3. MATERIALS AND METHODS

3.1 Research project location and experimental units

The experimental work was mostly carried out at the Research Station on Wastewater Treatment and Reuse located in Ginebra town, Valle del Cauca region in Southwest Colombia. This station is run under a cooperative agreement between Universidad del Valle-Instituto Cinara and the regional Water and Sewerage Company, ACUAVALLE S.A ESP. One of the full-scale dispersion experiments was also carried out at the WSP system of Toro town located on the north of the region. Figure 3.1 shows the general location of the sites where the current research was conducted.

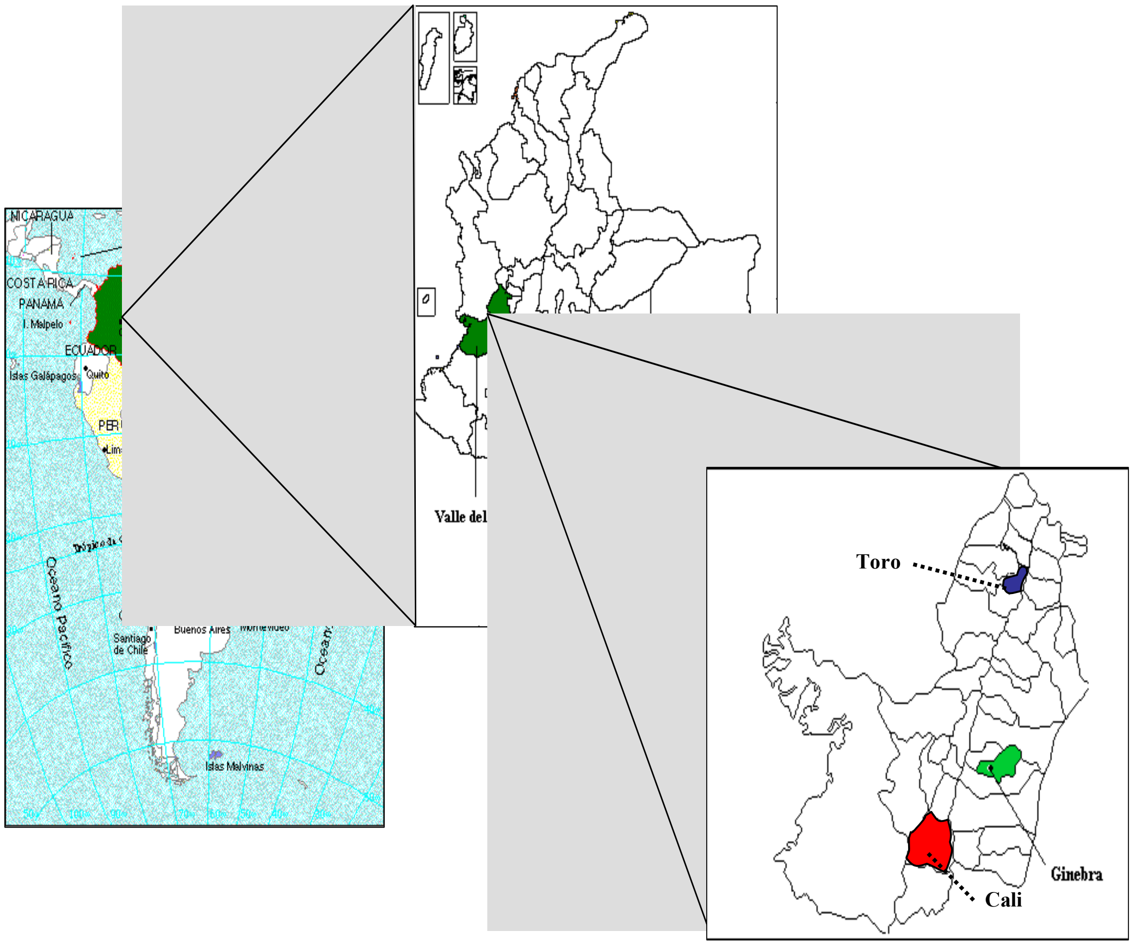

Figure 3.1 Location of research project.

The research station at Ginebra is located at the Wastewater Treatment Plant (WWTP) of the town and consists of a full-scale anaerobic pond followed by a secondary facultative pond. The general layout and features of the research station's infrastructure are displayed in Figure 3.2 and Table 3.1.

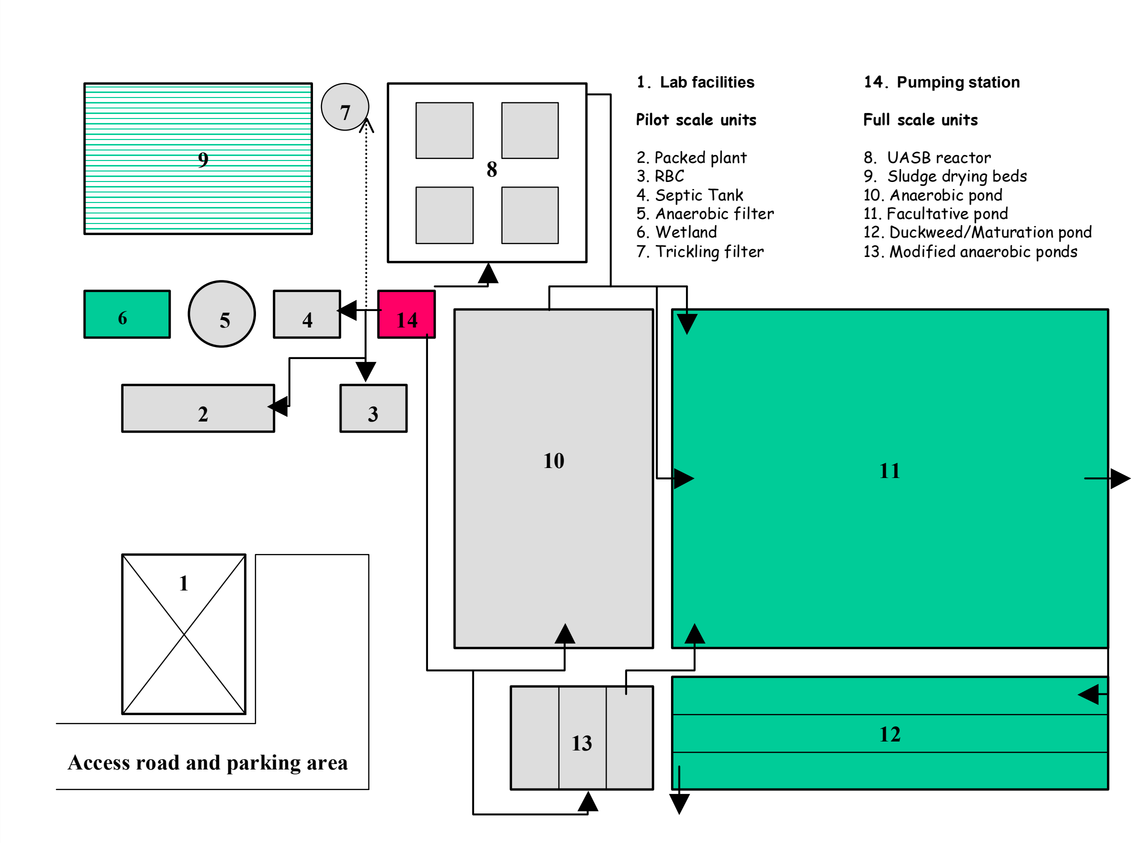

Figure 3.2 Layout of the research station at Ginebra, Colombia.

Table 3.1 General features of experimental units at Ginebra research station.

System	Scale	Flow (m^3/d)	HRT (d)	BOD rem. (%)	TSS rem. (%)	FC rem. Log
Anaerobic pond (AP)	Full	864	2.0	65.0	69.0	1
Facultative pond (FP)	Full	1728	7.0	35.0-45.0	30.0	1-2
Maturation pond (MP)	Pilot	864	3.0	20.0	20.0	2-3
UASB reactor	Full	864	0.3	70.0-75.0	65.0-75.0	< 1
Duckweed pond	Pilot	17.3	12-15	75.0-80.0	80.0-90.0	N.A
Modified pilot APs	Pilot	86.4	0.7-1.0	75.0-80.0	80.0-90.0	1
Septic tank	Pilot	1.7	0.5	40.0	40.0	N.A
Up flow anaerobic filter	Pilot	1.7	0.5	40.0-50.0	40.0	N.A
Constructed wetland	Pilot	1.7	0.4-2.0	30.0	33.0	N.A
RBC*	Pilot	8.6	0.3	80.0	90.0	< 1

* Includes an in-built settling compartment. N.A: Data not available.

Half of the total influent flow goes directly to the AP (i.e. 10-12 l/s) and the remaining half is split into the UASB (i.e. 9.0-10.0 l/s) and the pilot-scale units (i.e. 2.0-3.0 l/s). Data on trickling filter performance are not provided in the above table as this unit has only been recently commissioned. The wastewaters at the Ginebra and Toro sites are purely domestic in origin as these are two small municipalities, which are mainly residential with some agricultural activity. There is no industrial activity in any of the towns.

