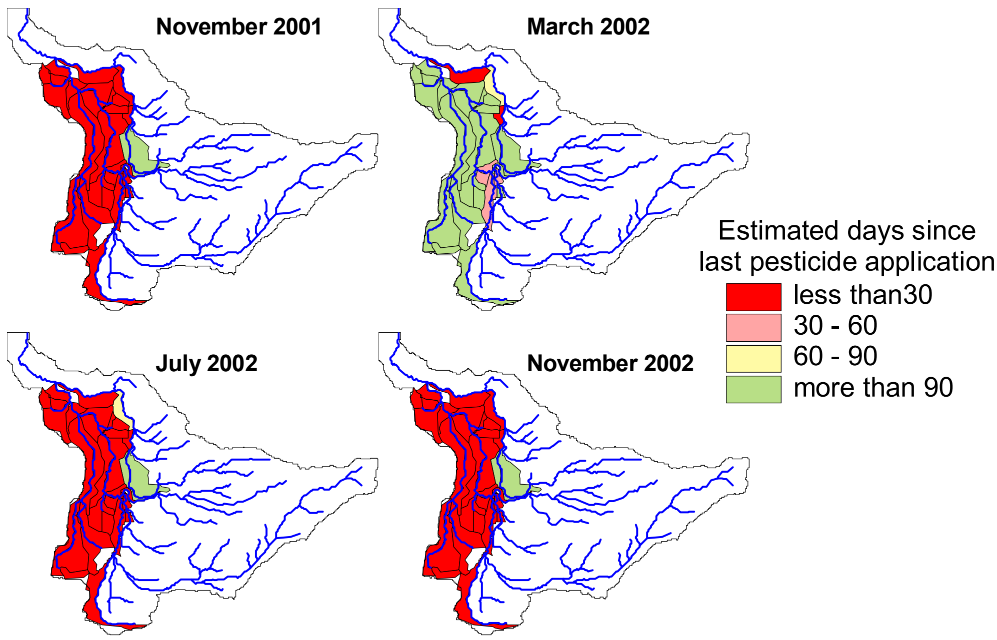


Figure 4.14. Estimated days since last application of propiconazole in the basin farms

The trial and error procedure consisted in running the model several times with different configurations of application sites and application dates until the predicted concentrations fit the measured values on the specific campaign date. This procedure could be avoided by producing monthly predictions. However, only event (daily) concentrations were measured in the sampling campaigns. Based on the findings of figure 4.14, the model was run and calibrated for each sampling day with estimated application dates. It can be seen that the farms located in the Zapote basin did not apply propiconazole on a more frequent basis than the farms located in the Middle-Chaguana basin.

Table 4.12 gives the statistical coefficients for the comparison between predicted and observed pesticide concentrations in Zapote, Chaguana and the whole catchment. Again, the model is not good to predict concentrations in the Zapote river. This weakness was expected as suspended sediments predictions were also not good[33]. Although calibration was done with few data, the pesticide prediction for the Chaguana river showed a better agreement. Figure 4.15 shows the comparison between measured and predicted pesticide concentrations for the entire Chaguana basin. In the figure, the sampling periods are depicted with different symbols. The model showed a good prediction agreement for pesticide concentrations during the rainy season (March 2002). This agreement decreases as less rain falls in the basin. However, there should be more data to get better conclusions.

Table 4.12. Summary of measured and predicted (Pesticide concentrations) statistics for the sampled reaches in Zapote, Chaguana and the whole river system

Statistics		*Zapote*	*Chaguana*	*Basin*
Predicted	**Mean**	0.024 µg/l	0.251 µg/l	0.179 µg/l
	Standard Deviation	0.060 µg/l	0.408 µg/l	0.354 µg/l
	Number of samples	13	28	41
Measured	**Mean**	0.059 µg/l	0.278 µg/l	0.209 µg/l
	Standard Deviation	0.119 µg/l	0.490 µg/l	0.421 µg/l
	Number of samples	13	28	41
Coefficient of Determination (r^2)		0.38	0.78	0.79
Coefficient of Efficiency (E)		0.03	0.60	0.61
Index of Agreement (d)		0.56	0.87	0.87
Mean relative bias (%)		52.43	-0.65	2.387

33 The model predicts pesticide concentrations as two states: attached and dissolved. The attached part depends on the amount of sediments transported by runoff. If there is poor agreement with the sediment prediction, then the pesticide prediction will also show a poor agreement. The calibration was done with the overall concentration because measured pesticide values were also reported as overall concentrations.

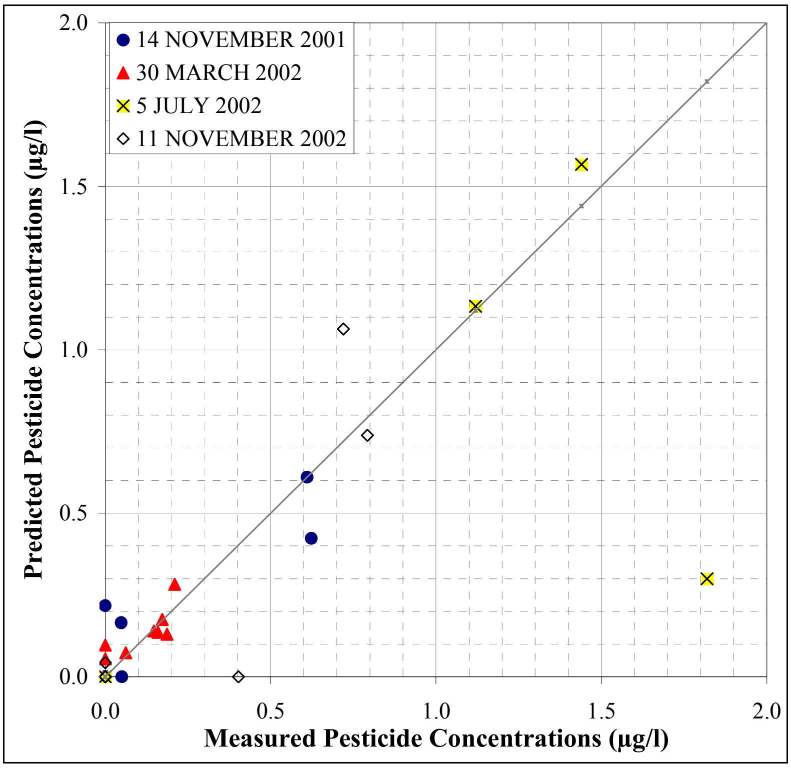


Figure 4.15. Predicted vs. observed pesticide values in all sampled reaches of the basin

4.3.3. Scenario Evaluation

Once the model was calibrated, some scenarios were evaluated to tackle the question proposed at the beginning of the research: what is the impact of fungicide use from the banana sector in the Chaguana basin. This issue was evaluated by running the model in some scenarios by assuming:

- Only propiconazole usage is considered in the evaluation. The model was not calibrated for other pesticide usage in terms of application rates and spraying dates,
- The farms in the evaluated scenarios are using the recommended dose of 100 grams of active ingredient per hectare.
- The application rates and spraying dates are the same for all farms based on the application plan obtained from one typical farm (see chapter 3, Table 3.32)

The AGNPS model was run on three worst-case scenarios: all banana farms in the basin are active (scenario 1), only banana farms in the Chaguana basin are active (scenario 2) and only farms in the Zapote basin are active (scenario 3). The runs were done on the same sampling dates to have an overview of the pesticide predictions based on the planned application schedules. Figure 4.16 gives the predicted pesticide concentrations for the first scenario (all banana farms are active throughout the year).

From the figure, it can be seen that the worst situation is produced during the rainy season when PECs can reach values higher than 5 ppb in the basin outlet. Conversely, during the dry season (mainly July), the river does not show significant values of propiconazole in all river reaches. The higher concentrations are produced because applications of propiconazole are more frequent during the rainy season and more particles attached with pesticide are transported with runoff into the river reaches. In the dry season, the transport of pesticide-soil particles from runoff is decreased because of the lack of rain events[34].

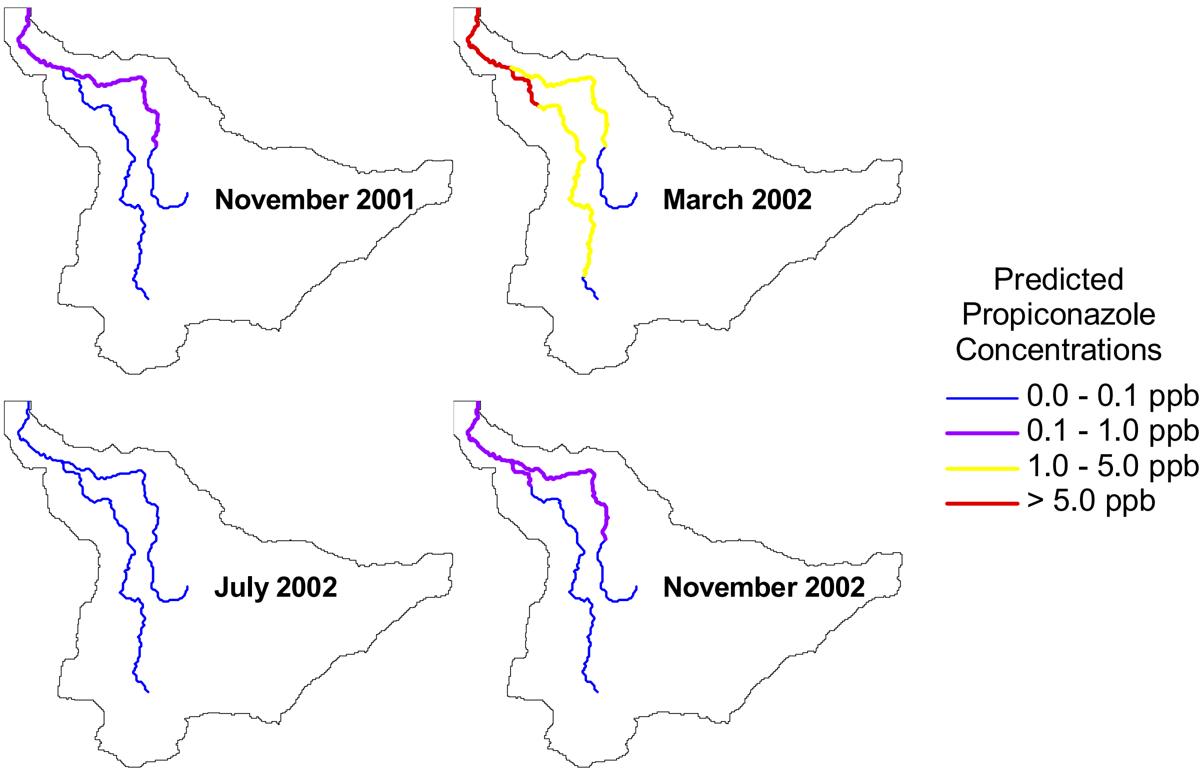


Figure 4.16. Predicted propiconazole concentrations when all banana farms in the basin are spraying with the same application schedule

Based on the analysis of scenarios 2 and 3, the pesticide pollution from Chaguana farms is more significant than that from Zapote farms. As can be seen in figure 4.17, during the rainy season (March event), the pesticide concentration near the outlet is still higher than 5 ppb, even when the Zapote farms are not active during the year.

