6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions are drawn from the results of the research carried out in this work:

1. The positioning of the inlets and outlets in AP together with pond geometry influence the sludge sedimentation patterns within them, which in turn affects water movement (advection) and mixing phenomena.

2. Pond desludging seems to have a greater impact on effluent quality than the incorrect positioning of the inlets and outlets. This has important implications for AP operation and maintenance with regard to sludge accumulation and desludging frequency.

3. Anaerobic ponds should be designed on the assumption of complete mixing, as the very nature of the biochemical processes occurring in them induces mixing and this may be optimised by reducing short circuiting and dead volumes through simple but effective engineering interventions such as baffles and zones with induced hydraulic mixing.

4. Changes in the relative positioning of inlets and outlets influence the mixing characteristics of the pond as evidenced by the increases in δ values and the experimental HRT figures in the AP at Toro.

5. 2D-CFD modelling is an adequate tool to study the hydrodynamic and advection-dispersion phenomena occurring in full-scale AP. Nonetheless, additional mixing caused by biogas bubbling has to be incorporated in the hydrodynamic and advection-dispersion equations to have a complete picture of pond behaviour.

6. CFD is a powerful tool to predict the effects of changes in sludge contents, baffling, inlet-outlet positioning and basin geometry on the hydrodynamic performance of WSP.

7. Sludge accumulation of 50 percent (or more) of total pond volume is detrimental to AP hydrodynamic and process performance. The provision of two baffles placed at 1/3L and 2/3L increases the pond retention factor and BOD_5 removal efficiency. Baffling and a better inlet-outlet positioning are simple interventions to improve the performance of WSP with a poor physical design.

8. The best configuration obtained in the CFD modelling was a rectangular AP (L: B = 2:1), with two baffles located at L/3 and 2L/3 and inlet-outlet devices located in diagonally opposite corners of the pond.

9. Unlike previous studies reported in the literature, the 2D-CFD package MIKE 21 (which is a depth-integrated model) was able to predict reasonably well the hydrodynamic and advection-dispersion phenomena in ponds, provided that a careful calibration and verification stage is carried out.

10. The successful application of CFD modelling to the hydrodynamic study of full-scale ponds depends on the availability of reliable field data to calibrate and validate the model. This prior stage is very important to carry out the simulations and obtain sensible results applicable to the solution of hydrodynamic problems related to inadequate pond design.

11. The start-up phase of the UASB at Ginebra was developed successfully and the methodology applied confirmed its advantages by shortening the start-up period down to only 9 weeks.

12. The selective pressure methodology (i.e. gradual increase of upflow velocity) proved to be an effective procedure to select the sludge with the best settling features. Consequently, small volumes of poor quality seed (inoculum) can be used to start-up a reactor in a short period of time provided that sludge washing is done prior to continuous operation to remove inert particles and fibres.

13. It can be concluded that the selective pressure methodology improved the sludge activity as shown by initial and final specific methanogenic activity results. All the stages previous to the start-up can be developed within a maximum of one to two weeks period.

14. The sludge bed evolution correlated well with increases in biogas production and upflow velocities along the start-up period. This suggests that start-up of a UASB reactor should commence with a flow rate capable of homogenising the bed from the beginning. Very low upflow velocities cause problems like sludge flotation, short-circuiting, dead zones and a generalised poor mixing pattern.

15. An UASB reactor treating domestic wastewater can be started with a poor quality seed at HRT varying between 12 to 15 h. Consequently, the start-up period can be reduced down to 4-5 weeks, which is a good result for full-scale reactors.

16. The implemented start-up methodology was effective from a technical point of view but most importantly was low cost (the full cost was less than U.S $ 3000). The latter due to the simplicity of parameter determination and the low sampling frequencies needed.

17. The UASB reactor at Ginebra showed an arbitrary flow pattern with dead zones and bypass flows for hydraulic loading rates lower than the design value. Nonetheless, a compartmental model with two completely mixed tanks in series (for hydraulic loading rates close to and slightly higher than the design values) described well the overall mixing pattern of the reactor when operating at its design capacity.

18. The water volume below the GLS seems to contribute greatly to the total dead volume of the reactor especially at low hydraulic loading rates. However, as hydraulic rate increases the dead volume fraction reduces and the overall mixing pattern of the reactor improves.

19. The effluent concentration of COD in the UASB was predicted reasonably well by the CSTR model with first-order kinetics. The values obtained for the overall first-order reaction constant (*k*) compare well with figures previously reported in the literature. However, the Wehner and Wilhelm model showed a better statistical correlation for reactor flow conditions that were not close to complete mixing.