3.1.1 Full-scale anaerobic ponds

The first part of the research was developed in the full-scale APs at Ginebra and Toro sites. Table 3.2 shows ponds dimensions and design parameters and Figures 3.3 and 3.4 present pictures of both APs. The AP at Ginebra received wastewater after preliminary treatment (i.e. screening and grit removal), whilst Toro pond received sewage after screening only.

Table 3.2 Dimensions and design parameters of the APs at Ginebra and Toro.

Design criteria	Ginebra	Toro
Design period (years)	10	10
Population equivalent	9000	9650
Design flow (l/s)	19.9	25.6
Hydraulic retention time (h)	48.0	48.0
Volumetric organic load (kg BOD_5/m^3d)	0.12	0.12
Raw wastewater BOD_5 (mg/l)	235	235
Dimensions at mid depth (m) (L:W)	42 : 17	32 : 29
Dimensions at the top (m) (L:W)	52 : 26	40 : 37
Length to breadth ratio: (L:W)	2 : 1	1.1:1
Effective depth (m)	4.0	3.5
Reactor volume (m^3)	3437	4468
Inlet-outlet arrangement	Positioned half width (In) submerged PVC pipe (Out) surface channel In-out aligned	Positioned adjacent corners (In) surface channel (Out) surface channel In-out aligned

Source: ACUAVALLE SA ESP (1994).

Figure 3.3 Aerial view of the AP at Ginebra.

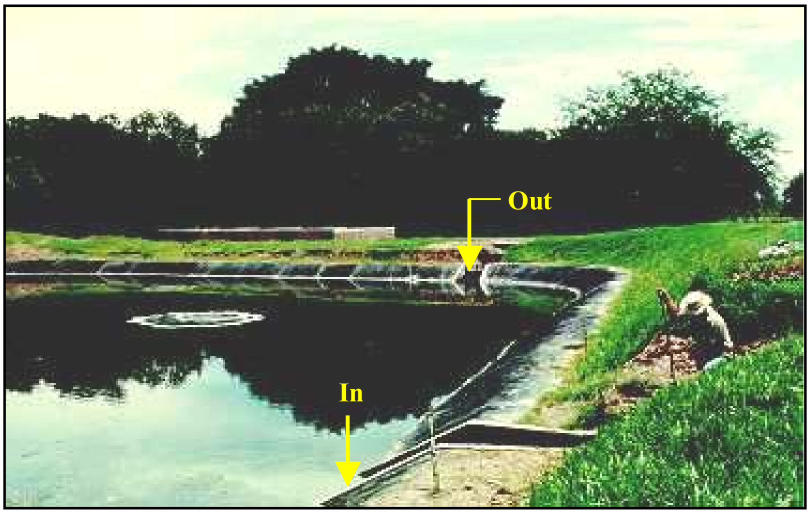

Figure 3.4 The AP at Toro.

3.1.2 Full-scale UASB reactor

The second part of the research was carried out on the full-scale UASB reactor recently constructed at that time in the station. Table 3.3 and Figure 3.5 show the main features of the reactor. The UASB received preliminary treated wastewater.

Table 3.3 Design criteria and dimensions of the UASB reactor.

Parameter	Value
Design period (years)	20
Design flows (l/s), average / maximum	10.8 / 19.4
Hydraulic retention time (h), average / minimum	7.1 / 3.9
Volumetric organic load (kg BOD_5/m^3-d), average / max.	0.71 / 1.29
Raw wastewater BOD_5 (mg/l)	209
Total depth / water depth (m)	4.3 / 4.0
Length / width (m) and [number of feeding points]	9.55 / 7.20 [24]
Total volume / effective volume (m^3)	295.7 / 275

Source: ACUAVALLE SA ESP (1994).

Figure 3.5 Aerial view of the UASB reactor at the Ginebra research station.

3.1.3 Pilot scale anaerobic ponds

The last experimental part of the research was carried out on three pilot-scale APs constructed adjacent to the full-scale AP at Ginebra (see Figure 3.2, No. 13). These pilot APs received preliminary treated wastewater. Table 3.4 and Figure 3.6 display the main characteristics of these experimental units where inlet-outlet arrangements and geometric shape were designed as recommended by Mara *et al.* (1992). Notice that some geometric features in AP2 changed depending on the experiment carried out. These changes in dimensions will be explained in the following section.

Table 3.4 Dimensions of the pilot APs and operation mode for both experiments.

Geometric features	Ponds		
	AP1	**AP2**	**AP3**
Length (m) [Top/Bottom]	11.30/8.70	11.30/8.60	11.30/8.40
Width (m) [Top/Bottom]	5.70/4.20	5.31/5.31	5.70/4.20
Water depth (m)	1.70	1.70/3.20*	1.70
Free board (m)	0.20	0.20	0.20
Effective volume (m^3)	88.4	91.0/104.0 *	82.0

* Values including the mixing pit provided for the second experiment.

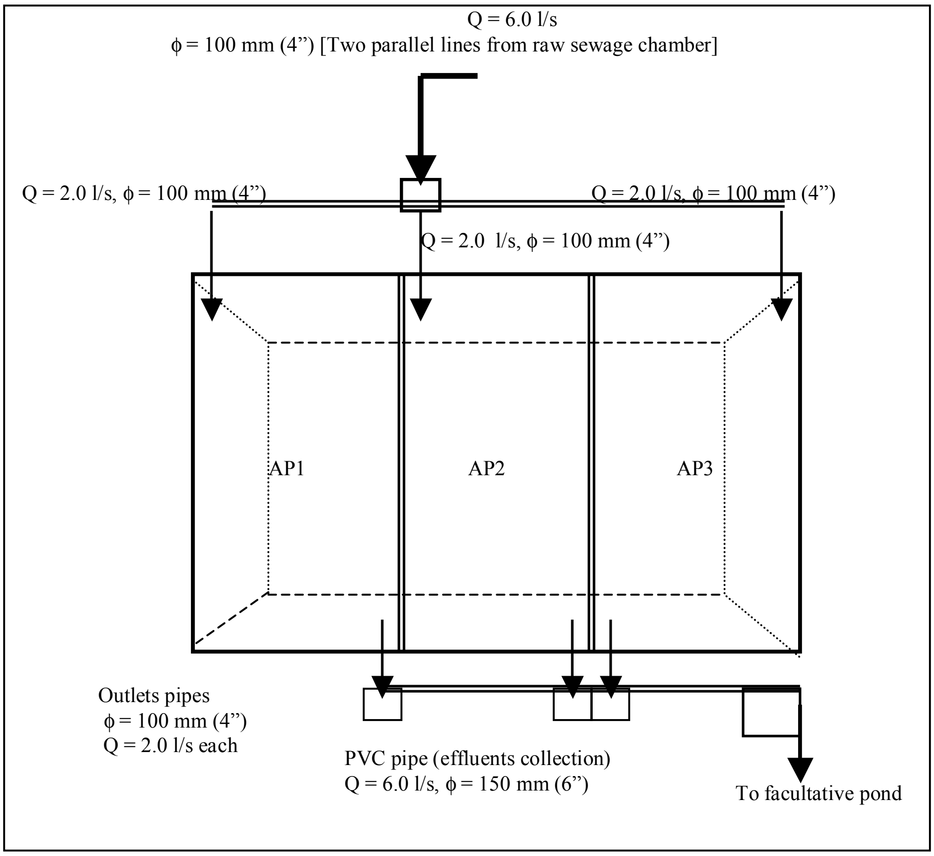

Figure 3.6 Schematic representation of the pilot-scale APs.

3.2 Experiments carried out

3.2.1 Full-scale experiments

Full-scale experiments were carried out first in the APs at Ginebra and Toro and secondly in the UASB reactor at Ginebra. A CFD modelling study of the AP at Ginebra was also carried out. Table 3.5 summarises the main aspects of these experimental activities.

Table 3.5 Description of full-scale experiments.

Description	Experimental unit	Number of runs	Period
Hydrodynamic study of full-scale APs	Ginebra / Toro	3 / 2	04/98-10/98, 09-99
CFD modelling of APs	AP at Ginebra	12	08/00-09/01
Start-up of UASB reactor	UASB at Ginebra	1	08/98-11/98
Hydrodynamic study of UASB reactor	UASB at Ginebra	4	08/99-12/99

Hydrodynamic study of full-scale APs. These experiments were aimed at finding out the hydrodynamic behaviour of two-full scale APs and its likely correlation with sludge accumulation (Ginebra AP) and incorrect inlet-outlet positioning (Toro AP). At the time of the fieldwork, the AP at Ginebra had been continuously working for five years and had a considerable degree of sludge accumulation (53 percent of its total volume). The AP at Toro had been working for nearly three years and had a lower degree of sludge accumulation (31 percent of its total volume).

[Li^+] was the tracer used in the dispersion studies carried out in both APs. This compound has been widely reported as a good tracer for water movement with the advantage of a very low solids attachment rate. The geometry of the APs was determined in the field by dividing the ponds into square cells (7.5 x 7.5 m). A coordinate system was set on the APs embankments and this allowed the determination of sludge profiles in each pond. The sludge depth was measured by the white towel test as described by Mara *et al.* (1992).

Preliminary tracer studies were carried out in both APs in order to establish the adequate LiCl mass to be added, tracer sampling time intervals at the pond outlet, and position and depth of in-pond sampling points. The general location of the sampling points is shown in Figure 3.7. More details on the experimental design of this part are given in Section 3.3.

