Chapter 1

Introduction

Wastewater is the water that has been used by a community and contains various materials (organic compounds, inorganic compounds, pathogens, etc) added to the water during its use. The significant composition of wastewater is the degradable organic compounds and these form an excellent diet for bacteria and are exploited in the biological treatment of wastewater. Untreated wastewater causes extreme damage to the environment and to public health because it contains high levels of pollutants and pathogens. In order to reduce the transmission of the excreta-related diseases and the damage to aquatic biota, it is necessary to treat wastewater to meet the consent requirements of the effluent quality set by the environmental regulatory agency (Mara, 2004).

Wastewaters produced by a community are collected in sewers. The flow in sewers is mostly by gravity, with pumps only being used in situations when this is unavoidable. Conventional sewerage is mostly used in developed countries because it is extremely expensive to procure and operate in developing countries. The design and construction of conventional sewerage is described in more detail in several wastewater textbooks such as (Horan, 1990; Tchobanoglous *et al.* 2003). Mara *et al.* (2001) have described a low-cost sewerage system that is suitable for use in both poor and rich areas alike called the ‘simplified’ sewerage.

In developing countries, only a small proportion of wastewater that is produced by sewered communities is treated prior to discharge. The World Health Organization (2000) indicates that less than 1% and 15% of the wastewaters collected in sewered cities and towns in Africa and Latin America, respectively, are treated in effective sewage treatment plants. Mara (2004, 1997) suggested that financial constraint and ignorance of the low-cost wastewater treatment facilities such as waste stabilization ponds are responsible for the lack of the wastewater treatment in developing countries.

Wastewater treatment is the engineering process that employs physical, biological and chemical processes to reduce the concentration of pollutants found in wastewater to a harmless or near-harmless level in the effluent. In developing countries where land is readily available and temperatures are high, the use of the conventional activated sludge sewage treatment plants is not recommended (Mara, 2004). These conventional wastewater treatment plants are very expensive to invest and sustain. The facilities consume considerable quantities of electrical energy and are complicated to operate so much so that skilled professionals are required. Waste stabilization ponds should be the first choice wastewater treatment facilities in developing countries as these operate extremely well in tropical regions at a low-cost (Mara, 1997; Mara and Pearson, 1998; Mara *et al.* 1992).

Mara (1976, 2004) describes waste stabilization ponds as large shallow basins enclosed by earthen embankments in which wastewater is biologically treated by natural process involving pond algae and bacteria. Typical hydraulic retention times range from 4 days to 100 days depending on the temperature of a particular region. Waste stabilization ponds are not only restricted in warm climates, but they have also been used widely in temperate climate regions of Europe and USA (Abis, 2002).

One of the advantages of using waste stabilization ponds to treat wastewater in developing countries is that they are simple to construct and operate. Earthmoving is the principal activity that is required and other civil engineering works are minimal. The operation of waste stabilization ponds involves routine tasks comprising cutting the embankment grass, removal of scum and any floating vegetation. These operations are carried out using unskilled labour. Arthur (1983) found that waste stabilization ponds cost the least for both capital and operation costs when compared with other wastewater treatment plants, up to a certain combination of land prices and discount rates - for example up to USD 5 per m^2 at a discount rate of 15% and up to USD 15 per m^2 at a discount rate of 5% (most land for wastewater treatment in developing countries costs much less than this).

Mara (2004) argued that waste stabilization ponds were extremely efficient and could be designed to achieve high removal of BOD_5, suspended solids and ammonia exceeding 90%. In addition, waste stabilization ponds could achieve high removals of bacteria, viruses and helminth eggs of up to 6 log units, 4 log units and 100%, respectively. Moshe *et al.* (1972) observed that waste stabilization ponds can cope with high levels of heavy metals of up to 60 mg/l that would be toxic to other wastewater treatment plants.

Despite these overwhelming advantages, waste stabilization ponds can release odour when they are overloaded. However, well-designed and operated waste stabilization pond systems do not produce odour as perceived by many wastewater designers (Mara, 2004).

Anaerobic, facultative and maturation ponds are the three major types of waste stabilization ponds. Conventionally, these waste stabilization pond systems are arranged in a series to achieve effective treatment of raw wastewater (Marais, 1974). Anaerobic and facultative ponds are used for BOD removal, while maturation ponds are employed for excreted pathogen removal. Maturation ponds are normally used when the treated wastewater is used for unrestricted crop irrigation complying with the World Health Organisation guidelines of less than 1000 *E. coli* per 100 ml (WHO, 2006). Maturation ponds are also used in situations where stronger wastewater with high nutrients (nitrogen, phosphorus) is to be treated prior to surface discharge (Mara, 1997).

The process design of anaerobic and facultative ponds is based on volumetric organic BOD loading rate and surface BOD loading rate respectively (Mara, 2004). However, maturation ponds are usually designed based on pathogen removal using the Marais (1974) equation. Although these classic methods are currently used to design and evaluate the treatment efficiency of waste stabilization ponds (Buchauer, 2006), the methods do not account for the hydraulic short-circuiting and stagnation regions that are inherent in many waste stabilization ponds. One can indeed raise a question about the effectiveness of classic pond design methods in using the nominal hydraulic retention times when designing and assessing the treatment efficiency of waste stabilization ponds. In addition, the classic methods treat the design parameters (population, influent flow, BOD, temperature, *E. coli* numbers etc) with high certainty. However, it was noted by von Sperling (1996) that design parameters are not known with high certainty in developing countries because of the limited research resources and he introduced modern methods of designing waste stabilization ponds based on uncertainty principles.