[34] The model is mainly a runoff model which predicts pesticide concentrations coming from chemicals attached to eroded particles and chemicals washoff from the crop. Pesticide falling directly into the river by drift or point source is not considered by the model.

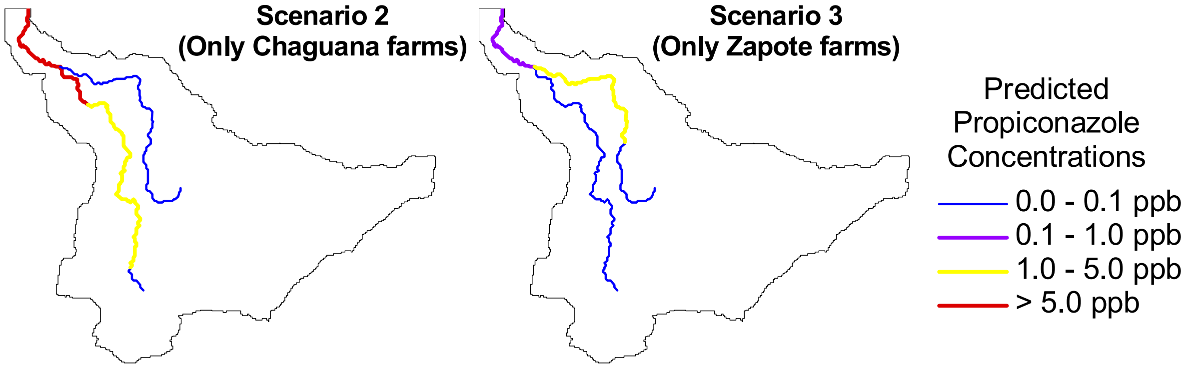


Figure 4.17. Predicted propiconazole concentrations for scenarios 2 and 3 during rainy season (March)

In addition, an analysis of pesticide predictions was done with synthetic daily rainfall data for a typical year to observe how pesticide concentration varies with rain events. The analysis was done only in the basin outlet by considering that all farms in the basin are active and they are using the same propiconazole application schedule (Scenario 1). Figure 4.18 shows the daily predictions for the basin outlet. The application schedule, based on the reference farm, is also shown in the figure by arrows. Ten propiconazole applications (100 g.a.i/Ha) were applied for running the model. It is seen that propiconazole is used more frequently during the rainy season (7 applications), and it is used at least every 10 days between the end of March and beginning of May. These extra applications are causing high predicted propiconazole concentrations during the rainy season.

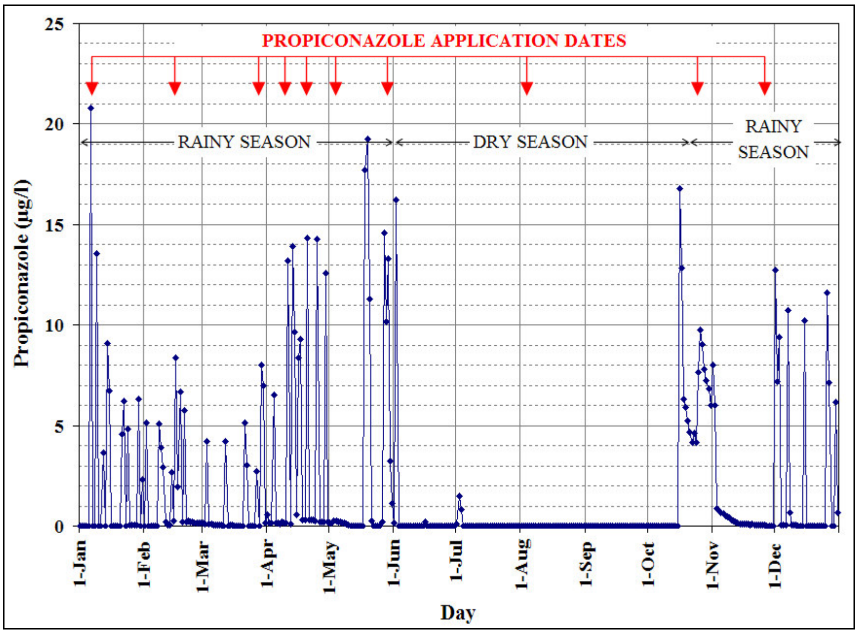


Figure 4.18. Predicted daily propiconazole concentration for the basin outlet after the model calibration.

From the environmental risk point of view, the basin outlet is very important. This last river reach crosses two areas of interest: shrimp farms at both sides of the river and the Tendales town, whose location is shown in Figure 3.13d. The annual predicted propiconazole concentrations can reach up to 20 µg/l during rainy events. Fortunately, these concentrations are still far below the reported geometric mean toxicity level of around 400 µg/l (Jolliet *et al.* 1998). However, there should be some concern in the integrated management of the Chaguana basin because, if the banana sector in the basin is expanded, the expected concentrations should increase causing an increase in environmental problems. An example of these problems is related to the Tendales town. It was observed that this town does not have a good potable water system and people living there use river water for multiple purposes (fishing, laundry, recreation, and so on). Therefore, there would be a potential human health threat during the rainy season as pesticide concentrations would be higher than the maximum allowable limits for human consumption (0.1 µg/l per pesticide – EU limit).

4.3.4. COMPARISON WITH ANOTHER RUNOFF MODEL: SWAT

One of the objectives in the current research was to compare AGNPS results with the outcome of another model. That issue was evaluated in a guided research done at ESPOL as a B.Sc. thesis (Bonini and Guzman 2003) using the SWAT modelling tool. The Chaguana basin was divided in 44 sub-basins, mainly based on the locations of the three existing gauging stations (Colorado, Zapote and Chaguana gauging stations), see figure 4.19.

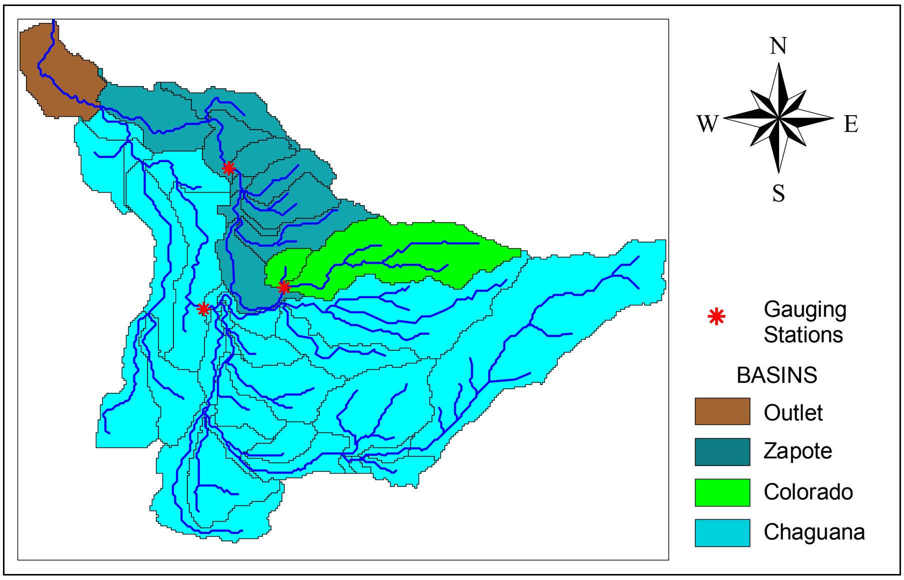


Figure 4.19. SWAT basin division of Chaguana river basin showing the three existing gauging stations.

Although both models require roughly the same amount of data, the data structure of SWAT is quite different from AGNPS. Table 5.10 shows several differences between both models.

Table 4.13. Differences between AGNPS and SWAT model

CHARACTERISTIC	*AGNPS*	*SWAT*
Unit of Analysis	Cell created from Sub-basin division (maximum three cells per sub-basin)	The basic unit of analysis is the sub-basin.
Input Data	All input data, except weather, is entered as one file	Several input files can define data regarding soil, management, chemical, reach, etc.
Climate Data	All climate data is entered as one file per weather station.	Several files are used to input data for climatic parameters, location of weather and gauging stations.
Number of Soil / Landuse types per unit of analysis	Only one type is allowed per AGNPS cell	Many types are allowed depending on the number of Hydrologic Response Units (HRUs) considered per sub-basin.
Information loss due to data aggregation within a cell/basin	Loss varies from 0 up to 50% depending on cell size and the number of data groups within one cell.	Information loss can be decreased significantly by using several HRUs in one sub-basin
ArcView GIS Interaction	The interface is used mainly to input data. The model is run outside GIS.	The ArcView interface is used to input data into the model, to run the model within GIS environment, and to process results
Execution time	For a basin with 192 cells and 78 reaches, the model took around 1 minute to run an annual simulation of daily events	For 44 subbasins, the model took less than 2 minutes to run the same annual event.

The calibration processes run for SWAT model followed the same considerations of the AGNPS model calibration by changing the same parameters (curve number, C and P factors). The coefficients of efficiency, determination and agreement were also estimated to look for the goodness of fit between the measured and predicted values (Table 4.14). Figures 4.20, 4.21 and 4.22 give the comparison between predicted and measured values for flow, suspended sediments and pesticide concentrations. The outcome of the SWAT model was shown to be more accurate than the AGNPS model. The efficiency (E) of the three calibration processes was above 0.8 for the entire Chaguana basin. Although predictions for the Zapote were improved, they are still below the ones for the Chaguana river.

Table 4.12. Summary of measured and predicted statistics for the sampled reaches in the whole river system (SWAT runs)

Statistics	*Flow*	*SS*	*Pesticide*
Coefficient of Determination (r^2)	0.91	0.97	0.99
Coefficient of Efficiency (E)	0.82	0.93	0.98
Index of Agreement (d)	0.95	0.98	0.99
Mean relative bias (%)	15.66	27.09	2.87

The main reason for the result improvement is that the SWAT model uses the concept of *Hydrologic Response Units* (HRU) to couple land cover and soil information within each sub-basin. As described in the SWAT user's manual, Hydrologic Response Units are portions of a sub-basin that possess unique landuse, management and soil attributes.

Although this concept is similar to the attribute of an AGNPS cell, the main difference is that a SWAT sub-basin can have many HRUs within it. On the other hand, AGNPS sub-basins can only contain a maximum of three AGNPS cells. Therefore, the information loss in SWAT can be reduced significantly when aggregating data in a sub-basin. This improvement results in better predictions because of a better characterisation of the evaluated basin. However, the improvement on the accuracy could be jeopardised if soil or land cover information is not accurate too.