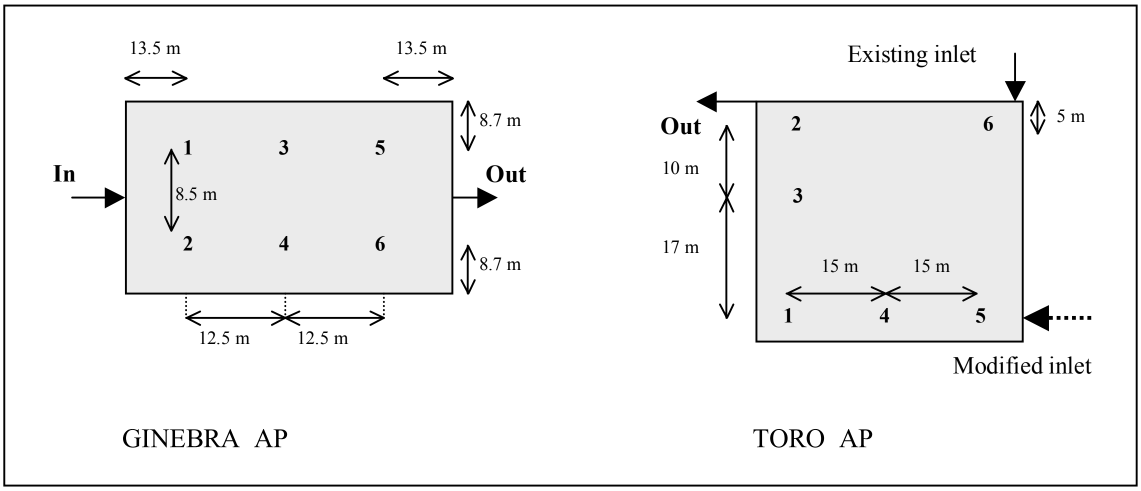

Figure 3.7 Sampling point location at the Ginebra and Toro APs.

CFD modelling of APs. This part of the research was aimed at studying in more depth the hydrodynamic features of the full-scale AP at Ginebra by applying a mathematical model. Data from the experimental dispersion studies presented earlier were used to calibrate the model. The MIKE 21 CFD package was used for the simulations (DHI, 1995). This is a gravity-flow modelling system that calculates velocities (currents), water depths and substances concentrations at each point of a two-dimensional (2D) calculation mesh. The model solves the hydrodynamic equations for unsteady flow in shallow waters. MIKE 21 is a depth-integrated model as it calculates the average horizontal velocity in the water depth by integrating the 3D Navier-Stokes equations in the vertical axis. This model solves the equations of continuity, horizontal and vertical momentum and transport. The main assumption is that vertical velocities are small, thus, vertical accelerations are negligible with respect to the horizontal component. Consequently, the vertical momentum equation is simplified to the hydrostatic pressure distribution. Meanwhile, dispersion phenomena are described by the advection-dispersion equations.

MIKE 21 is a comprehensive model able to integrate the study of different phenomena ranging from pure advection in small basins up to tidal studies and sediment transport phenomena in estuaries. However, for the present work only the hydrodynamic (HD) and advection-dispersion (AD) modules were used. The successful implementation of MIKE 21 for a particular situation comprises six sequential tasks as stated in its technical reference manual (DHI, 1995). These tasks are: definition of the problem, data collection, model setting up, calibration and verification, simulation runs and results presentation. The AP configuration at Ginebra (with 53 percent sludge accumulation plus available field data) was used to calibrate the model. The validation step was run on the same AP configuration but with a 30 percent sludge accumulation. Once confirmed that the CFD model was able to predict the experimental results of the hydrodynamic behaviour of the pond with an error less than 10 percent, then a total of 12 different configurations were simulated to find out likely improvements in the AP. More details of this study are presented in the experimental design section.

Start-up of UASB reactor. The UASB was first started-up in order to study its hydrodynamic behaviour under steady state conditions soon thereafter. An innovative methodology was used to shorten the start-up phase of the reactor. The first stage was the identification of a suitable and acceptable quality anaerobic seed (inoculum). Sludge samples from the bottom of the full-scale AP at the research station -treating the same wastewater- were taken. The AP was divided into four sectors according to the intensity of biogas bubbling observed. A composite sludge sample was taken from each sector at depths varying between 1.0 to 3.0 m. All these samples were analysed for specific methanogenic activity (SMA) and sludge concentration according to Dolfing (1985). Details of the SMA test are given in Section 3.3.3.

The results of SMA tests showed that sludge from the second section of the AP had the best properties to be used as seed. Thus, a total sludge volume of 55 m^3 (equivalent to 20% of the reactor volume) with an average concentration of 59 $kgVS/m^3$ was pumped from the AP into the UASB. Once seeded, an increasing up-flow velocity (i.e. a process called *selective pressure*) was applied to the reactor in order to select the sludge particles with better settling properties.

In the following step the reactor was left in batch mode for 10 days with raw wastewater. After this batch period the reactor was continuously fed and the influent flow rate was steadily increased up to the design value. Consecutive hydraulic loading rate increments were set based on the stable behaviour of process monitoring parameters for a given operating condition. Further detailed information on this part of the research is given in Section 3.3.

Hydrodynamic study of the UASB reactor. This experiment was aimed at determining the hydrodynamic features of the UASB operating under four different hydraulic loading rates. Figure 3.8 shows the reactor layout and sampling point locations during tracer experiments. The information gathered from this experiment along with the results from dispersion studies in the full-scale APs and the CFD modelling of the AP at Ginebra, allowed the design of the modified pilot-scale APs described in Section 3.2.2. The full-scale AP and the UASB at Ginebra received the same wastewater under the same environmental conditions.

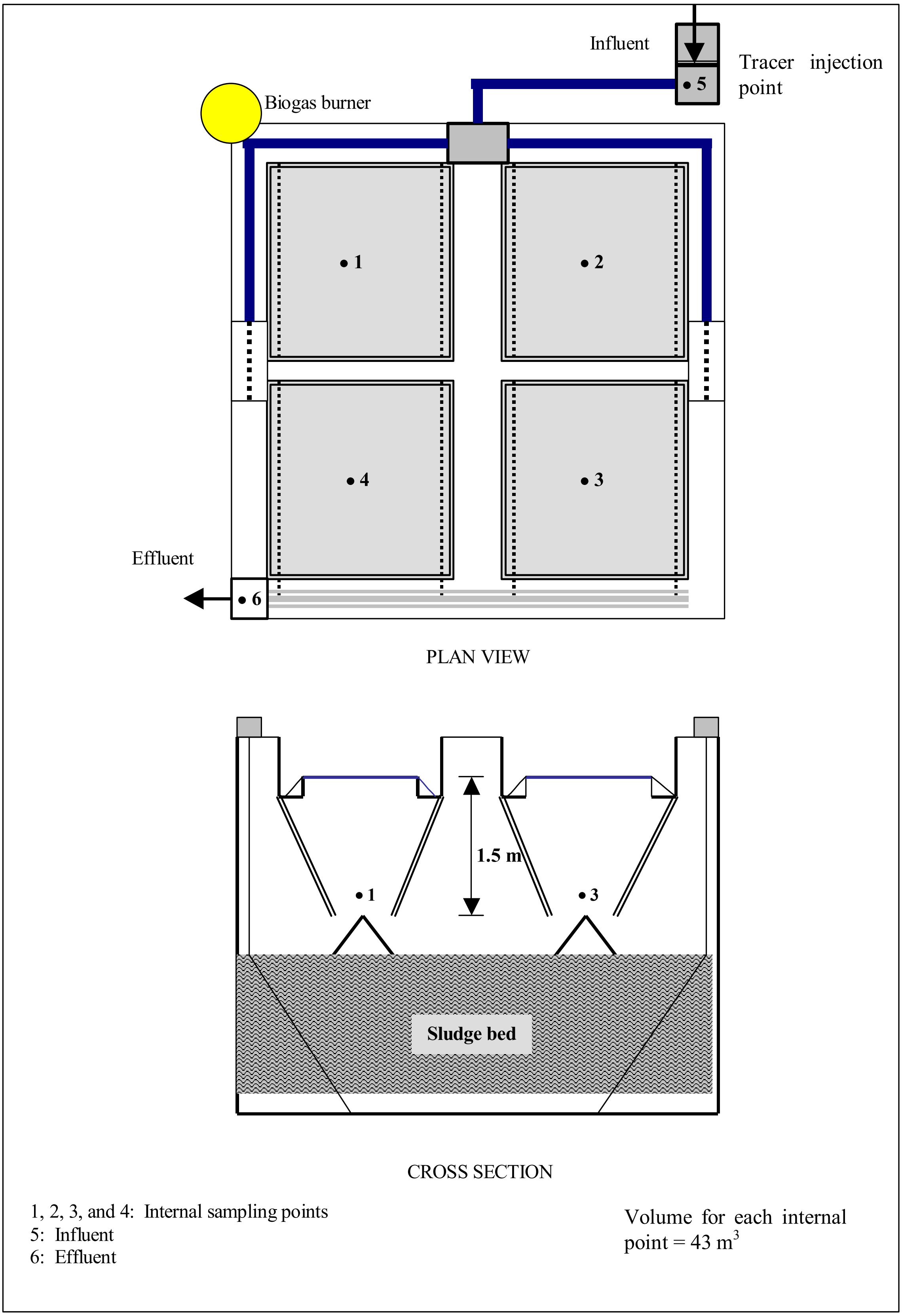

Figure 3.8 Layout of UASB reactor and tracer sampling point locations.