Although modern design procedures for waste stabilization ponds can manage the uncertainty of the design variables by considering the range of every design parameter depending on the level of its uncertainty, the method does not account for the improved treatment efficiency that is initiated when baffles of various configurations are installed in waste stabilization ponds (Shilton and Mara, 2005). In addition, both classic and modern design procedures do not account for the effects of wind and thermo-stratification at the design and operational stages of waste stabilization ponds.

Incorporation of thermo-stratification and wind effects into classic and modern pond design methods could significantly improve the design and assessments performance of waste stabilization ponds as these factors are critical to pond performance. In addition, the use of baffles in facultative ponds could be one area of designing efficient waste stabilization ponds as this might obviate the need for maturation ponds. Mangelson and Watters (1972); Thackston *et al.* (1987); Muttamara and Puetpaiboon (1995, 1996); Pearson *et al.* (1995); Shilton and Mara (2005) observed improved performance when baffles were fitted in waste stabilization ponds. However, this benefit of the improved pond performance is not utilized in the current design procedures when sizing waste stabilization ponds. There is a design risk that the area of waste stabilization ponds that are provided could be more than what is actually required. This suggests that an innovative design approach is required to overcome the limitations of classic and modern design procedures for waste stabilization ponds. One such 'innovative design approach' is computational fluid dynamics (CFD), which is the principal research focus of this thesis.

1.1 Aims and objectives

The aim of this research is to use CFD as an innovative design tool that assesses the improvement in the hydraulic and treatment efficiency of baffled waste stabilization ponds. In addition, CFD is used as a reactor model to simulate the *E. coli* and BOD removals and the spatial residence time distributions in baffled waste stabilization ponds. The principal objectives towards achieving the aim of the research are as follows:

1. To develop source term functions that represent the spatial residence time distribution, the decay of *E. coli* numbers and BOD_5 concentration using the *user defined function* facility provided by the CFD software (FLUENT).
2. To investigate the optimal baffle length that initiates a plug-flow pattern in waste stabilization pond fitted with conventional baffles of various configurations.
3. To investigate whether short baffle (5- 30% pond-width baffles) configurations can compete with conventional baffles (70% pond-width baffles) in improving the treatment efficiency of waste stabilization ponds to satisfy crop irrigation guidelines (WHO, 2006).
4. To develop a CFD-based design for waste stabilization ponds that incorporates the effects of wind speed and its prevailing direction on the treatment efficiency of waste stabilization ponds.
5. To simulate the effects of thermo-stratification in the CFD model to enable assessment of the treatment efficiency of waste stabilization ponds that are thermally stratified.
6. To investigate whether BOD overloading develops in the first baffle compartment of a primary facultative pond with two or four baffles.

1.2 Arrangement of Thesis

Chapter 2 outlines the literature review that has been carried out. The weakness of classic methods in designing baffled waste stabilization ponds is presented. The hydraulic flow patterns that are currently assumed in designing and evaluating the performance of waste stabilization ponds are reviewed, and their shortcomings in assessing the treatment efficiency of baffled waste stabilization ponds are discussed. Modern methods of designing waste stabilization ponds are presented. The weakness of Monte Carlo design simulations and von Sperling's (1996; 1999) empirical equations to assess effects of various baffle configurations on the hydraulic and treatment efficiency of waste stabilization ponds is reviewed. The chapter finally presents a literature review on mathematical development of CFD equations and its applications.

Chapters 3 and 4 present the CFD and fieldwork methodologies used to implement the research objectives.

Chapter 5 presents results of CFD models of a primary facultative pond that was fitted with conventional baffles of various configurations (2 - 10 baffles) with baffle length in a range of 70% - 82% pond-width. The chapter also presents results of CFD models of a similar pond when fitted with short baffles that ranged from 5% to 30% pond-width. The chapter provides results of the optimal baffle configuration that initiates plug flow pattern in baffled waste stabilization ponds. The chapter finally presents results of CFD models of unbaffled and baffled waste stabilization ponds with simulated effects of wind speed and direction.

Chapter 6 presents results of the pilot-scale primary facultative pond that was run with two and four baffle configurations. Results of the unbaffled pilot-scale primary facultative pond are also presented as the baseline of the investigation. The experimental data is analysed statistically using histogram and frequency curves to validate the CFD model results. The results are also analysed to assess the effects of baffles on the performance of the pilot-scale primary facultative pond.

Chapter 7 provides discussion of the results obtained from the CFD model and the pilot-scale primary facultative pond. Experimental data (pH, dissolved oxygen and chlorophyll-a) from the pilot-scale primary facultative pond is discussed to assess the BOD loading condition in the baffle compartments of the two-baffle and four-baffle pilot-scale primary facultative ponds. The chapter proposes the design procedure for determining the safe number of the 70% pond-width baffles that can be fitted in the secondary facultative pond based on the BOD loading in the two-baffle and four-baffle pilot-scale primary facultative ponds. The chapter presents practical aspects how classic and modern pond design methods can be optimised using CFD to design efficient waste stabilization ponds.

Chapter 8 presents conclusions of the work carried out and recommendations for the future work.