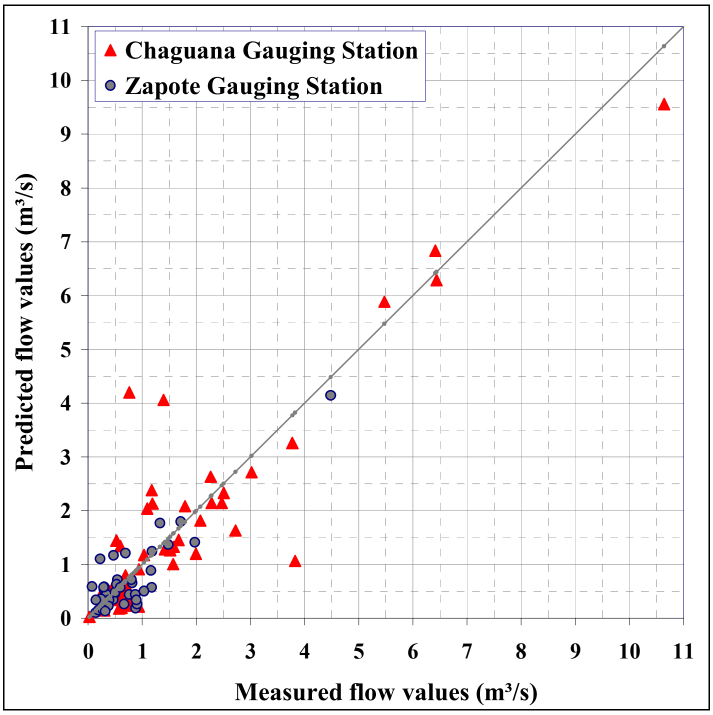


Figure 4.20. Comparison of predicted (SWAT) and measured values for flow in the whole sampled watershed.

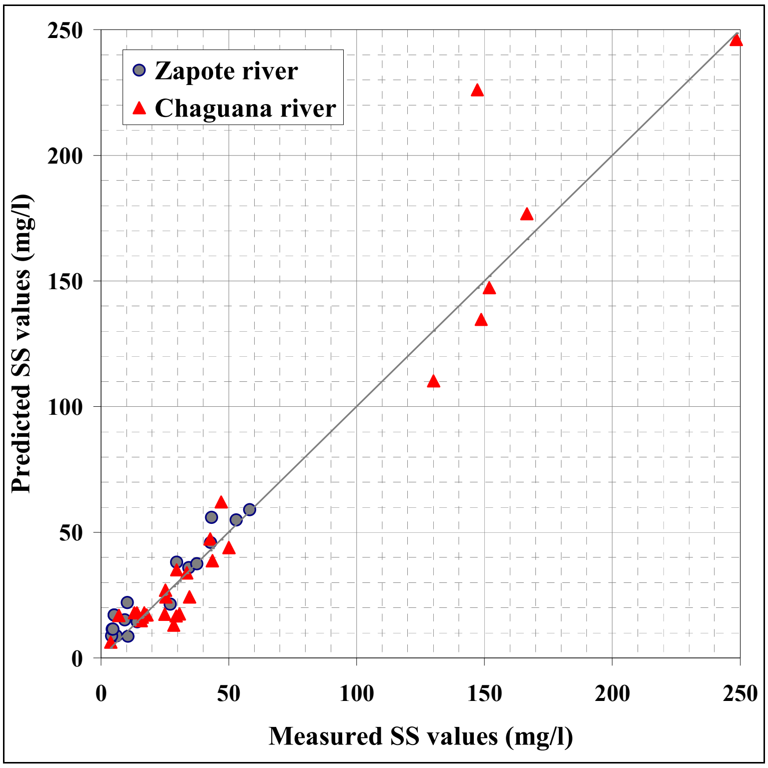


Figure 4.21. Comparison of predicted (SWAT) and measured values for suspended sediment in the whole sampled watershed.

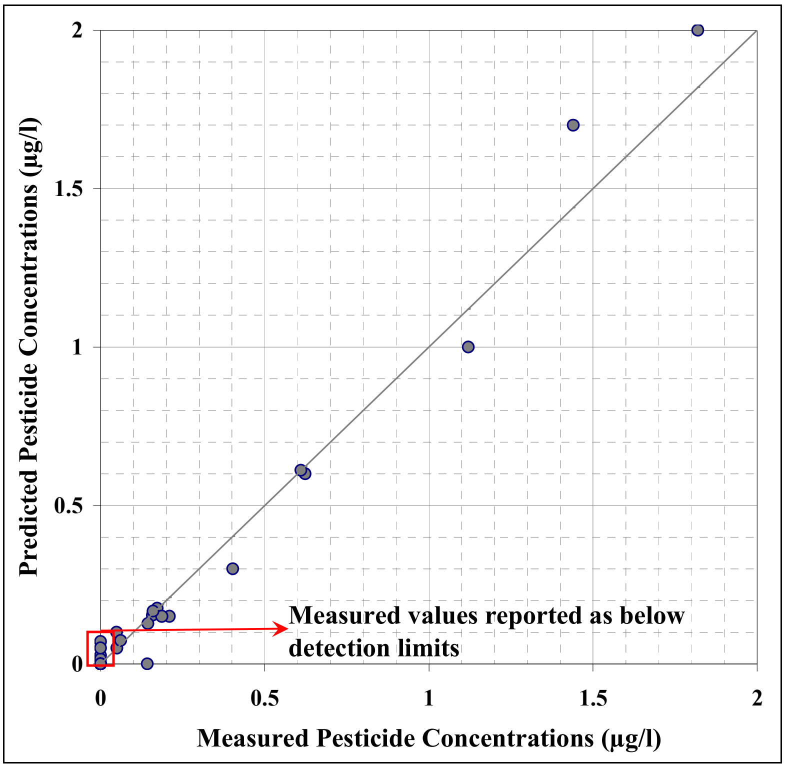


Figure 4.22. Comparison of predicted (SWAT) and measured values for pesticide concentration in the whole sampled watershed.

4.3.5. DISCUSSION

Another important issue observed in the model comparison is the influence of values reported as “Not Detected - ND” or “Traces” over the net efficiency of the comparison between predicted and measured values. There is not enough information regarding the way those ND values should be considered in a model assessment. In European countries, those ND values are assumed to be ⅓ of the corresponding detection limit. In USA, some researchers prefer to assume ½ of the detection limit such as in a soil pollution study conducted in Seattle (Glass 2000). In this study, the half-value criterion was selected because some overlapping problem with the quantified values occurred when the reported detection limits varied on different tests.

In the current research, the ND values were included as “zero” values to ease the calculations (see the marked square at the origin of Figure 4.20). The reason to do that was that the laboratory reported different detection limits for the same pesticide on each sampling campaign, ranging between 0.05 and 0.15 μg/l.

Therefore, it was a simplification to put those reported values as zero. In addition, a sampled reach was characterised to have no pesticide presence when the lab reported no indication at all for the pesticide in the evaluated reach, neither ND value nor “Traces” indication. This type of reach represents around 50% of the sampled reaches in the basin for all sampling campaigns.

As a result, there are two important questions that should be answered in future investigations to assure that a model can predict pesticide concentrations in a basin based on what Ecuadorian labs are reporting now:

1. *Can a zero value predicted by any model be properly compared with an absence of a reported value in the corresponding measured point?*
2. *How significant are the observations below detection threshold compared to the existing Environmental Policy in Ecuador[35] and abroad?*

[35] Right now, Propiconazole is not regulated in the Ecuadorian Environmental Law. However, world banana markets could force regulators and producers to control that fungicide in the near future.

CHAPTER 5. GENERAL DISCUSSION AND FUTURE PERSPECTIVES

Upper course of the Chaguana river, Ecuador

5.1. INTRODUCTION

The research in this thesis was supported under the framework of Project 4 of the VLIR-ESPOL Research Programme. This project was aimed, among others, to develop tools to help in the development of decision support systems for Integrated River Basin Management in Ecuador. A first step in the VLIR-ESPOL project involved the determination of potential environmental impacts produced from pesticide usage in the banana sector, and potential conflicts between productive sectors in the basin.

This thesis, as part of that project, was mainly focused on the evaluation of modelling tools that could help in predicting pesticide concentrations at specific points in the selected basin. The decision of evaluating models instead of developing new models was based on the fact that it usually requires a long time to produce a reliable tool to be applied in the field. Besides, there were two important facts that supported this decision:

1. There was no previous experience in Ecuador regarding modelling agrichemicals at a regional level (basin). Therefore, the logistics for agrichemical modelling issues in Ecuador are not well prepared to develop a new modelling tool without facing considerable obstacles.
2. The research was restricted to 4 years to produce an outcome that could generate interest at the management level of river basins. Thus, awareness was to be produced in Ecuadorian institutions, the private sector and society to join efforts for modelling as a tool for Integrated River Management.

The selected basin can be used as the starting point to perform further research as some basic important data have been collected and processed in the present thesis. The Chaguana river basin can also be used as a pilot basin for the development of an Integrated River Basin Management Programme in Ecuador.

5.2. METHODOLOGY

As said at the beginning of this thesis, the main goal of this research was to develop procedures and to group existing methodologies that could help the Ecuadorian environmental modelling scientist in processing information under poor data conditions, such as the Ecuadorian environment. All data needed for hydro-environmental modelling was structured in such a way that modellers should not spend too much time seeking ways to improve or realize how to get to specific data normally required for the majority of water quality models.

This thesis used ArcView version 3.2 as a GIS platform for data processing. The use of this platform presents advantages and disadvantages. The main advantage is that models can be linked to the platform in order to input data, run the model and/or process output results. The main disadvantage is that ArcView is not as complete a GIS platform as ArcInfo, ERDAS or ArcGis. Despite the GIS platform used, some procedures should sometimes be programmed or done in third-party software such as add-on external graphical user interfaces or object oriented internal databases (Bian *et al.*1996). Although this task is not difficult, an extra effort should be dedicated to accomplish it.

5.3. POOR DATA CONDITIONS

The present research faced several challenges due to the lack of available, updated and reliable data required to perform a modelling assessment of the selected basin. Donigian and Huber (2001) have stated that the required data for basin modelling can be divided in three groups for an easy understanding of the problem: system parameters, transformation parameters and input variables. However, it can also be overwhelming to deal with so many data at the same time. The analysis turns to be more complex when the majority of the data is not easily available or does not exist at all such as the case of the Chaguana river basin.

In this research, it was necessary to develop a complete GIS-based procedure to process all gathered information and obtain the minimum amount of data required to run models for predicting pesticide concentrations in a river basin. Spatial analysis and data aggregation were the main procedures applied in the data processing step. Some Avenue (ArcView Macro Language) scripts were developed or modified to ease the work. In addition, interpolation techniques such as *Kriging* and *Spline* were applied to develop raster maps which later were aggregated to obtain the required data.

Kriging interpolation was used to derive the soil and the topography (DEM) raster maps because it was the most suitable technique to be applied on those cases. Residuals between observed and estimated values were within acceptable ranges (r^2 between 0.7 and 0.85). The DEM was built based on digitized contour lines from scanned information and soil maps were obtained from the interpolation of soil sampling points. Burshtynska and Zayac (2002) have demonstrated that the Kriging method can produce optimal results for DEM construction without giving any further information, but considering extra data, the differential spline method can give a higher accuracy when dealing with soft surfaces. The latter method was not applied in the current research because it requires some extra information that was difficult to obtain (extra elevation points measured in "flat" areas).

The climatic maps (precipitation and temperature) were produced by applying Spline interpolation. This technique has been recommended worldwide to derive climatic spatial data (Hutchinson and Bishof 1983, Hutchinson 1996, Hutchinson and Corbett 1993). In addition, this method has been applied successfully in irregular terrains with high elevation difference such as in the Chaguana river basin. However, it has been more used on a continental scale (Kesteven and Hutchinson 1996)

As mentioned before, the research achieved to create a structure of several procedures by searching several methodologies that can be applied in related projects where data was the main limiting issue. This group of procedures should be considered as a starting point because it only deals with hydrology and agricultural components of a river basin. In an integrated river basin management framework, other components, such as economics and legal issues, should be added to improve the data generation procedure.