It is known that high-rate anaerobic reactors exhibit a mixing pattern close to the CSTR model and this explains to some extent their higher efficiencies compared to low-rate reactors. Therefore, likely modifications to a conventional AP configuration were proposed in subsequent pilot scale experiments -in order to improve its hydrodynamics and process performance- based on the mixing patterns found in the UASB reactor and the CFD modelling results from improved configurations.

The tracer used in the dispersion studies was [Li^+]. The four applied hydraulic loading rates produced four different HRT values in the reactor. Thus, two dispersion experiments per HRT were run so as to check for results replicability. Hydraulic loading rates varied from 7.7 to 15.5 l/s producing HRT values from 10.0 to 5.0 hours. Tracer sampling frequencies and LiCl masses added were defined based on preliminary experiments. Tracer sampling points were set based on previous work reported in the literature (Bolle *et al.,* 1985; Long, 1990). [Li^+] was determined at the reactor outlet and at four internal points as shown in Figure 3.8. Further details of the experimental work are given in Section 3.3.

3.2.2 Pilot-scale experiments

Table 3.6 summarises the experiments performed to determine the hydrodynamic behaviour and process performance of the modified pilot-scale APs shown in Figure 3.6. These experiments were designed taking into consideration most of the results from full-scale experiments and the CFD modelling study run on the AP at Ginebra. Figure 3.9 displays the configurations evaluated in Experiments I and II.

Table 3.6 Description of the pilot-scale experiments.

Description	Experimental units	Number of runs	Period
Experiment I: Hydrodynamics of pilot APs	A1, A2, A3	4	07/00-12/00
Experiment II: Hydrodynamics of pilot APs	A1, A2, A3	4	03/01-06/01
Experiment III: Process performance of pilot APs	A1, A2, A3	3	07/01-12/01

Experiment I on hydrodynamics of pilot APs. This experiment comprised the evaluation of a vertically baffled AP (VBAP), an AP fitted with two cross-sectional plastic nets (PNFAP) and a conventional AP. The VBAP had two baffles placed at L/3 and 2/3L. A free vertical space of 0.30 m along the pond width was left in each baffle to allow for water flow. Meanwhile, the PNFAP had two cross-sectional plastic nets placed at L/3 and 2/3L. The plastic net screens consisted of two curtain-like arrangements and each one had two layers of netting. Following the flow direction the first layer had a net with holes of 19 mm diameter and hexagonal shape (void ratio 0.77). The second layer had holes of 12.7 mm diameter and same hole shape (void ratio 0.69). Figure 3.10 shows details of these configurations. The conventional AP configuration was run as a control unit in both Experiments I and II.

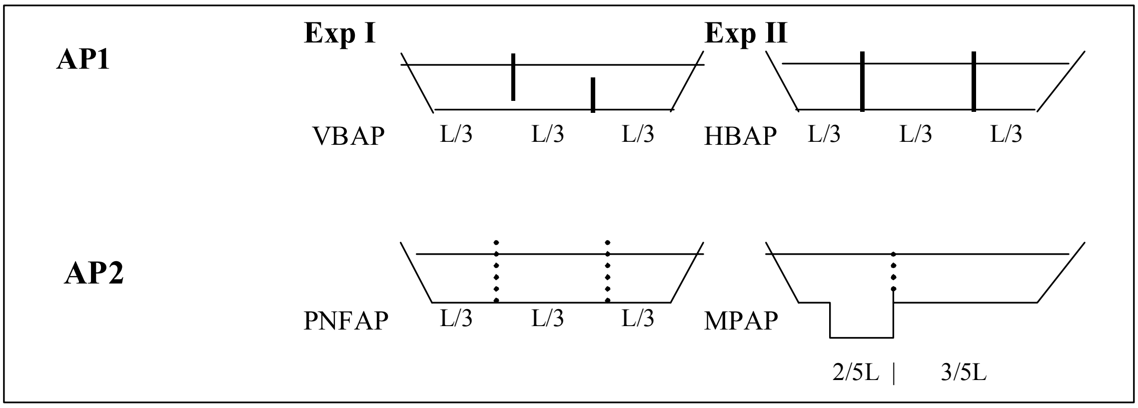

Figure 3.9 Mixing devices implemented in the modified AP configurations.

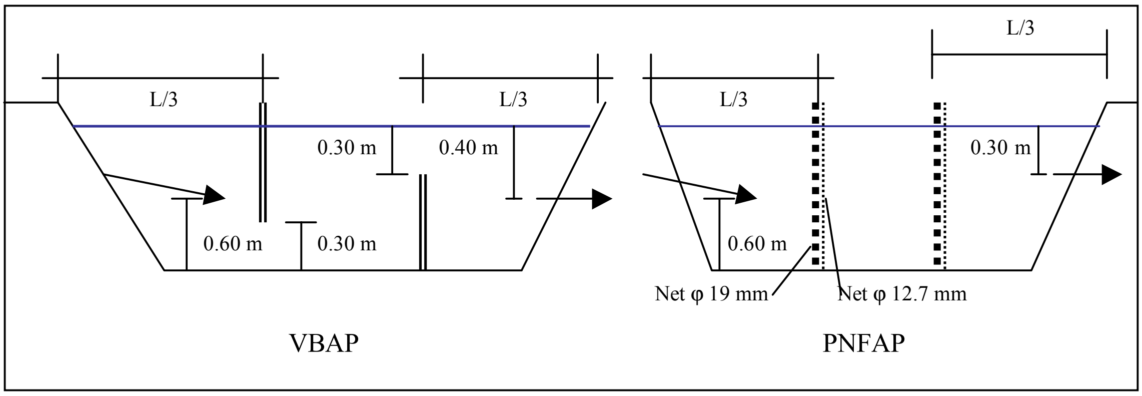

Figure 3.10 Details of VBAP and PNFAP configurations in experiment I.

Experiment II on hydrodynamics of pilot APs. This experiment evaluated a horizontally baffled AP (HBAP), a mixing pit fitted AP (MPAP) and a conventional AP. The HBAP had two baffles placed at L/3 and 2/3L. A free space (0.80 m width x 1.70 m height) was left at the end of each horizontal baffle to allow for water flow at the turning points. The MPAP was provided with an inlet up-flow mixing and reaction chamber resembling a UASB reactor. Wastewater was fed at the bottom of the chamber through three inlet points. Hence, the resulting density of feeding points (given a surface chamber area of 8.8 m^2) was 2.9 m^2/inlet point. This value is equal to the feeding point density of the UASB at Ginebra and it is also in agreement with design guidelines for

UASB reactors treating domestic sewage at temperatures equal to or more than 20 °C (van Haandel and Lettinga, 1994). Figure 3.11 shows the details of these configurations.

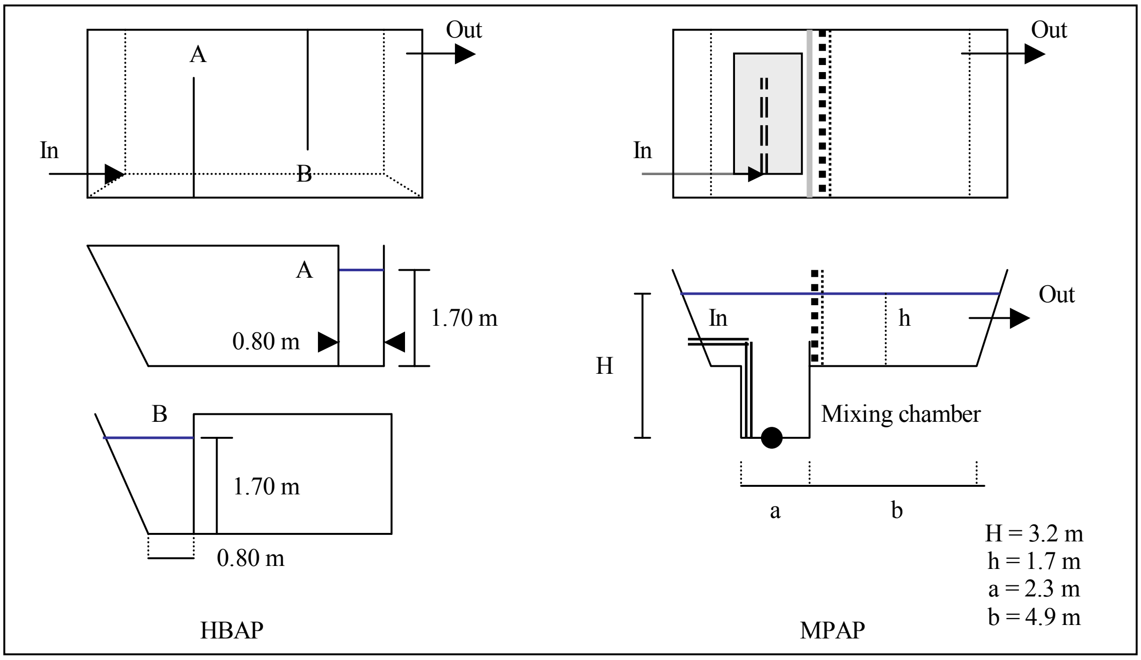

Figure 3.11 Details of HBAP and MPAP configurations in experiment II.