20. The UASB had problems of biomass retention (sludge washout) for hydraulic loading rates higher than the design value. This seems to be a weakness of this system particularly for the treatment of domestic wastewater given the continuous variation of the inflow rate throughout the day. A regulation tank prior to the reactor might overcome this limitation but it will increase the investment and running costs.

21. The modified AP configurations improved their hydrodynamic features as evidenced by the dispersion numbers and HRT_e values obtained. The results of statistical tests on the removal efficiency data sets also confirmed the enhanced performance of the APs.

22. It seems possible to improve the hydrodynamic features of current AP configurations and their concomitant degradation rates by introducing simple engineering modifications to current design and construction practices. However, in developing more efficient AP, simplicity and ease of O&M must not be forgotten.

23. The provision of a high-rate reaction zone (mixing chamber) to a conventional AP clearly improved its hydrodynamic efficiency. The results showed that MPAP was the best configuration followed by the VBAP, the HBAP and then, the conventional AP.

24. The results obtained in the hydrodynamic study showed the potential to increase current AP removal efficiencies to values of around 75 percent in terms of COD and TSS at reduced HRT (e.g. 0.5 day). This will clearly improve the technical and economic feasibility of WSP technology as a whole.

25. Results from process performance evaluation under steady state conditions showed that the highest CODt removal efficiencies occurred in the MPAP (77-79%), followed by the HBAP (65-51%) and then the AP (67-49%).

26. Improved hydrodynamics and an enhanced contact pattern along with a better biomass retention may explain the increasing COD filtered removal efficiencies found in the MPAP (50-78%). Meanwhile, the HBAP and the AP removal efficiencies for COD filtered were (41-44%) and (44-53%) respectively. The removal of filtered COD is achieved mainly by direct biological action, which in turn depends on a good external mass transfer process to and from the cells.

27. The removals of organic matter and microbiological indicators achieved in the modified AP configurations compare well with several results from studies reported in the literature for high-rate anaerobic reactors. Nonetheless, the conventional low-rate AP operating beyond the maximum permissible organic loading rates and HRT values recommended in the literature yielded poor removal efficiencies for all the parameters.

28. The first order kinetic constant for organic matter removal (CODt) was higher in the MPAP (k = 0.365 h^{-1}), followed by the HBAP (k = 0.086 h^{-1}) and then, the AP (k = 0.084 h^{-1}). These k values were obtained at T = 25 °C and HRT of 12, 18 and 24 h in the MPAP, HBAP and AP respectively.

29. The high organic matter (COD_t) removal efficiencies and first-order reaction constant values obtained in the modified pilot-scale AP at HRT values as low as 18 and 12 h, confirmed the high-rate character of these pond configurations, specially the MPAP.

30. The whole set of results showed that it is possible to improve the performance of AP by enhancing its hydrodynamics and related transport phenomena. The high removal efficiencies achieved together with the enhanced biomass retention and the possibility of biogas recovery confirmed the advanced primary treatment features of these APs.

31. Based on the differences between total, maximum, filtered COD and TSS removal efficiencies in the MPAP, it seems likely to improve the performance of this AP by another 5%. This increase in COD and TSS removal efficiencies may be achieved by enhancing the biomass retention in the mixing pit and the transition zone together with improvements in the settling compartment.

32. The CSTR model with first order kinetics described well the performance of the MPAP throughout the three stages of the process performance evaluation. Meanwhile, the Wehner and Wilhelm model for dispersive flow and first-order kinetics described better the performance of the HBAP and the AP throughout the evaluation period.

6.2 Recommendations for further research

The following topics may be further investigated in order to continue with the development and refinement of the high-rate AP concept:

1. Specific studies on biogas production and composition should be carried out in order to confirm the advantages of the high-rate AP concept proposed herein.

2. Studies of the process microbiology would be useful to find out similarities and differences with other high-rate anaerobic reactors. This sort of studies will also provide useful information to know the threshold limits for the steady operation of anaerobic degradation processes within these particular reactor configurations.

3. Since the high-rate AP will have an increased yield of biomass, it is important to study different modes of operation. Thus, it would be desirable to know whether

maximum sludge build-up or periodic sludge withdrawals affect the removal efficiency of the system and also the operation and maintenance costs and requirements.

4. The validation of the pilot-scale results reported herein could be done in a full-scale high-rate AP for a small community. This sort of experience would also provide valuable information on the real investment and operational costs as well as the true requirements of O&M for this technology. These data would also allow the sustainability of this technology to be assessed under real conditions.

5. It is believed that the analysis and modelling of the information gathered in the topics mentioned above will allow the establishment of reliable criteria for the biological process and physical design as well as the operation and maintenance of the high-rate AP technology for domestic wastewater treatment.