5.4. PESTICIDE USAGE IN ECUADOR

In 1999, 6040 tons out of 14000 tons of the imported pesticides were used in the Ecuadorian banana sector. This amount is grouped in 30 different chemical families distributed among 250 trade marks. The application rate is still below other banana countries such as Panama and Costa Rica (UNEP, 2000). However, more research should be done in the near future regarding the following related aspects:

- The current Ecuadorian Environmental Management Law has a gap in the pesticide regulation because it only controls 4 out of the 30 chemical groups used in Ecuador.
- Ecuador does not have sufficient installed capacity to detect and monitor pesticide concentrations in several media (water, soil, sediments and organic tissues).

These two issues can create potential problems for future research, environmental tool development and law application as the Ecuadorian society is not well prepared to face pesticide pollution problems. However, this thesis can serve as a starting point in searching solutions for those issues.

Although pesticides can help to increase the agricultural productivity of the country, it is also important to control their use in a more efficient way. The probability of polluting Ecuadorian rivers is directly related to the lack of scientific knowledge on how these chemicals move in the environment as clearly stated by Ongley (1996). This research is putting an initial step in the Ecuadorian society to increase that knowledge.

This thesis has only assessed some pesticides used in the banana sector. More scientific research should be done in other Ecuadorian agricultural activities such as cocoa, sugarcane, rice and palm. It should be a fact that the more knowledge is collected regarding pesticide fate from those activities, the less the related conflicts arising from the potential pollution in a river basin will be.

5.5. ENVIRONMENTAL BASELINE OF CHAGUANA RIVER BASIN

As mentioned before, there was no information regarding the environmental quality of the Chaguana river basin. The present research began to fill this gap by performing water quality sampling campaigns. Although sampling was too limited, it can be considered as an environmental baseline, which can be increased with future research.

By analysing the monitored environmental parameters, it can be concluded that the environmental quality in the Chaguana river basin is still within the majority of acceptable quality standards. The measured levels of conventional pollution (organic matter, solids content, and conductivity) were below the maximum allowable concentrations at the moment of the sampling campaigns. The monitored pesticide concentrations were below 6 ppb, and thus not exceeding the mean toxicity levels, reported by Jolliet *et al.* (1998), that could affect the aquatic biota normally living on those water bodies. However, such pesticide levels are above the maximum recommended concentrations for water consumption (European and United States environmental limits). As the people living in the Chaguana basin do not have potable water systems, they may be taking water directly from the river. Therefore, there is a potential risk to human health but its evaluation was out of this thesis scope.

5.6. PESTICIDE FATE MODELLING

Two groups of models were evaluated: screening and integrated models. The results from the screening models were used to help in planning the sampling campaigns. Propiconazole and Imazalil were evaluated. Based on the model outcomes, imazalil affects more the water compartment than the others. Therefore, there is more chance to find this pesticide in river water. Regarding propiconazole, it affects more the soil compartment. However, the soil surface is influenced by erosion, and eroded particles with attached pesticides finally reach the surface water bodies. Therefore, water samples for pesticide analysis were taken during sampling campaigns instead of soil samples. Some river bed sediment samples were obtained just to confirm that other pesticides were present in the sediment instead of imazalil and propiconazole.

The main model evaluated in this thesis was AGNPS (Agricultural Non Point Sources). The main drawback of the model is the loss of information because of data aggregation in the evaluated cells (Matamoros *et al.* 2004, *in press*). This can be decreased by increasing the number of evaluated cells in a basin. However, a large number of cells would lead to the need for an overwhelming amount of values that are not available and they should be estimated.

The flow calibration of the model was restricted to three gauging stations whose data were only recorded between 1979 and 1983 (there was no data for 1981). In addition, rainfall data was only available as total monthly values. A synthetic daily rainfall data set was generated with those monthly values, the monthly maximum 24-hour precipitation and the number of rainfall days in a month. That synthetic daily rainfall data corresponds to the period when flow data is available.

As a measured of quality of the flow predictions, the coefficient of efficiency E (Nash and Sutcliffe 1970) ranged from 0.37 to 0.73. The higher value corresponds to the gauging station which has a larger drainage area (middle course of the Chaguana basin). Although the flow data set is small, a good prediction can be achieved for basins with a large drainage area. In other studies, such as in Grunwald and Frede (1999), coefficient of efficiency can reach over 0.9 for smaller basins than the Chaguana river, but with a better rainfall data set.

The sediment calibration was done based only on the four measurement days (11 November 2001, 30 March 2002, 5 July 2002 and 14 November 2002). Due to the lack of rainfall information for those days, precipitation was estimated by using inverse modelling techniques with the flow predictions obtained in the previous step. Although the use of this technique implies potential risks of getting wrong results, it can be useful in problems with a very small data set such as the Chaguana river basin.

The sampled branch of the Chaguana river showed a high coefficient of efficiency (0.88) for the sediment predictions. That was not the case for the sampled Zapote river where this coefficient was zero. This low agreement between measured and predicted values is related to the fact that flow calibration in this stream was also worse, and there was less sampled data in the Zapote river than in the Chaguana river. The information loss by data aggregation during the creation of AGNPS cells can also be the cause for this low agreement in the Zapote area.

Regarding pesticide modelling, the main difficulty was to estimate at what moment farmers sprayed propiconazole. A reference application planning obtained from one farmer was used for this. A trial and error procedure was applied to know which farms supplied the pollutant at the moment of the measurement campaign.

The SWAT model gave a better assessment for the basin probably because the tool includes the use of Hydrological Response Units (HRU's) in the evaluated sub-basins. These HRUs significantly decrease the loss of information in the sub-basin, because more than one soil and landuse type can be used for each evaluated unit.

The imazalil assessment was not possible to be done neither with AGNPS nor with SWAT. Imazalil is discharged as point source pollution, and both models only predict pesticides from non-point sources (runoff process). Both AGNPS and SWAT have a module to include point source pollution. However, none of them considers point source pollution for pesticides.

5.7. FUTURE PERSPECTIVES

The use of a natural resource, such as water, can create complex conflicts that usually demand actions from the Government, who could not be prepared to face them. The Government should take advantage of the type of research conducted in this Ph.D. study to improve the knowledge of issues such as non-point pollution.

The recent Ecuadorian Environmental Management Law should be updated and improved regarding agrichemicals by considering all chemical families used in Ecuador. Most of the pesticides not considered by the Law can produce significant toxic levels in water, soil and air, which should be determined by proper scientific research.

The Ecuadorian Government should learn from other countries' experiences such as the EU Water Framework Directive. This can be an opportunity to increase the research cooperation agreements between European Universities and Institutions with Ecuador.

Any improvement should be done together with the decision to invest in laboratory capacity to monitor agrichemical products. Currently, Ecuadorian labs can detect less than 25% of the total agrichemical products imported to Ecuador. Lab equipments are very expensive, and they require highly trained personnel. However, this is another opportunity to create training programmes with foreign universities, such as Ghent University, which have the adequate experience in analysing agrichemicals.

Regarding the modelling of the Chaguana basin, it is advisable to perform more sampling campaigns during the year, as the model was calibrated only for 4 rain events in the year. The Zapote river should be assessed with more sampling points to have the same characterisation level as the Chaguana river.

BIBLIOGRAPHY

ARNOLD, J.G., WILLIAMS, J.R., SRINIVASAN, R., KING, K.W. AND GRIGGS, R.H., 1995. *SWAT - Soil and Water Assessment Tool: User's Manual*. Temple, Texas: Agriculture Research Service, U.S. Department of Agriculture.

BAILEY, G.W., MULKEY, L.A. AND SWANK, R.R. JR., 1985. Environmental implication of conservation tillage: A systems approach. *In*: F.M. D'ITRI, ed. *A systems approach to conservation tillage*. Chelsea, MI: Lewis Publishers, 240-265.

BAUMER, O., KENYON, P. AND BETTIS, J., 1994. Prediction of Soil Properties. *In*: Map Unit Use File (MUUF) version 2.14 User's Manual.

BENHAM, E., AHRENS, R.J. AND NETTLETON, W.D., 2001. *Clarification of Soil Texture Class Boundaries*. Lincoln, Nebraska: National Soil Survey Center, National Resource and Conservation Center, U.S. Department of Agriculture.

BENJAMIN, J., AND CORNELL, C.A., 1970. *Probability, Statistics and Decision for Civil Engineers*. New York: McGraw-Hill, 273-275.

BIAN, L., SUN, H., BLODGETT, C., EGBERT, S., LI, W., RAN, L. AND KOUSSIS, A., 1996. *An integrated interface system to couple the SWAT model and Arc/Info*. *In: 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling, 21-25 January 1996 Santa Fe, New Mexico*. USA: U.S. National Center for Geographic Information and Analysis (NCGIA).

BLACK, R., HAGGLAND, A. AND VOSS, F., 2000. Predicting the probability of detecting Organochlorine Pesticides and Polychlorinated Biphenyls in Stream Systems on the basis of Land Use in the Pacific Northwest, USA. *Environmental Toxicology and Chemistry*, 19(4), 1044–1054.

BLOMME, G., SWENNEN, R., TENKOUANO, A., ORTIZ, R. AND VUYLSTEKE, D., 2001. Estimation of root development from shoot traits in plantain and banana (Musa spp.). *InfoMusa*, 10(1), 15-17.

BLOMME, G., TENKOUANO, A. AND SWENNEN, R., 2001. Influence of leaf removal on shoot and root growth in banana (Musa spp.). *InfoMusa*, 10(2), 10-13.

BOEIJE, G., 1999. *Chemical Fate Prediction for Use in Geo-referenced Environmental Exposure Assessment*. Thesis (PhD). Ghent University, Belgium.

BOERINGA, M., 2002. *Kriging Interpolator SA version 3.2* [online]. Nieuwland Automatisering, Wagenigen, the Netherlands. Available from: http://www.nieuwland.nl

BOESTEN, J., JONES, R., BUSINELLI, M., DELMAS, A-B, GOTTESBÜREN, B., HANZE, K., JARVIS, T., KLEIN, M., VAN DER LINDEN, A.M.A., MAIER, W-M, REKOLEINEN, S., RESSELLER, H., STYCZEN, M., TRAVIS, K. AND VANCLOOSTER, M., 1999. *The development of FOCUS scenarios for assessing pesticide leaching to groundwater in EU registration*. *In: Brighton Conference - Weeds Proceedings, Volume 3*. Brighton, UK, 527-536.

BONINI, J. AND GUZMAN, E., 2003. *Flow and Sediment Estimation in Chaguana River Basin by using SWAT model*. Thesis (BSc). Escuela Superior Politecnica del Litoral, Ecuador (*in Spanish*).

BOSCH, D.D., BINGNER, R.L., THEURER, F.D., FELTON, G. AND CHAUBEY, I., 1998. *Evaluation of the AnnAGNPS Water Quality Model*. *In: 1998 ASAE Annual International Meeting, 12-16 July 1998 Michigan*. USA: ASAE, paper No 982195.

BURNS, L.A., 1981. *Validation of exposure models: The role of conceptual verification, sensitivity analysis, and alternative hypotheses*. *In: American Society of Testing and Materials Symposium on Aquatic Toxicology, 15 October 1981 St. Louis*. USA: ASTM, Spec. Tech. Publ., Vol STP-802.