Once the wastewater passes through the mixing and reaction chamber in the MPAP, it flows horizontally through a quiescent settling zone and towards the outlet. The transition between the mixing chamber and the settling zone is done with a four-layered arrangement of the same plastic nets used in the PNFAP in experiment I. In this case, however, there are double consecutive layers of each net instead of one.

Experiment III on process performance of pilot APs. This experiment was the last fieldwork activity and it was aimed at studying process removal efficiencies of the best –in terms of hydrodynamics- two modified AP configurations evaluated in Experiments I and II. The conventional AP was also evaluated as control unit. HBAP, MPAP and conventional AP were evaluated in steady state conditions during 22 weeks (5.5 months) under three different hydraulic loading rates. The response to each hydraulic loading rate applied was evaluated for six weeks under steady state conditions in each AP. Periods of two weeks were allowed between loading rate changes to re-establish steady state conditions. The latter was judged as achieved when differences between values of the removal efficiency for a given parameter were less than or equal to 10 percent. The following section provides details of the experimental design for all the experiments described above.

3.3 Experimental design

3.3.1 Hydrodynamic study of full-scale APs

Type of experiment. The experiment was designed as a comparative study with two main factors: degree of sludge accumulation (Ginebra AP) and inlet-outlet positioning (Toro AP).

Dispersion studies. Three runs were carried out at Ginebra AP for three different sludge accumulation volumes. Two runs were performed at Toro AP: one with the existing inlet-outlet arrangement and the other with a modified inlet layout (see Figure 3.7). Table 3.7 summarises the [Li^+] mass added in each run and the respective C_o values. The LiCl solution was prepared the day before each run to allow for enough cooling time given its exothermic behaviour. A funnel-like plastic pipe was used in every run to apply the tracer slug at the same point in the influent stream. Control samples of raw wastewater and sludge were taken to check for [Li^+] background contents and likely [Li^+] adsorption onto solids, respectively. An average of 20 grab samples for [Li^+] determination were taken in each AP outlet and internal points. The latter samples were taken at the surface and at 1.0 m depth with a submerged bottle sampler.

[Li^+] concentrations were determined by an atomic absorption spectrophotometer (Perkin Elmer model, S100 PC, air-acetylene flame method at 670.80 nm) with a minimum detection limit of 0.01 mg/l. Preliminary tests showed that [Li^+] concentration decreased below its detection limit four days after tracer dosing. Thus, tracer sampling was done for four days in all runs. One ml of HNO_3 (EM Science, 69% v/v) was added to the effluent samples containing [Li^+] and refrigerated as recommended in *Standard Methods* (APHA, 1992).

Table 3.7 Summary of [Li^+] added in each tracer run.

Run	W LiCl (g)	W [Li^+] (g)	Co * (mg Li^+/l)
Preliminary Ginebra	1803.5	294.5	0.09
Ginebra 1 (53% sludge)	1801.3	292.1	0.08
Ginebra 2 (30% sludge)	3000.0	491.4	0.14
Ginebra 3 (20% sludge)	3093.3	505.2	0.15
Preliminary Toro	2010.0	328.3	0.07
Toro 1 (adjacent in-out layout)	1450.0	236.8	0.05
Toro 2 (diagonally opp. in-out)	1450.0	236.8	0.05

* Calculated as W [Li^+] divided by the AP volume (see figures in Table 3.2).

Tracer data sets (RTD curves) were analysed with the dispersion model applied to a closed vessel boundary condition (Levenspiel, 1999). The closed vessel assumption fits the APs evaluated as flow patterns in the inlets and outlets differ from the main flow pattern within the reactors. The wastewater flowed into the APs via a pipe (pressure flow) in the Ginebra AP and a gravity flow channel in the Toro AP. Effluent left both APs through free discharge rectangular weirs.

The basic dispersion model equations for continuous and discrete data are listed below. Equations 3.4, 3.5 and 3.6 for discrete data were used to calculate the hydrodynamic parameters of interest (i.e. mean hydraulic retention times, dispersion numbers and flow deviations).

$$\bar{\theta} = \frac{\int_0^\infty \theta . E_\theta d\theta}{\int_0^\infty E_\theta d\theta} \tag{3.1}$$

$$\bar{\theta} = \bar{t} / HRT_t \tag{3.2}$$

$$\sigma^2 = \frac{\int_0^\infty \theta^2 E_\theta d\theta}{\int_0^\infty E_\theta d\theta} - \bar{\theta}^2 \tag{3.3}$$

$$\bar{\theta} = \frac{\sum \theta_i E_{\theta i} \Delta\theta_i}{\sum E_{\theta i} \Delta\theta_i} \tag{3.4}$$

$$\sigma^2 \cong \frac{\sum \theta_i^2 E_{\theta i} \Delta\theta_i}{\sum E_{\theta i} \Delta\theta_i} - \bar{\theta}^2 \tag{3.5}$$

$$\sigma^2 = 2\delta - 2\delta^2 (1 - e^{-1/\delta}) \tag{3.6}$$

where $\bar{t}$ = Mean hydraulic retention time (d)

HRT_t = Theoretical hydraulic retention time (V/Q) (d)

σ^2 = Variance of RTD curve data

δ = Dispersion number

$\theta_i = t_i / HRT_t$

$E_i = C_i / C_o$

Process performance. 12-h composite samples of raw wastewater and AP effluent were taken daily during the tracer experiments. These samples were analysed for pH, temperature, COD, BOD_5, TSS and settled BOD_5. Predominant wind direction was recorded on-site and the average wind speed was estimated from three years historical data records at local meteorological stations. Flow readings were recorded every hour from 0600 to 2000 h during the four days of every tracer run. For this purpose, a calibrated V-notch weir was used at the Ginebra AP and a Parshall flume at the Toro AP. All laboratory analyses were carried out according to *Standard Methods* (APHA, 1992).

Statistical analysis of data. Tracer data sets were analysed by using equations 3.4, 3.5 and 3.6. Equations 3.4 and 3.5 calculate the first and second momentums of the RTD curves respectively. The physical meanings of these parameters are the hydraulic efficiency of the reactor ($\bar{\theta} = \bar{t} / HRT_t$), and its advection-dispersion features (σ^2 and δ).

Process performance data were analysed by descriptive statistics such as variation ranges, arithmetic averages, standard deviations and coefficient of variation. The Excel 2000 (Microsoft Corporation) package was used to carry out all statistical analyses.

3.3.2 CFD modelling of anaerobic ponds

Type of study. This study was mainly a desk activity aimed at forecasting likely improvements of hydrodynamic features in a full-scale AP under different configurations. For this purpose, the 2D-CFD MIKE 21 package was used to study the AP at Ginebra site. This study also included the collection of fieldwork information and data from the dispersion studies carried out at the site and described in Section 3.3.1.

AP configurations modelled. The alternatives depicted in Figure 3.12 were studied as some of the most likely options to improve new physical designs or upgrade existing malfunctioning units on the basis of previous work reported in the literature and the current AP configuration at Ginebra site.

Table 3.8 presents the main factors studied and further details of the configurations evaluated.

Configurations A, B, and C conform to the dispersion studies described in Section 3.3.1. Thus, they were used to calibrate and validate the CFD model. Configurations D, E and F included the baffling factor, but were geometrically equal to the full-scale AP. Configurations G, H and I included changes in inlet-outlet positioning combined with baffling, but kept the same geometry of the full-scale AP.

Configurations J, K and L kept the same volume and surface area of the full-scale AP, but arranged in a square geometry.

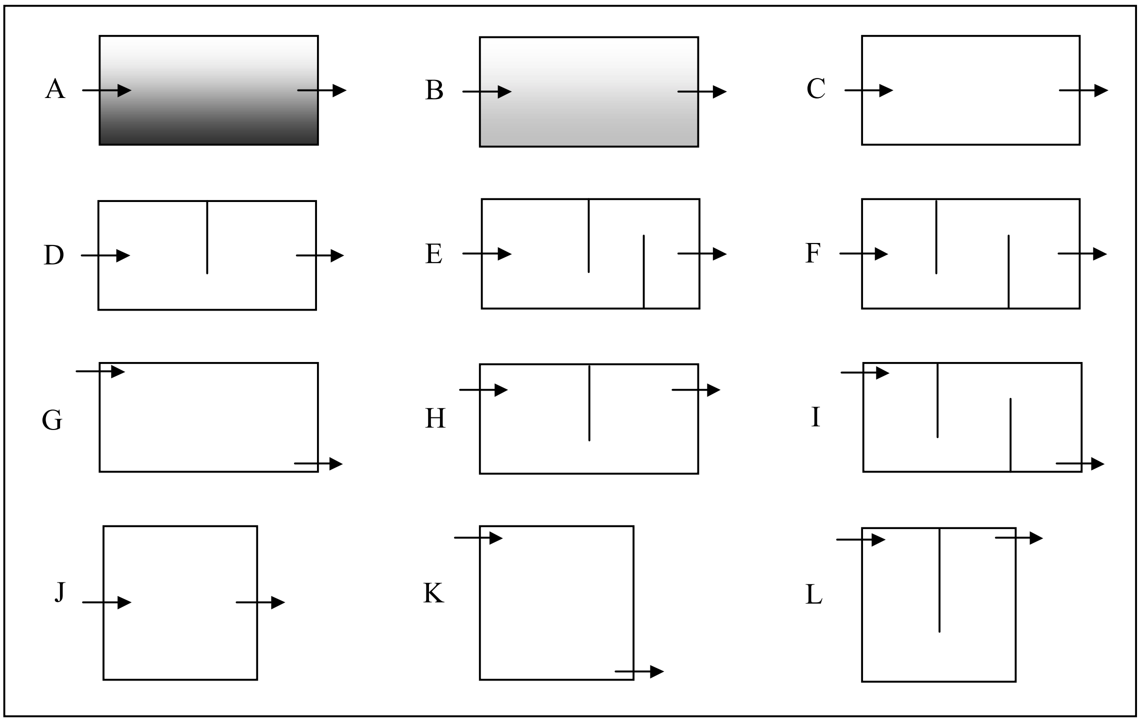

Figure 3.12 Schematic representation of AP configurations modelled.