BURNS, L.A., 1996. *Exposure Analysis Modeling System. User's Guide for EXAMS II Version 2.96*. Georgia, USA: Office of Research and Development, U.S. Environmental Protection Agency.

BURNS, L.A., 2002. *Exposure Analysis Modelling System (EXAMS): User Manual and System Documentation*. EPA/600/R 00/081, Revision F. Georgia, USA: Environmental Protection Agency.

BURSHTYNSKYA, K. AND ZAYAC, A., 2002. *Application of Differential Splines for Relief Simulation. In: Symposium on Geospatial Theory, Processing and Applications, 8-12 July 2002 Ottawa*. Canada: International Society for Photogrammetry and Remote Sensing (ISPRS).

CARSEL, R.F., SMITH, C.N., MULKEY, L.M., DEAN, J.D. AND JOWISE, P., 1984. *User's Manual for the Pesticide Root Zone Model (PRZM): Release 1*. EPA-600/3-84-109. Georgia, USA: Environmental Protection Agency.

CARSEL, R.F., IMHOFF, J.C., HUMMEL, P.R., CHEPLICK, J.M. AND DONIGIAN, A.S., 1999. *PRZM-3: A model for predicting pesticide and nitrogen fate in the crop root and unsaturated soil zones*. Georgia, USA: Environmental Protection Agency, AQUA TERRA Consultants, Waterborne Environmental Inc. and the National Exposure Research Laboratory.

CEMA, 1998. *Monitoring Carbon and Nitrogen in the banana sector of El Oro and Los Rios Provinces at Ecuador*. Guayaquil, Ecuador: Centre of Environmental Studies, Escuela Superior Politecnica del Litoral.

CHARNOCK, T.W., ELGY, J. AND HEDGES, P.D., 1996. *Application of GIS linked environmental models over a large area. In: 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling, 21-25 January 1996 Santa Fe, New Mexico*. USA: U.S. National Center for Geographic Information and Analysis (NCGIA).

CHENG, H.H., 1990. *Pesticides in the soil environment - An overview*. *In*: H.H. CHENG, ed. *Pesticides in the soil environment: Processes, impacts, and modeling*. Wisconsin, USA: Soil Science Society of America Book Series No. 2, 1-5.

CHINKUY, A., MEIXNER, T., GISH, T. AND DAUGHTRY, C., 2003. *Identification of sensitive parameters in GLEAMS model using a multi-objective sensitivity analysis procedure. In: ASAE Annual International Meeting 2003, 26–28July 2003 Las Vegas*, USA: ASAE.

CSANADY, G.T., 1973. *Turbulent Diffusion in the Environment. In: Geophysics and Astrophysics Monographs*, Volume 3. USA: D. Reidel Publ. Co.

CORPEI, 1999. *Report on Banana Exportations*. Guayaquil, Ecuador: Ecuadorian Corporation for Export Promotion and Investments.

DAILY, C., NEILSON, R.P. AND PHILLIPS, D.L., 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology*, 33, 140-158.

DESMET, P.J.J. AND GOVERS, G., 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. *J. Soil and Water Cons.*, 51(5), 427-433.

DI LUZIO, M., SRINIVASAN, R. AND ARNOLD, J.G., 1997. *An Integrated User Interface for SWAT using ArcView and Avenue. In: 1997 ASAE Annual International Meeting, , 10-14 August 1997 Minneapolis, Minnesota*. USA: ASAE, paper No. 972235.

DONINGIAN, A.S. AND HUBER, W.C., 1991. *Modeling of non-point source water quality in urban and non-urban areas*. Report EPA/600/3-91/039. Georgia, USA: Environmental Protection Agency.

ECETOC (1999) *GREAT-ER: A Geography-referenced Regional Exposure Assessment Tool for European Rivers*. Brussels, Belgium: European Centre for Ecotoxicology and Toxicology of Chemicals, (Special Report No.16).

ENFIELD, C.G. AND YATES, S.R., 1990. *Organic chemical transport to groundwater*. *In* H.H. CHENG, ed. *Pesticides in the soil environment: Processes, impacts, and modeling*. Wisconsin, USA: Soil Science Society of America Book Series No. 2, 271-302.

EPA, 1997. *Volunteer Stream Monitoring: A Methods Manual*. Washington: Office of Wetlands, Oceans and Watersheds, U.S. Environmental Protection Agency, (Technical Report 841-B-97-003).

FEIJTEL, T.C.J., BOEIJE, G., MATTHIES, M., YOUNG, A., MORRIS, G., GANDOLFI, C., HANSEN, B., FOX, K., HOLT, M., KOCH, V., SCHRÖEDER, R., CASSINI, G., SCHOWANEK, D., ROSENBLOM, J. AND NIESSEN, H., 1997. Development of a Geography-referenced Regional Exposure Assessment Tool for European Rivers – GREAT-ER. *Chemosphere*, 34(11), 2351-2374.

FOSTER, G.R., LANE, L.J., NOWLIN, J.D., LAFLEN, J.M. AND YOUNG, R.A., 1980. *A model to estimate sediment yield from field-sized areas: Development of model*. *In* W.G. KNISEL, ed. *CREAMS: A field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems*. USA: Department of Agriculture, Report No. 26, 36-64.

FREEZE, R.A. AND CHERRY, J.A., 1979. *Groundwater*. New Jersey: Prentice Hall.

GARBRECHT, J. AND MARTZ, L.W., 1993. Network and subwatershed parameters extracted from Digital Elevation Models: The Bills Creek Experience. *AWRA Water Resources Bulletin*, 29(6), 909-916.

GARBRECHT, J., MARTZ, L.W. AND GOODRICH, D.C., 1996. *Subcatchment parameterization for runoff modelling using Digital Elevation Models. In: ASCE Hydraulics Conference, North American Water and Environment Congress '96, 24-28 July 1996 Anaheim, California*. USA: ASCE.

GARBRECHT, J. AND MARTZ, L.W., 1999. *TOPAZ: An automated digital landscape analysis tool for topographic evaluation, drainage identification, watershed segmentation and subcatchment parameterization: TOPAZ Overview*. Oklahoma, USA: Department of Agriculture, ARS Publication No. GRL 99-1.

GILBERT, R.O., 1987. *Statistical Methods for Environmental Pollution Monitoring*. New York: Van Nostrand Rienhold Company Inc.

GLASS, G.L., 2000. *Vashon/Maury Island soil study*. Seattle, USA: Environmental Health Division of Seattle & King County, Technical Report.

GOVERNMENT OF MANITOBA, 2001. *Soil Sampling Strategies for Site Specific Management*. Manitoba, Canada: Soil and Conservation Department.

GRUNWALD, S. AND FREDE, H.-G., 1999. Using the modified agricultural non-point source pollution model in German watersheds. *Catena*, 37(1999), 319–328.

HARDY, B., 1998. *ITS-90 Formulations for vapor pressure, frostpoint temperature, dewpoint temperature, and enhancement factors in the range –100 to +100 °C. In: 3rd International Symposium on Humidity & Moisture, April 1998 Teddington, London, England*.

HE, C., RIGGS, F.J. AND KANG, Y., 1993. *Integration of Geographic Information Systems and a Computer Model to Evaluate Impacts of Agricultural Runoff on Water Quality*. *In*: J.M. HARLIN AND K.J. LANFEAR, eds. *AWRA Conference on Geographic Information Systems and Water Resources, 1993 Bethesda, Maryland*. USA: AWRA, 79-87.

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, eds. *Hydrological information in water law and policy: current practice and future potential*. Paris: UNESCO/WMO/HELP Programme, Kluwer International Publishers and National Water Law and Policy Series (*in press*).

HIMEL, C.M., LOATS, H. AND BAILEY, G.W., 1990. *Pesticide Sources to the soil and principles of spray physics*. *In:* H.H. CHENG, ed. *Pesticides in the soil environment: Processes, impacts, and modelling*. Wisconsin, USA: Soil Science Society of America Book Series No. 2, 7-50.

HUTCHINSON, M.F., 1996. *A locally adaptive approach to the interpolation of digital elevation models*. *In: 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling, 21-25 January 1996 Santa Fe, New Mexico*. USA: U.S. National Center for Geographic Information and Analysis (NCGIA).

HUTCHINSON, M.F. AND BISHOF, R.J., 1983. A new method for estimating the spatial distribution of mean seasonal and annual rainfall applied to the Hunter Valley, New South Wales. *Australian Meteorological Magazine*, 31, 179-184.

HUTCHINSON, M.F. AND CORBETT, J.D., 1993. *Spatial Interpolation of Climate Data using Thin Plate Smoothing Splines*. *In: The FAO Expert Consultation on the Coordination and Harmonization of Databases and Software for Agroclimatic Applications, 29 November – 3 December 1993, Rome*. Rome: Food and Agriculture Organization, FAO Agrometeorology Series Working Paper No.13.

INAMHI, 2001. *Climate records of Machala, Santa Isabel, La Cuca, Huertas and Tenguel meteorological stations*. Guayaquil, Ecuador: Instituto Nacional de Meteorología e Hidrología.

JACOBSEN, J., 1999. *Soil Compiling and Testing*: Soil Sampling, Montana: Montana State University Extension.

JANSSEN PHARMACEUTICA, 2000. *Imazalil Technical: Material Safety Data Sheet*. Belgium: Janssen Pharmaceutica.

JANSSEN PHARMACEUTICA, 2000. *Imazalil Sulphate: Material Safety Data Sheet*. Belgium: Janssen Pharmaceutica.

JANKOWSKI, P. AND HADDOCK, G., 1993. *Integrated Nonpoint Source Pollution Modeling System. In: 2nd International Conference/Workshop on Integrating Geographic Information Systems and Environmental Modeling, 26-30 September 1993, Brackenridge, Colorado*. USA: U.S. National Center for Geographic Information and Analysis (NCGIA).

JENSON, S.K. AND DOMINQUE, J.O., 1988. Extracting topographic structure from digital elevation data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing*, 54(11), 1593-1600.

JOLLIET, O., MARGNI, M., ROSSIER, D. AND CRETTAZ, P., 1998. *Life cycle impact assessment of pesticides on human health and ecosystems. In: VITO conference on Life Cycle Assessment in agriculture, agro industry and forestry, 3-4 December 1998 Brussels*. Belgium: VITO, 109-119.

KESTEVEN, J. AND HUTCHINSON, M., 1996. *Spatial Modelling of Climatic Variables on a Continental Scale. In: 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling, 21-25 January 1996 Santa Fe, New Mexico*. USA: U.S. National Center for Geographic Information and Analysis (NCGIA).

KRAUSS, U., SOBERANIS, W. AND JARRA, J., 2001. Evaluation of FHIA Hybrids in comparison with local Musa clones in a black Sigatoka-free area of eastern Peru. *InfoMusa*, 10(1), 21-26.

KUMAR, N., KRISHNAMOORTHY, V., NALINA, L. AND SOORIANATHASUNDHARAM, K., 2002. A new factor for estimating total leaf area in banana. *InfoMusa*, 11(2), 42-43.

LEGATES, D.R. AND MCCABE, G.J., 1999. Evaluating the use of "Goodness of Fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, 35, 233-241.