Table 3.8 Anaerobic pond configurations and factors studied.

Factor	Configurations	Remarks
Sludge accumulation	A, B, C	A: 50% sludge volume, B: 30% sludge volume C: Desludged pond
Baffling	D, E, F	D: One baffle at L/2, E: Baffles at L/2 and ¾ L F: Baffles at L/3 and 2/3 L
In-out positioning + baffling	G, H, I	G: Diagonally opposite in-out, H: One baffle at L/2 I: Baffles at L/3 and 2/3 L
Geometric shape	J, K, L	J: Square shape, K: Diagonally opposite in-out, L: One baffle at L/2

Fieldwork activities. The main activities comprised a detailed characterization of existing inlet-outlet arrangements, on-site velocity field measurements, water levels measured at inlet and outlet regions, sludge profile determinations, influent flow readings and collection of hydrometeorological information. All this information was organized and used to feed the 2D-CFD model input requirements.

Problem definition. The AP at Ginebra site has a simple configuration with a single inlet and outlet and it is also a closed system. The latter means that liquid particles can only enter and leave the pond once. Particular assumptions were not made on the type of mixing pattern expected. Circulation patterns were considered in terms of velocity distributions, which in turn are affected by the pond base shape and water depth changes. The modelling area was equal to the AP surface area since likely hydrodynamic changes were studied along the entire reactor.

Data collection. Information was collected as previously mentioned and fieldwork campaigns were developed in December 2000. A coordinate (x, y) system was established to carry out sludge profiles by using the white towel test (Mara *et al.*, 1992). In-pond liquid velocities were measured by using watertight PVC pipes (1.2 m lengths stoppered at both ends) partially submerged. A submergence of about 90% was achieved by putting small amounts of sand into the pipes. The average velocity values measured in different points were reproducible and judged reliable. Experimental velocity values varied from 1.89×10^{-3} to 7.68×10^{-3} m/s, depending on point location. Differences in water levels along the pond were measured by using topographic electronic equipment and the maximum value recorded was 0.1 cm. This confirmed that likely vertical velocity fields were not important and model assumptions were consistent with field conditions.

Model setting up. A rectangular uniform mesh of finite elements with 2912 calculation nodes represented the AP. Boundary conditions were defined according to field data and model requirements. Initial conditions such as inflow rate, water levels, sludge profiles, mesh size, simulation time and inlet-outlet features were defined prior to model calibration. The mesh resolution is a function of calculation time, details of flow field and physical phenomena. Calculation times in CFD modelling processes depend on area size, resolution of the calculation mesh and calculation time intervals. Thus, Courant number is a parameter that accounts for the interrelation between these factors so as to achieve computational stability in mathematical simulation. Courant number in 2D models is given by the following equation.

$$C_r = \Delta t.c\left[\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}\right]^{1/2} \qquad (3.7)$$

where C_r = Courant number (dimensionless)

Δt = time interval (s)

c = wave celerity ($c = \sqrt{g.h}$) (m/s)

h = water depth (m)

Δx = mesh size in x-axis (m)

Δy = mesh size in y-axis (m)

A Courant number of 20 showed a good computational stability given the uniformity of bottom sludge profiles found in the AP. The total modelled area was 1456 m^2 and a calculation mesh of square cells (0.5 m x 0.5 m) was found to produce reasonably good results within reasonable time and computational requirements.

Calibration and verification. This stage allowed fine-tuning of the CFD model by comparing a simulation run results with experimental values. The goal was to obtain minimum differences between the model outputs and field data. The following parameters were adjusted in order to obtain the best representation of hydrodynamic phenomena: water levels, inflow rate, pond base roughness coefficient, wind direction, wind speed and friction plus dispersion number. The AD module was calibrated by using the experimental data obtained in the same AP for a 53% sludge accumulation. The existing inlet device (i.e. a PVC pipe 200 mm in diameter) was simulated by a narrow channel whose dimensions were calculated based on hydraulic similarity (i.e. flow rate and velocity values). The existing outlet channel was modelled as it was.

Simulation runs and results presentation. The MIKE 21 package was applied to study hydrodynamic and advection-dispersion phenomena in the AP configurations shown in Figure 3.12, once calibration was completed satisfactorily. The output interface allows results to be presented either graphically (2D and 3D charts or videos) or numerically. For the purpose of this work, however, only 2D flow fields and normal RTD charts are presented.

Resources. The MIKE 21 CFD package was used under an academic license held by the School of Natural Resources and Environmental Engineering (formerly Fluid Mechanics Department) at Universidad del Valle in Cali, Colombia. The package was run under the Windows ME (Microsoft Corp) operating system. Hardware resources comprised a networked PC equipped with an Intel Pentium III processor running at 700 MHz and 20 GB hard disk.

Analysis of data. Flow velocity fields and RTD curves were analysed together with dispersion numbers and retention factors to find the best AP configuration. The potential of CFD modelling as a design and optimisation tool for ponds hydrodynamics is also discussed. It has to be said that the hydrodynamic modelling performed with the MIKE 21 package takes into account only the hydrodynamic phenomena related to water movement. Hence, hydrodynamic disturbances induced by biogas bubbling from the pond base (sludge layer) are not included in the mathematical algorithm and model outputs.

3.3.3 Start-up of UASB reactor

Type of experiment. This activity was designed as a one-factor experiment steadily varied in time. Thus, the applied hydraulic loading rate was gradually increased in the start-up phase once the reactor was seeded and continuous feeding started.

Reactor inoculation. Once seeded, the UASB was fed with wastewater under varying flow conditions as follows: the initial flow rate applied for 24 hours was the maximum allowed by the hydraulic capacity of the system. After this, seeded sludge was exposed to a further selection process by the application of increasing up-flow velocities as shown in Table 3.9. This procedure was aimed at improving settling properties of the remaining biosolids particles.

Table 3.9 Up-flow velocities applied during inoculation.

Flow rate (l/s)	Up-flow velocity (m/h)	HRT (h)
10	0.56	7.7
15	0.83	5.1
20	1.11	3.9

The UASB was left in batch mode for 10 days once the above velocities were applied. During this period the COD concentration was monitored in the supernatant until a reduction of 70 percent was detected in relation to the influent COD at the beginning of the batch mode period.

Gradual flow rate increase. This phase started with continuous feeding of the reactor at a flow rate of 3.1 l/s, corresponding to an average HRT of 24.9 h. Table 3.10 shows the hydraulic loading rates applied during the start-up.

Table 3.10 Average flow rates and related HRT values applied during start-up.

Average flow rate applied (m^3/h)	Average flow rate applied (l/s)*	n / σ	Average HRT (h)
11.1	3.1	30 / 1.49	24.9
17.3	4.8	30 / 1.02	16.1
19.5	5.4	25 / 0.72	14.3
28.3	7.9	25 / 0.43	9.8
33.6	9.3	25 / 0.56	8.3
41.6	11.5	25 / 0.86	6.7

* Flow rate was controlled via a calibrated V-notch and a flow valve.

The low flow rates applied at the beginning were aimed at adapting gradually the seeded biomass to the design loading rates and also at preventing early wash out of biosolids from the reactor. The hydraulic loading rate was increased based on steady state behaviour of process monitoring parameters for a given operating condition. The goal of the whole procedure was to bring the UASB to an average operating HRT of 7.0 h (design value) under steady state conditions.

Process performance. The reactor behaviour was monitored during the start-up phase through different parameters. Temperature, pH, Volatile Fatty Acids (VFA), Buffer Index (BI), total COD, filtered COD, BOD_5, TSS and Settleable Solids were monitored in the liquid phase. TS, VS, Methanogenic Activity (MA) and Settleability tests were performed on sludge samples. Biogas production readings were taken from a gas meter installed upstream of the biogas burner. Flow readings were recorded and adjusted daily throughout the start-up period as shown in Table 3.10. Table 3.11 summarises the monitoring programme and Table 3.12 shows the analytical techniques and laboratory equipment used.

Table 3.11 Summary of sampling campaign.

Parameter	No of samples	Type of sample
	Liquid phase	
pH	51	Grab
Temperature	51	Grab
VFA	35	Grab
BI (Buffer index)	36	Grab
COD_t	29	Composite
COD_f	18	Composite
BOD_5	14	Composite
TSS	25	Composite
Settleable Solids	25	Composite
	Solid phase	
TS	6	Grab
VS	6	Grab
Settleability tests	2	Integrated*
SMA	2	Integrated*
	Gaseous phase	
Biogas flow rate	18	Meter readings

* Samples from four sampling ports were integrated into a single volume.

The specific methanogenic activity (SMA) test was developed according to the procedure of Dolfing (1985) and the modifications recommended by Molina and Alazard (1997), at a temperature of 30 °C and a pressure of 689 mm Hg. The calculations of the SMA values were based on the maximum slope of the methane volume versus time curves, the conversion factor of methane to COD, the volume of sludge inoculated and the concentration of VS in the sludge sample.

Table 3.12 Analytical techniques and laboratory equipment used.

Parameter	Method	Equipment
pH	4500*	ORION pH-meter 230A
Temperature	2550C*	ORION T-meter 230A
VFA	According to Field (1994)	Stirrer, Hotplate and Titration equipment
BI	According to Rojas (1994)	Titration equipment
COD	5220*	HACH Micro-digestion reactor, Spectronic 21D
BOD_5	Respirometric	OXITOP kit, Incubator
TSS	2540D*	Filtration kit, furnace, analytical balance
Settleable Solids	2540F*	Imhoff cones
TS	2540B*	Furnace, analytical balance
VS	2540E*	Crucible, analytical balance
Settleability	213B*	Glass cylinder (250 ml)
SMA	According to Dolfing (1985)	Gas chromatograph GC-8A SHIMADZU, Serum bottles

* *Standard Methods* coding.

Statistical analysis of data. Start-up process monitoring data were analysed by descriptive statistics (i.e. variation ranges, arithmetic averages, standard deviations and coefficient of variation). Correlations between different variables were performed and behaviour of different parameters with time was plotted. The Excel 2000 (Microsoft Corporation) package was used to carry out all statistical analyses of data and graphs.

3.3.4 Hydrodynamic study of UASB reactor

Type of experiment. This study was statistically designed as a one-factor experiment. The factor intentionally varied at four levels (i.e. treatments) was the inflow rate, which in turn produced four different values for the reactor HRT, as shown in Table 3.13.

Table 3.13 Experimental conditions for the hydrodynamic evaluation of the UASB.

Level (Treatment)	Flow rate applied (l/s)	HRT (h)	Tracer sampling period (h)
1	7.7	10	30
2	9.7	8	26
3	12.8	6	20
4	15.5	5	17

Preliminary tracer tests with a HRT of 6.7 h (value achieved after start-up) were performed so as to define the tracer sampling period, LiCl mass to be added and tracer injection point. Table 3.13 shows that 3 x HRT was found as the best sampling period since the [Li^+] concentration fell below its detection limit around this time.

Dispersion studies. Two tracer runs were performed for each flow rate condition so as to check for results replicability. A solution containing 519 g LiCl (84.9 g Li^+) was applied in every tracer run. The expected [Li^+] average concentration in the reactor volume was C_o = 0.30 mg/l. The LiCl solution was prepared the day before each run to allow for enough cooling time given its exothermic behaviour. Control samples of raw wastewater and reactor sludge were taken to check for [Li^+] background contents and likely [Li^+] adsorption onto biosolids, respectively. Table 3.14 summarises the amount of grab samples taken for [Li^+] determination per sampling point and per run. The internal points were sampled at 1.50 m depth as shown in Figure 3.8.

[Li^+] concentrations were determined by an atomic absorption spectrophotometer (Perkin Elmer model, S100 PC, air-acetylene flame method at 670.80 nm) with a minimum detection limit of 0.01 mg/l. One ml of HNO_3 (EM Science, 69% v/v) was added to the effluent samples containing [Li^+] and refrigerated as recommended in *Standard Methods* (APHA, 1992).

Table 3.14 Amount of tracer samples taken per sampling point and per run.

Level (Treatment)	Flow rate applied (l/s)	HRT (h)	No of samples
1	7.5	10	55
2	9.7	8	50
3	13.4	6	37
4	15.3	5	35

Tracer data sets (RTD curves) were analysed with the dispersion model applied to a closed vessel boundary condition (Levenspiel, 1999). The closed vessel assumption fits the UASB studied as flow behaviour in inlet and outlet differs from the main flow pattern within the reactor. Water flows into the reactor via pipes (pressure flow) and leaves the reactor through slow-flowing free discharge rectangular gutters.

Equations 3.4, 3.5 and 3.6 for discrete data were used to calculate the hydrodynamic parameters of interest (i.e. mean hydraulic retention times, dispersion numbers and flow deviations).

Process performance. Organic matter removal was monitored during the tracer runs. Total COD, filtered COD, TSS and settleable solids were measured according to the monitoring campaign shown in Table 3.15. Temperature and pH were measured as process control variables. Flow rates applied were controlled via a calibrated V-notch weir and a flow valve. Flow readings were recorded hourly throughout each of the tracer runs. A gas meter installed upstream of the biogas burner permitted recording of the biogas production rate. This parameter, however, could only be measured during the first run (HRT = 10 h) as the gas meter broke down. Hence, from the second run on the biogas production was estimated from organic load removal by using Equation 3.8 given by van Haandel and Lettinga (1994) and biogas production data from the start-up phase.

$$Q_b = \frac{f_m * 1.28T}{Pm} \tag{3.8}$$

where Q_b = *b*iogas volume per kg COD digested (l/kg COD)

f_m = fraction of collected methane (typically between 0.5 to 0.8)

P_m = *p*artial pressure of methane in the reactor (0.75 atm at 25 °C)

T = temperature in degrees K

Table 3.15 Summary of sampling campaign.

HRT (h)	Sampling period (h)	Parameters	Type of sample	Frequency	No of samples inf. / effl.
10	30	CODt, CODf, TSS and Set. Solids	Composite	Every 5 h	6 / 6
8	24		Composite	Every 4 h	6 / 6
6	18		Composite	Every 3 h	6 / 6
5	15		Composite	Every 3 h	5 / 5

Microbiological indicators (FC and helminth eggs) were also measured in grab samples at each sampling period to estimate their removal efficiencies in the UASB. Table 3.16 presents the analytical techniques and laboratory equipment used.

Table 3.16 Analytical techniques and laboratory equipment used.

Parameter	Method	Equipment
pH	4500*	ORION pH-meter 230A
Temperature	2550C*	ORION T-meter 230A
COD	5220*	HACH Micro-digestion reactor, Spectronic 21D
TSS	2540D*	Filtration kit, furnace, analytical balance
Settleable Solids	2540F*	Imhoff cones
Faecal coliforms	Membrane filtration	DelAgua membrane filtration kit. Oxoid membrane lauryl sulphate broth
Helminth eggs	Ayres and Mara (1996)	Centrifuge, PLEUGER microscope, McMaster counting chamber

* *Standard Methods* coding.

Statistical analysis of data. The following scientific hypothesis was stated for this experiment: "*The hydrodynamic behaviour of the UASB may affect its process performance*". In other words, there may be noticeable differences in the reactor's removal efficiency caused by variable hydrodynamic conditions. In statistical terms, this hypothesis may be expressed as:

$$H_o: \mu_1 = \mu_2 = \mu_3 = \mu_4 \quad (3.9)$$

$$H_a: \text{not all } \mu\text{'s are equal} \quad (3.10)$$

The null hypothesis (Equation 3.9) states that the mean removal efficiencies or effluent concentrations of a given parameter for each treatment (flow rate value) are all equal. Meanwhile, The alternate hypothesis (Equation 3.10) states that not all of the means are equal and so there is a difference between treatments (flow rate values). A one-factor ANOVA analysis allowed testing the above hypotheses in order to accept/reject H_o with a confidence level of 95 percent. At the same time, it was necessary to apply a technique to compare all possible pairs of means so as to find which of them were equal. Tukey's test for multiple comparisons was applied for this purpose as described in the literature (Montgomery, 1997; Kvanli *et al.,* 2000).

The one-factor ANOVA and Tukey tests were run for the effluent concentrations data of COD, CODf and TSS in order to accept/reject the statistical hypotheses. Descriptive statistics were applied to single parameters and correlations between different variables were also performed. SPSS release 10.1.3 (SPSS Inc.) and Excel 2000 (Microsoft Corporation) packages were used to carry out all statistical analyses of data.

3.3.5 Hydrodynamic studies on the pilot-scale APs

Type of experiment. These studies were statistically designed as two-factorial comparative experiments. The factors intentionally varied were hydraulic loading rate and in-pond mixing device. Table 3.17 shows the factors and levels (treatments) evaluated in each experiment and Figure 3.13 displays pictures of the pilot APs.

Both experiments were carried out in the same experimental APs shown in Figure 3.6 and during the time periods shown in Table 3.6. Both periods corresponded to dry seasons so as to minimise any confounding factors related to varying climatic conditions. The levels of both factors in Table 3.17 were randomly assigned with the purpose of reducing error sources. A total of 12 combinations (treatments) resulted from each experiment.

Table 3.17 Details of the factorial pilot scale experiments.

Factors	**Experiment I**	**Experiment II**
	Levels	Levels
Mixing device	VBAP, PNFAP, AP	HBAP, MPAP, AP
Hydraulic loading rate (l/s)	1.0, 1.2, 1.5, 2.0	1.0, 1.2, 1.5, 2.0

Figure 3.13 (a) Conventional AP. (b) Mixing pit fitted AP.