LEONARD, R.A., 1990. Movement of pesticides into surface waters. *In:* H.H. CHENG, ed. *Pesticides in the soil environment: Processes, impacts, and modelling*. Wisconsin, USA: Soil Science Society of America Book Series No. 2, 303-349.

LINDERS, B.H., JANSMA, J.W. AND MENSINK, B., 1994. *Pesticides: Benefaction or Pandora's box? A synopsis of the environmental aspects of 243 pesticides*. Bilthoven, the Netherlands: National Institute of Public Health and Environmental Protection (RIVM), Report No. 679101014.

LOVANH, N., ZHANG, Y-K, HEATHCOTE, R.C. AND ALVAREZ, P.J.J., 2000. *Guidelines to Determine Site-Specific Parameters for Modeling the Fate and Transport of Monoaromatic Hydrocarbons in Groundwater*. Iowa: University of Iowa, the Iowa Institute of Hydraulic Research and the Iowa Department of Justice.

MACKAY, D., PATERSON, S., DI GUARDO, A. AND COWAN, C.E., 1996. Evaluating the environmental fate of a variety of types of chemicals using the EQC Model. *Environ. Toxicol. Chem.*, 15(9), 1627-1637.

MACKAY, D. AND PATERSON, S., 1981. Calculating fugacity. *Environ. Sci. Technol*. 15, 1006-1014.

MADHUND, Y.A. AND FREED, V.H., 1990. *Impact of pesticides on the environment*. *In:* H.H. CHENG, ed. *Pesticides in the soil environment: Processes, impacts, and modelling*. Wisconsin, USA: Soil Science Society of America Book Series No. 2, 429-460.

MAIDMENT, D.R., 1996. *GIS and hydrologic modeling: an assessment of progress*. *In: 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling, 21-25 January 1996 Santa Fe, New Mexico*. USA: U.S. National Center for Geographic Information and Analysis (NCGIA).

MATAMOROS, D., 1999. *Ecuador: Banana and Pesticides*. Guayaquil, Ecuador: Escuela Superior Politecnica del Litoral, First Semester Report of Component 4.1 in ESPOL – VLIR Project.

MATAMOROS, D., BONINI, J., GUZMAN, E., RAMIREZ, G. AND VANROLLEGHEM, P.A., 2002. Design and implementation of a measuring campaign to model pesticide impacts in an Ecuadorian watershed. *Water Science and Technology*, 46(9), 37-45.

MATAMOROS, D., DUQUE, J., AND CORNEJO, M.P., 2001. Preliminary assessment of laboratory availability for pesticide detection in soil and water samples at Ecuador. Guayaquil, Ecuador: Escuela Superior Politecnica del Litoral, Second Year Report of Component 4.1, ESPOL – VLIR Project.

MATAMOROS, D., VAN BIESEN, L. AND VANROLLEGHEM, P.A., 2004. *Development of a Geographical Information System for pesticide assessment on an Ecuadorian watershed. In: 4th IWA World Water Congress and Exhibition, 19-24 September 2004, Marrakech*. Morocco: IWA (in press)

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

MELANCON, P.A., 1999. *A GIS-based watershed analysis system for Tillamook Bay, Oregon*. Thesis (MSc). University of Texas at Austin, USA.

MITAS, L., BROWN, W.M. AND MITASOVA, H., 1997. Role of dynamic cartography in simulations of landscape processes based on multi-variate fields. *Computers and Geosciences*, 23(4), 437-446.

MITAS, L. AND MITASOVA, H., 1999. *Spatial Interpolation*. *In*: P. LONGLEY, M.F. GOODCHILD, D.J. MAGUIRE, AND D.W. RHIND, eds. *Geographical Information Systems: Principles, Techniques, Management and Applications*. USA: GeoInformation International and Wiley Inc., 481-492.

MITASOVA, H., HOFIERKA, J., ZLOCHA, M. AND IVERSON, L.R., 1996. Modelling topographic potential for erosion and deposition using GIS. *International Journal of Geographical Information Science*, 10(5), 629-641.

MONTGOMERY, J.H., 1993. *Agrochemical desk reference: Environmental data*. Ann Harbor, MI, USA: Lewis Publishers.

MOORMAN, T., JAYNES, D., CAMBARDELLA, C., HATFIELD, J., PFEIFFER, R. AND MORROW, A., 1999. Water Quality in Walnut Creek Watershed: Herbicides in Soils, Subsurface Drainage and Groundwater. *J. Environ. Qual.*, 28(1), 35-45.

NASH, J.E. AND SUTCLIFFE, J.V., 1970. River flow forecasting through conceptual models: Part I - A discussion of principles. *J. Hydrol.*, 10, 282-290.

NEITSCH, S.L., ARNOLD, J.G., KINI, J.R., WILLIAMS, J.R. AND KING, K.W., 2002. *Soil and Water Assessment Tool: Theoretical documentation, Version 2000*. Texas, USA: Texas Water Resources Institute, TWRI Report TR-191.

ONGLEY, E.D., 1996. *Control of water pollution from agriculture*. Rome: Food and Agriculture Organization of the United Nations, FAO Irrigation and Drainage Paper No. 55.

PARSONS, J.E., 2001. *Model Summary Tables* [online]. *In* J.E. PARSONS, D.L. THOMAS AND R.L. HUFFMAN, eds. *Agricultural Non-Point Source Water Quality Models: Their Use and Application*. North Carolina, USA: North Carolina State University, Southern Cooperative Series Bulletin No. 398. Available from: http://www3.bae.ncsu.edu/Regional-Bulletins/Modeling-Bulletin/

PLIMMER, J.R., 1992. *Dissipation of pesticides in the environment*. *In* J.L. SCHNOOR, ed. *Fate of pesticides and chemicals in the environment*. USA: Wiley-Interscience Publication, 79-90.

REM (2003). *Register of Ecological Model: a meta-database* [online]. Germany: University of Kassel and the National Research Center for Environment and Health (GSF). Available from: http://eco.wiz.uni-kassel.de/ecobas.html

RENARD, K.G., FOSTER, G.R., WEESIES, G.A., MCCOOL, D.K. AND YODER, D.C., 1996. *Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*. USA: Agricultural Research Service, U.S. Department of Agriculture, Agriculture Handbook No. 703.

RICHARDS, L.A., 1931. Capillary conductivity of liquids through porous media. *Physics*, 1, 318-333.

RICKERT, D., 1993. *Water quality assessment to determine the nature and extent of water pollution by agriculture and related activities. In: FAO Expert Consultation on Prevention of Water Pollution by Agriculture and Related Activities, 20-23 October 1992 Santiago, Chile*. Rome: Food and Agriculture Organization, Water Report No. 1, 171-194.

RIETVELD, M.R., 1978. A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine. *Agricultural and Forest Meteorology*, 19, 243-52.

SAXTON, K.E., RAWLS, W.J., ROMBERGER, J.S. AND PAPENDICK, R.I., 1986. Estimating generalized soil-water characteristics from texture. *Soil Science Society of America Journal*, 50(4), 1031–1036.

SCHNOOR, J.L., 1992. *Chemical fate and transport in the environment*. *In* J.L. SCHNOOR, ed. *Fate of pesticides and chemicals in the environment*. USA: Wiley-Interscience Publication, 1-24.

SCHOWANEK, D., FOX, K., HOLT, M., SCHROEDER, F.R., KOCH, V., CASSANI, G., MATTHIES, M., BOEIJE, G., VANROLLEGHEM, P.A., YOUNG, A., MORRIS, G., GANDOLFI, C. AND FEIJTEL, T.C.J., 2000. GREAT-ER: A new tool for management and risk assessment of chemicals in river basins. *Wat. Sci. Tech.*, 43(2), 179-185.

SEMENOV, M.A. AND BARROW, E.M., 1997. Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change*, 35, 397-414.

SEMENOV, M.A., BROOKS, R.J., BARROW, E.M. AND RICHARDSON, C.W, 1998. Comparison of the WGEN and LARS-WG stochastic weather generators in diverse climates. *Climate Research*, 10, 95-107

SMITH, C.N. AND CARSEL, R.F., 1984. Foliar washoff of pesticides (FWOP) model: Development and evaluation. *Journal of Environmental Sciences and Health*, B19, 323-342

SPOSITO, G., 1995. Recent advances associated with soil water in the unsaturated zone [online]. *Reviews of Geophysics*, 33, Supplement 1995. Available from: http://www.agu.org/revgeophys/sposit00/sposit00.html

SRINIVASAN, R. AND ARNOLD, J.G., 1994. Integration of Basin-Scale Water Quality Model with GIS. *Water Resources Bulletin*, 30(3), 453-462.

SYRACUSE RESEARCH CORPORATION. *Environmental Fate Databases* [online]. Available from: http://esc.syrres.com/

TCHOUKANSKI, I., 2002. *Edit Tools version 3.6, an extension for ArcView* [online]. Available from: http://www.ian-ko.com

TOMLIN, C., ed., 1997. *The Pesticide Manual*. 11th ed. Surrey, UK: Brithish Crop Protection Publications.

UNEP (2001). *Reduction of Pesticide Runoff to the Caribbean Sea*. Panama City, Panama: Caribbean Regional Coordinating Unit, United Nations Environmental Programme, (Final GEF Project Report included in the documents from GEF Regional Workshop, January 2001)

UNIVERSITY OF CORNELL. *Pesticide Profiles* [online]. Ithaca, New York: Pesticide Management Education Program, University of Cornell. Available from: http://pmep.cce.cornell.edu/profiles

USBR (1991). *Inventory of Hydrologic Models*. Colorado, USA: Global Climate Change Response Program, United States Bureau of Reclamation.

USDA-NRCS (1986). *Urban Hydrology for Small Watersheds*. USA: Natural Resource Conservation Service, U.S. Department of Agriculture, Technical Release No. 55.

VAN GRIENSVEN, A. AND BAUWENS, W., 2000a. *Development of an integral water quality model for rural catchments. In: 1st World Congress of the International Water Association, 2000 Paris.* France: IWA.

VAN GRIENSVEN, A. AND BAUWENS, W., 2000b. *Integral modelling of catchments. In: WATERMATEX Conference, 17-19 September 2000 Gent*. Belgium: IWA.

VAN LEEMPUT, L., SWYSEN, E., FIRLEFYN, R., MEULDERMANS, W. AND HEYKANTS, J., 1986. *The adsorption of Imazalil in soil*. Belgium: Janssen Pharmaceutica.

VAN LEEMPUT, L., SWYSEN, E., HENDRICKX, J., LAUWERS, W., MEULDERMANS, W. AND HEYKANTS, J., 1984. *The transformation of 14C-imazalil in Watervliet loam, incubated at 25ºC in flow-through soil metabolism systems*. Belgium: Janssen Pharmaceutica.

VAN LEEMPUT, L., SWYSEN, E., HENDRICKX, J., BOCKX, M. AND HEYKANTS, J., 1988. *On the photolysis of Imazalil in the aquatic environment*. Belgium: Janssen Research Foundation.

VAN REMORTEL, R., HAMILTON, M. AND HICKEY, R., 2001. Estimating the LS factor for RUSLE through iterative slope length processing of digital elevation data. *Cartography*, 30(1), 27-35.

VILLACIS, M., GALARRAGA, R. AND FRANCOU, B., 2001. *Influencia de El Niño-Oscilación del Sur (ENOS) sobre la precipitación en los Andes centrales del Ecuador. In: 3rd Water Meeting 24–26 October Santiago, Chile (in Spanish)*.