Dispersion studies. One tracer run was performed for each mixing device and flow rate combination. Effluent tracer concentration was monitored during a sampling period equal to three times the theoretical HRT. A pulse signal (one litre solution containing 261 g LiCl [42.47 g Li^+]) was applied to the influent stream of each AP, making sure that application points were exactly the same for every run.

The LiCl solution was prepared the day before each run to allow for enough cooling time given its exothermic behaviour. A total of 60 samples per AP effluent per run were taken to obtain the RTD curves. Control samples of raw sewage and APs sludge were taken to check for [Li^+] background contents and likely [Li^+] adsorption onto biosolids respectively. The expected [Li^+] average concentrations in the APs (assuming an instantaneous mixing of Li^+ mass in the APs volume) are shown in Table 3.18. Concentrations of [Li^+] were determined by using the same technique and laboratory equipment described in previous sections.

Table 3.18 Expected [Li^+] average concentrations after dosing.

Concentration	Experiment I			Experiment II		
	VBAP	PNFAP	AP	HBAP	MPAP	AP
C_o (mg Li^+/l)	0.48	0.47	0.52	0.48	0.41	0.52

Tracer data sets (RTD curves) were analysed with the dispersion model applied to a closed vessel boundary condition (Levenspiel, 1999). The closed vessel assumption fits the pilot APs since flow behaviour at inlets and outlets differs from the main flow pattern within the ponds. Water flowed into and left from the APs by pipes.

Equations 3.4, 3.5 and 3.6 were used to calculate the hydrodynamic parameters of interest (i.e. mean hydraulic retention times, dispersion numbers and flow deviations).

Ponds seeding and start-up. Each AP was seeded with a biosolids contents accounting for five percent of its total volume. The seed was pumped from the active zone of the adjacent full-scale AP. The pilot APs were commissioned once seeded and were left in batch mode for a week. After this period, inflow rates were gradually increased up to the initial values defined in the experimental design for the first run. The amount of seed was purposefully kept low to minimise its effect on the APs hydrodynamics.

Process performance. A minimum sample size was calculated for the physico-chemical parameters based on the 12 combinations (treatments) and likely interactions of the two factors (Montgomery, 1997). Composite samples of raw wastewater and AP effluents were taken daily from 0700 to 1900 h during the dispersion study runs. According to the experimental design (taking into account a likely interaction between the two factors), 21 COD, 12 TSS and 12 settleable solids determinations were done in the influent and each of the effluents per run. Temperature and pH were also measured in the influent and each of the effluents during tracer runs. Table 3.19 summarises the monitoring campaign for both experiments.

Table 3.19 Summary of monitoring campaign.

Parameter	Type of sample	Samples per AP per day	Samples per run (3 APs & 3 days)	Samples per Exp. (4 runs)	Total 2 Exp
COD	Composite 2-h	7	63	252	504
TSS	Composite 3-h	4	36	144	288
Set. Solids	Composite 3-h	4	36	144	288
pH	Grab	14	126	504	1008
Temperature	Grab	14	126	504	1008

Flow data were recorded hourly at each AP influent during every tracer run. A V-notch weir was calibrated for each AP and three control valves allowed adjustment of inflow rates. Effluent flow rates were measured volumetrically once per run in order to check for total water losses due to evaporation. Negligible infiltration losses were expected since all APs were lined with HD polyethylene (Geofort Inc).

All laboratory analyses were carried out according to *Standard Methods* (APHA, 1992). Specific techniques and laboratory equipment used were the same than those listed in Table 3.16, but excluding the microbiological parameters.

Statistical analysis of data. The amount of samples per combination of factors and levels (treatment) allowed the determination of significant differences in process performance between each AP configuration with a 95 percent confidence level. Thus, the following scientific hypothesis was stated for this experiment: *"Physical configuration and variations of hydraulic loading rate may affect the performance of an AP"*. In other words, there may be noticeable differences in pond removal and hydrodynamic efficiencies caused by both variable physical configuration and hydraulic loading rates. In statistical terms, this hypothesis may be expressed as follows:

$$H_{o,\,AB}: \mu_{a1} = \mu_{a2} = \mu_{a3} = \ldots\ldots\ldots \mu_{nj} \qquad (3.11)$$

$$H_a: \text{not all } \mu\text{'s are equal} \qquad (3.12)$$

H_o *and* H_a are the null and alternate hypotheses respectively, and μ_{nj} is the mean of the n_{th} and j_{th} combination of the factors (treatments) mentioned before. Thus, the null hypothesis states that variations in AP configuration (in-pond mixing device) and hydraulic loading rates do not affect the performance of the pond (i.e. all treatments means are equal). The alternate hypothesis states that there are differences between treatments means (i.e. there is a noticeable influence of the two factors on the performance of the AP).

Therefore, a two-factor ANOVA analysis allowed testing the above hypotheses in order to accept/reject H_o with a 95 percent confidence level. Tukey's test for multiple comparisons and examination of pairwise differences between the various treatments means was also used (Montgomery, 1997; Kvanli *et al.,* 2000).

The two-factor ANOVA and Tukey's tests were run for effluent concentration data of COD and TSS in order to accept/reject the statistical hypotheses. Descriptive statistics were applied to single parameters and correlations between different variables were also performed. SPSS release 10.1.3 (SPSS Inc.) and Excel 2000 (Microsoft Corporation) packages were used to carry out all statistical analyses of data.

3.3.6 Process performance of pilot APs

Type of experiment. This comparative study was designed to evaluate process performance (under steady state conditions) of the best two AP configurations found in the hydrodynamic studies. Table 3.20 shows the experimental conditions for the APs evaluated, including the conventional AP as a control unit.

Table 3.20 Experimental conditions for the evaluation of process performance.

AP configuration	Flow rates applied (l/s)	HRT (h)	Monitoring period per flow rate (weeks)
HBAP	1.0 / 1.3 / 2.0	24.6 / 18.9 /12.3	6
MPAP	1.1 / 1.5 / 2.3	26.0 / 19.3 /12.6	6
AP	0.9 / 1.3 / 1.8	25.3 / 17.2 / 12.7	6

Process performance. Composite samples of 12-h were taken in raw sewage and APs effluent once per week on the same day every week. Flow data were recorded hourly at each AP influent on the sampling day. A V-notch weir was calibrated for each AP and three control valves allowed the inflow rates to be adjusted on a daily basis. Effluent flow rates were measured volumetrically once per week to check for water losses due to evaporation. Negligible infiltration losses were expected since all APs were lined with HD polyethylene (Geofort Inc.). Table 3.21 shows the monitoring programme carried out.

Table 3.21 Monitoring programme for process performance evaluation.

Parameter	Type of sample	Total samples per AP	Total samples
Liquid phase			
pH	Grab	216	648
Temperature (° C)	Grab	216	648
ORP* (Redox potential) (mV)	Grab	216	648
VFA (meq/l)	Composite 12-h	18	54
SO_4^{2-} (mg/l)	Composite 12-h	18	54
Alkalinity (mg $CaCO_3$/l)	Composite 12-h	18	54
CODt (mg/l)	Composite 12-h	18	54
CODf (mg/l)	Composite 12-h	18	54
TSS (mg/l)	Composite 12-h	18	54
VSS (mg/l)	Composite 12-h	18	54

* ORION analog 108 ORP (range: +/- 999mV; accuracy: +/- 5mV; resolution: +/- 1mV)
This table continues on the next page.

Faecal coliforms (UFC/100 ml)	Grab	9	27
*E. coli** (UFC/100 ml)	Grab	9	27
Helminth eggs (No./l)	Composite 12-h	9	27
	Solid phase		
TS (g/l)	Composite	16***	48
VS (g/l)	Composite	16***	48
Sludge depth (m)	White towel test**	12***	36

* Membrane filtration technique. Agar cromocult broth. Merck.
** According to Mara *et al.* (1992).
*** Samples were taken at two internal points (L/3 and 2L/3) from each AP.

Biosolids samples were taken from the bottom of the APs by using an electrical DAYTON-AC GEAR 5K940D peristaltic plug pump (Dayton, USA) as shown in Figure 3.14. BOD_5, NTK, $N\text{-}NH_3$ and H_2S were additionally measured during the last six week period (HRT = 12 h). The average volumetric organic loading rate was much higher for a 12-h HRT than the figures currently recommended in the literature for conventional APs. Thus, these additional parameters allowed the checking of likely biological process disturbances. All laboratory analyses were carried out according to *Standard Methods* (APHA, 1992). Specific techniques and laboratory equipment used were the same as those listed in previous sections.

Statistical analysis of data. Multivariate correlation analyses between different parameters and operational variables were performed. A two-way ANOVA test was run on effluent CODt, CODf, TSS and VSS concentration data to check for significant differences at a 95 percent confidence level. The APs performance and process stability were compared so as to determine the optimum loading rates for each configuration. Two overall kinetic models were also applied to the data series. Descriptive statistics were applied to single parameters. SPSS release 10.1.3 (SPSS Inc.) and Excel 2000 (Microsoft Corporation) packages were used to carry out all statistical analyses of data.

Figure 3.14 Biosolids sampling and laboratory facilities at Ginebra site.