VIVAS, C., 2004. *Hydraulic Model Analysis of Chaguana River System by using HEC-RAS Model*. Thesis (BSc). Escuela Superior Politecnica del Litoral, Ecuador (*in Spanish*).

WAGENET, R.J. AND RAO, P.S.C., 1990. *Modeling pesticide fate in soil*. *In:* H.H. CHENG, ed. *Pesticides in the soil environment: Processes, impacts, and modelling*. Wisconsin, USA: Soil Science Society of America Book Series No. 2, 351-400.

WAUCHOPE, R.D., BUTTLER, T.M., HORNSBY, A.G., AUGUSTIJN BECKERS, P.W.M. AND BURT, J.P., 1992. Pesticide properties database for environmental decision-making. *Rev. Environ. Contam. Toxicol.* 123, 1–157.

WEBSTER, E. AND MACKAY, D., 2003. *Defining uncertainty and variability in environmental fate models*. Ontario, Canada: Canadian Environmental Modelling Centre, Trent University, Report No. 200301.

WHITLOCK, C.H., BROWN, D.E., CHANDLER, W.S., DIPASQUALE, R.C., MELOCHE, N., LENG, G.J., GUPTA, S.K., WILBER, A.C., RITCHEY, N.A., CARLSON, A.B., KRATZ, D.P. AND STACKHOUSE, P.W., 2000. *Release 3 Nasa Surface Meteorology and Solar Energy Data Set for Renewable Energy Industry Use* [online]. *In: 26th Annual Conference of the Solar Energy Society of Canada and Solar Nova Scotia, 21-24 October 2000 Halifax, Nova Scotia*. Available from: http://eosweb.larc.nasa.gov

WILLIAMS, J.R. AND BERNDT, H.D., 1972. Sediment yields computed with Universal Equation. *Journal of Hydraulics*, ASCE, 102(HY9), 1241-1253.

WILLMOTT, C.J., 1981. On the validation of models. *Phys. Geog.*, **2**, 184-194.

WILSON, J.P., 1996. GIS-based land surface/subsurface modeling: New potential for new models? *In: 3rd International Conference/Workshop on Integrating GIS and Environmental Modeling, 21-25 January 1996 Santa Fe, New Mexico*. USA: U.S. National Center for Geographic Information and Analysis (NCGIA).

YOUNG, R., ONSTAD, C.A., BOSCH, D.D. AND ANDERSON, W.P., 1987. *AGNPS Agricultural Non-Point Source Pollution Model: a watershed analysis tool*. Washington: Agricultural Research Service, U.S. Department of Agriculture, Report No. 35.

NOMENCLATURE

AGNPS	Agriculture Non Point Source
ARS	Agricultural Research Service
CEMA	Centro de Estudios Medio Ambientales
EQC	Equilibrium Criterion
ECETOC	European Centre for Ecotoxicology and Toxicology of Chemicals
ESPOL	Escuela Superior Politécnica del Litoral
EXAMS	Exposure Assessment Modelling System
g.a.i.	Grams of active ingredient
kg.a.i.	Kilograms of active ingredient
IGM	Instituto Geográfico Militar
INAMHI	Instituto Nacional de Meteorología e Hidrología
MUSLE	Modified Universal Soil Loss Equation
SCS	Soil Conservation Service
SWAT	Soil and Water Assessment Tool
RUSLE	Revised Universal Soil Loss Equation
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation

NOTATION

A_{LEAF}	Mean leaf area of the plant	cm^2
$A_{pesticide\ (t)}$	Application rate of pesticide applied to the plant at time t	$kg.s^{-1}$
AM_{ROOT}	Estimated unitary root mass	$kg.Ha^{-1}$
B	Benefit factor	-
$BOD_{domestic}$	Biochemical Oxygen Demand for domestic wastewater	$mg.l^{-1}$
C	Concentration of the chemical	$mg.l^{-1}$
C_0	Initial concentration at the point of discharge	$mg.l^{-1}$
Cl	Clay soil fraction	%
C_h	Pesticide concentration at the height of release	$\mu g.m^{-3}$
$C_{hydrophilic}$	Pesticide concentration in the hydrophilic state (water phase)	$mg.l^{-1}$
$C_{lipophilic}$	Pesticide concentration in the lipophilic state	$mg.kg^{-1}$
C_M	Cover management factor in USLE approach	-
C_X	Predicted environmental concentration at distance X from source	$mg.l^{-1}$
C_S	Pesticide concentration attached to the soil particle	$mg.kg^{-1}$
C_Z	Pesticide concentration at the height of reception	$\mu g.m^{-3}$
C_W	Pesticide concentration in the surrounding water	$mg.l^{-1}$
CN	Curve Number	-
D	Dispersion coefficient of the chemical in the water	$m^2.s^{-1}$
Den	Plant population density in the farm	$plants.Ha^{-1}$
Dg	Geometric mean soil particle diameter	-
D_X	Diffusion coefficient in x direction	$m^2.s^{-1}$
D_Y	Diffusion coefficient in y direction	$m^2.s^{-1}$
D_Z	Diffusion coefficient in z direction	$m^2.s^{-1}$
E	Energy produced by the impact of a typical raindrop	$MJ.Ha^{-1}$
E_T	Actual vapour pressure for a specific temperature	mbar
E_W	Saturation vapor pressure over water	mbar
H_{SUCKER}	Height of the tallest sucker	cm
i	Intensity of the rain	$mm.h^{-1}$
I_{30}	Maximum 30-min intensity for a specific storm	$mm.h^{-1}$

k	First-order degradation rate of the chemical	s^{-1}
K	Effective soil hydraulic conductivity	$cm.s^{-1}$
k_d	Solid-liquid partitioning coefficient	$l.kg^{-1}$
k_F	Pesticide first-order degradation rate on the foliage including photolysis, chemical reaction, hydrolysis, biodegradation and volatilization.	s^{-1}
K_{OW}	Octanol-Water partition coefficient for the pesticide	-
K_S	Soil erodibility factor in USLE approach	$Ton.Ha^{-1}.Ha.MJ^{-1}.mm^{-1}.h$
k_T	Transformation rate coefficient (hydrolysis, biodegradation, volatilization)	s^{-1}
l_{daily}	Average linear distribution of BOD loading along the river length	$kg.day^{-1}.km^{-1}$
L_{river}	Length of monitored river stream	km
L_{SLOPE}	Length of the maximum downhill slope	m
$Load_{daily}$	BOD loading on daily basis	$kgBOD.day^{-1}$
LS	Slope-length factor in USLE approach	-
$M_{foliage\ (t)}$	Mass of pesticide on foliage at time t	kg
N	Number of inhabitants	-
n_T	Total porosity of the aquifer matrix	-
P	Erosion-control practice factor in USLE approach	-
P(i)	Probability	-
P_{month}	Maximum 24-h precipitation for a specific month	mm
Q_{sewage}	Domestic wastewater flow	$m^3.s^{-1}$
q_U	Unitary sewage production	$l.hab^{-1}.day^{-1}$
R	Annual Rainfall energy factor in USLE approach	$MJ.Ha^{-1}.year^{-1}.mm.h^{-1}$
R_I	Rainfall energy factor for a specific storm	$MJ.Ha^{-1}.mm.h^{-1}$
R_F	Retardation factor	-
s	Terrace slope grade or ground slope	%
$Sink_{water}$	Water transported by other mechanisms than flow (e.g. evapotranspiration)	s^{-1}
S_{LOSS}	Estimated soil loss	$ton.ha^{-1}.year^{-1}$
S_{month}	Standard deviation of the mean 24-h precipitation for the month	mm
Sn	Sand soil fraction	%
St	Silt soil fraction	%
T_{AIR}	Dry air temperature	ºC
T_{DEW}	Dew point temperature	ºC
T_{RETURN}	Recurrence interval of precipitation	years
T_{WET}	Wet bulb temperature	ºC
v	Velocity of the river	$m.s^{-1}$

V	Uniform horizontal groundwater flow velocity	$m.s^{-1}$
V_X	Uniform flow velocity in x direction	$m.s^{-1}$
V_Y	Uniform flow velocity in y direction	$m.s^{-1}$
V_Z	Uniform flow velocity in z direction	$m.s^{-1}$
w	Mean water content ratio of the root system	-
$W_{pesticide\ (t)}$	Washoff rate of pesticide wiped out from foliage	$kg.s^{-1}$
X_{month}	Mean 24-h precipitation for a specific month	mm
α	Dispersion fitting parameter in Gumbel equation for precipitation	mm^{-1}
γ	Euler's constant (γ = 0.577215664901…)	-
δ	Slope angle	radians or degrees
θ	Volumetric soil-water content	-
μ	Mode fitting parameter in Gumbel equation for precipitation	mm
ρ_b	Bulk density of the aquifer matrix	$kg.m^{-3}$
σ	Standard deviation of the spraying cloud distribution	m^2
Φ_C	Arithmetic mean diameter of clay size boundaries	mm
Φ_{PSEUDO}	Pseudostem circumference	cm
Φ_{St}	Arithmetic mean diameter of silt size boundaries	mm
Φ_S	Arithmetic mean diameter of sand size boundaries	mm
ψ	Soil-water potential	-
ω	Variate used to calculate the recurrence interval of precipitation	-

SUMMARY

Ecuador has a tradition built on banana production. Nowadays, more than 30% of the exportable items correspond to bananas. This banana cultivation has led to an environmental concern on other sectors that share land in some river basins across the country. In 1994, the shrimp sector claimed that a disease occurring at some shrimp farms had been caused by pesticide pollution from the banana sector. Based on that situation, Escuela Superior Politécnica del Litoral (ESPOL), an Ecuadorian University, began a research project to tackle potential solutions to environmental conflicts in Ecuadorian river basins. The present Ph. D. thesis is one of the results obtained in this project.

The thesis briefly shows the differences between Ecuadorian Water Quality Law and acceptable environmental standards across the world regarding pesticide pollution. It also presents the common pesticide management inside an Ecuadorian banana plantation. The pesticides mostly used in banana farms are propiconazole, thiabendazole and imazalil.

By applying screening models, it is shown that the aquatic compartment is more affected by imazalil and thiabendazole. On the other hand, based on screening model runs propiconazole tends to affect the soil compartment significantly more.

The main difficulty in this research was the data gathering process and the subsequent model calibration and application. Ecuador is a poor developing country where environmental data are not recorded on a continuous basis affecting any assessment outcome done on environmental issues such as pesticide pollution. To solve this problem, the first part of the research proposed a methodology for such data-poor conditions to gather and process information to be used for pesticide fate evaluation. The methodology will be useful for future related research in gathering information in an efficient and understandable way for developing countries like Ecuador. The gathered data were then converted to a ready-to-use format to be imported in models and Geographical Information Systems.

The second part of the research evaluated the AGNPS and SWAT models as potential tools to assess non-point pollution problems in Ecuadorian river basins. The Chaguana river basin was selected as a case study. Banana farms cover around 30% of the total surface area of 32000 Ha, humid forest 26% and shrimp farms 6%. The banana farms are mainly located at the downstream section of the river basin, while shrimp farms are located near the outlet.

Four sampling campaigns were performed to collect data for model calibration (water quality and flow data) at 13 sampling sites along the river during different weather conditions throughout one year. Lab results showed that the majority of the environmental parameters did not show levels above the Ecuadorian standards. Pesticide concentrations were below 6 ppb, which is significantly lower than the reported No-Observed Effect Levels for shrimp and other aquatic organisms. However, the measured concentrations are higher than the European and American maximum residue levels in water for human consumption. Therefore, the Chaguana basin is showing to be a main concern for human health as around 7000 people are settled on the river banks, and they do not have potable water services.

For the model evaluation, the calibration process was done in three steps:

1. Flow calibration of the river basin with (only) three existing gauging stations.
2. Calibration of suspended sediment loadings performed with the sampling campaign results.
3. Calibration of environmental concentrations on the river with the sampling campaign results.

Both models predicted environmental pesticide concentrations on a monthly basis within the expected ranges. Differences between observed and predicted values were not significant. In conclusion, the developed data gathering process and model application proved to be useful for the prediction of pesticide concentrations in a data-poor environment.

SAMENVATTING

Ecuador heeft een lange traditie in bananenteelt. Heden ten dage bestaat meer dan 30% van de export van Ecuador uit bananen. Deze bananenteelt heeft geleid tot milieuzorgen bij andere sectoren die in dezelfde stroomgebieden in het land actief zijn. In 1994 stelde de garnaalsector dat bepaalde ziekten die in sommige garnaalkwekerijen voorkwamen, veroorzaakt werden door pesticiden afkomstig van de bananensector. Gebaseerd op deze situatie begon de Escuela Superior Politécnica del Litoral (ESPOL), een Ecuadoriaanse universiteit, een onderzoeksproject om mogelijke oplossingen voor dit milieuconflict in de Ecuadoriaanse rivierbekkens uit te zoeken. Deze Ph.D. thesis behoort tot de resultaten van dit project.

De thesis geeft kort de verschillen tussen de Ecuadoriaanse waterkwaliteitswetgeving en de aanvaardbare milieustandaarden met betrekking tot pesticidencontrole in de wereld weer. Ze schetst ook het algemeen pesticidengebruik in de Ecuadoriaanse bananenplantages. De meest gebruikte pesticiden in de bananenboerderijen zijn propiconazol, thiabendazol en imazalil.

De toepassing van screeningsmodellen bracht aan het licht dat de aquatische compartimenten meer effect ondervinden van imazalil en thiabendazole. Daarentegen heeft propiconazole significant meer invloed op het bodemcompartiment.

De voornaamste moeilijkheid in dit onderzoek was het proces om gegevens te verzamelen voor de de kalibratie en toepassing van de modellen. Ecuador is een arm ontwikkelingsland waar gegevens over het milieu niet op een continue basis worden verzaneld en bewaard, waardoor berekeningen in milieuzaken zoals de pesticidenvervuiling worden bemoeilijkt.

Om dit probleem op te lossen werd in het eerste deel van het onderzoek een methodologie voorgesteld voor het verzamelen en verwerken van elke vorm van informatie dat van enig nut kan zijn bij het evaluaren van pesticiden. Deze methodologie is nuttig voor toekomstig verwant onderzoek in ontwikkelingslanden als Ecuador om op een efficiënte en begrijpbare manier informatie te verwerken. De verzamelde gegevens werden verder omgezet naar direct bruikbare formaten die in modellen en geografische informatiesystemen kunnen worden ingeladen.

Het tweede deel van het onderzoek evalueert de AGNPS en SWAT modellen als mogelijke middelen om diffuse pollutieproblemen in te schatten in Ecuadoriaanse rivierbekkens. Als testbekken werd het Chaguana rivierbekken gekozen. Bananenboerderijen nemen ongeveer 30% van het totale oppervlak van 32000 Ha, vochtige bossen 26% en garnaalkwekerijen 6%. De bananenboerderijen bevinden zich vooral in de lagere gedeelten van het rivierbekken, de garnaalboerderijen bevinden zich nabij de monding.

Vier meetcampagnes werden uitgevoerd om gegevens te verzamelen voor het kalibreren van de modellen (waterkwaliteit en debieten) op 13 meetpunten langs de rivier onder verschillende weerscondities over een tijdspanne van een jaar. Laboresultaten toonden aan dat de meerderheid van de milieuparameters de Ecuadoriaanse standaarden niet overschreden. De pesticidenconcentraties waren lager dan 6 ppb, wat significant minder is dan de gerapporteerde “No-Observed Effect Levels” voor garnalen en andere aquatische organismen. Deze concentraties zijn echter wel hoger dan de Europese en Amerikaanse maximale residu niveau’s in water voor menselijke consumptie. Daardoor blijkt dat het Chaguanabekken een belangrijke zorg naar de menselijke gezondheid moet zijn vermits ongeveer 7000 mensen rond de rivier wonen en over geen drinkwatervoorzieningen beschikken.

Ter evaluatie van de modellen werd een kalibratieproces in drie stappen uitgevoerd:

1. Kalibratie van de debieten van de rivier met (slechts) 3 bestaande meetstations.
2. Kalibratie van de belasting met zwevende stoffen, uitgevoerd met de resultaten van de meetcampagne.
3. Kalibratie van de immissieconcentraties in de rivier met de resultaten van de meetcampagne.

Beide modellen voorspelden maandelijkse pesticideconcentraties binnen de verwachte grenzen. De verschillen tussen waargenomen en voorspelde waarde waren niet significant. Ter conclusie kan gesteld worden dat bewezen werd dat het ontwikkelde proces voor het verzamelen van gegevens en de modeltoepassingen nuttig is voor het voorspellen van pesticideconcentraties in een gegevensarme omgeving.

Curriculum Vitae

Personal

David Matamoros Camposano	Born 25/02/1964 (Guayaquil, Ecuador)
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Education

1981 – 1987	B.Sc. in Geotechnical Engineering at Escuela Superior Politécnica del Litoral, Faculty of Earth Sciences, Guayaquil, Ecuador.
1993 – 1995	M.Sc. at University of New Orleans, Faculty of Engineering, Department of Civil and Environmental Engineering, New Orleans, United States.
2000 – 2003	Ph.D. training in Applied Biological Sciences, Ghent University, Ghent, Belgium.

Additional Courses

2000	Land information systems (GIS): Ghent University, Belgium
2000	Ecotoxicology: Ghent University, Belgium
2000	Easy PC logging and instrument control: Ghent University, Belgium
2000	Modelling biosystem dynamics: Ghent University, Belgium
2000	Bioinformatics: Ghent University, Belgium

Study visits

2001 – 2002 Escuela Superior Politécnica del Litoral, VLIR – ESPOL Programme, Guayaquil, Ecuador.

Collecting water quality data, assessing water quality problems and evaluating the applicaton of river water quality models in Chaguana River Basin, Ecuador.

Employment

2000 – Present Department of Applied Mathematics, Biometrics and Process Control (BIOMATH), Faculty of Agricultural and Applied Biological Sciences, Ghent University, Belgium. Ph.D. student.
Research project: Predicting pesticide concentrations from Ecuadorian banana plantations.

1995 – 2000 Escuela Superior Politecnica del Litoral, Faculty of Earth Sciences, Lecturer in Civil Engineering Department, Guayaquil, Ecuador.

1995 – 1999 EFFICACITAS Environmental Consultant Company, Consultant Project Engineer, Guayaquil, Ecuador

1993 – 1995 University of New Orleans, Faculty of Engineering, Department of Civil and Environmental Engineering, Research Assistant, New Orleans, USA

1991 – 1993 Several Public and Private Engineering Firms, Independent Consultant, Guayaquil, Ecuador

1987 – 1991 CONSULNAC Inc. Soil Mechanics Laboratory, Senior Lab Assistant, Guayaquil, Ecuador.

1984 – 1986 University of Guayaquil, Institute of Advanced Research, Research Assistant.

Prizes

2003 First prize for the best paper presentation on the 2nd Science Workshop ESPOLCIENCIA, Escuela Superior Politécnica del Litoral, Guayaquil, Ecuador.

Membership of professional organizations

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Publications

Herrera P., Matamoros D., Espinel R., Cornejo M.P., Vanhuylenbroeck G., Van Biesen L., Cisneros Z., Duque J. and Vanrolleghem P.A. (2004). Information use, and water resources laws and policies in Ecuador. In: *Hydrology and Water Law - Bridging the Gap*. UNESCO – IWA (*in press*).

Matamoros D., Van Biesen L. and Vanrolleghem P.A. (2004). Development of a geographical information system for pesticide assessment on an ecuadorian watershed. In: *IWA World Congress and Exhibition*, September 19–24 2004, Marrakech, Morocco, (*accepted for presentation*).

Matamoros D., Guzman E., Bonini J. and Vanrolleghem P.A. (2004). AGNPS and SWAT Model Calibration for Hydrologic Modelling of an Ecuadorian River Basin under Data Scarcity. In: *IWA World Congress and Exhibition*, September 19–24 2004, Marrakech, Morocco, (*submitted*).

Verdonck F.A.M., Deksissa T., Matamoros D. and Vanrolleghem P.A. (2003). Dealing with variability in chemical exposure modelling in rivers. *Environmental pollution,* (*submitted*).

Matamoros D., Bonini J., Guzman E., Ramirez G. and Vanrolleghem P.A. (2002) Design and implementation of a measuring campaign to model pesticide impacts in an Ecuadorian watershed. *Wat. Sci. Tech., **46** (9), 37-45.*

Verdonck F. A. M., Deksissa T., Matamoros D., Vandenberghe V. and Vanrolleghem P.A. (2002). Spatio-temporal probabilistic environmental modelling. *Med. Fac. Landbouww. Univ. Gent, **67** (4), 205-208.*

Cornejo M. P., Matamoros D., Bayot B., Apolo I., Nolivos I., Cisneros Z. and Van Biesen L. (2002). Management of environmental problems through geographical information systems (GIS) in Ecuador. In: Proceedings of the International Conference BITWORLD 2002, Guayaquil, Ecuador, June 2002.

Matamoros D. and Vanrolleghem P.A. (2001) Pesticide assessment of the banana sector in an Ecuadorian watershed. *Med. Fac. Landbouww. Univ. Gent,* ***66*** *(2b), 863-872.*

International conferences and symposiums

IWA World Congress and Water Exhibition, Marrakech, Morocco, 19 – 23 September 2004 (accepted Oral presentation)

2nd Science Congress ESPOLCIENCIA, Escuela Superior Politécnica del Litoral, 13 November 2003, Guayaquil, Ecuador (Oral presentation).

5th World Congress on Information Technology BITWORLD, 3 – 5 June 2002, Guayaquil, Ecuador. (Oral and Poster presentation)

54th International Symposium on Crop Protection. 8 may 2002, Gent, Belgium.

IWA World Congress “Water & Wastewater Management for Developing Countries”, Kuala Lumpur, Malaysia, 26 – 27 October 2001 (Oral presentation)

International Seminar on Integrated River Basin Management – Seminario Internacional sobre Manejo Integral de Cuencas Hidrográficas (SIMICH 2001). Rosario, Argentina, 1 – 4 October 2001. (Poster presentation)

53rd International Symposium on Crop Protection. 8 May 2001, Gent, Belgium. (Poster presentation)

5th International Symposium, Systems analysis and computing in water quality management, WATERMATEX 2000, 18 – 20 September 2000, Gent, Belgium.

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