PERFORMANCE OF AS-SAMRA WASTE STABILIZATION POND SYSTEM

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الخلاصة :

تحتوي محطة (السَّمْرة) لتنقية المياه العادمة (٣٠) حوضاً تغطي مساحة تقارب (١٨١) هكتاراً وتخدم حوالي (١,٥) مليون نسمة في مدينتي عمان والزرقاء في الأردن . وتتكوّن المحطة من ثلاثة مسارب للمعالجة ، وكلّ مسرب يتكون من عشرة أحواض متتابعة . وبحلول عام ١٩٩٤ ، ازدادت الأحمال العضوية لتصل أكثر من ١٧٠ بالمئة من قدرة المحطة التصميمية ، وملأت الحمأة الأحواض الأولى ، إذ وصلت تراكيز الملوثات إلى ١٢٠ ملغم/لتر من الأكسجين الممتص حيويا وإلى ١٥٠ ملغم/لتر من المواد الصلبة المعلقة . ويُعزى فشل المحطة في تحقيق أهدافها التصميمية إلى عدم توافر معلومات محلية كافية للتصميم ، وضعف التنبؤ بالظروف المحلية . وتعرض هذه الدراسة كفاءة المحطة خلال الفترة ١٩٨٦ الى ١٩٩٤ . وتبيّن الدراسة أن نظام المعالجة الكلي يمكن تمثيله بثلاثة مفاعلات متوازية ذات معاملات تشتيت منخفضة . وقد تَمَّ استخدام المفاعلات المكافئة الثلاثة لتكوين نماذج رياضية لوصف كفاءة المحطة خلال تسع سنوات من التشغيل .

ABSTRACT

The As-Samra waste stabilization pond system consists of 30 ponds occupying an area of approximately 181 hectares and receiving wastewaters generated by a population of approximately 1.5 million in Jordan's major cities: Amman and Zarqa. The ponds are arranged in three treatment trains consisting of ten in-series ponds. The BOD loading to the ponds exceeded the design capacity from the start of operation in 1985. Nevertheless, the organic loading continued to increase and by 1994, the BOD loading exceeded the design capacity by more than 170 percent, the accumulated sludge filled the first three anaerobic ponds, and the quality of the effluent exceeded 120 mg/l BOD and 150 mg/l TSS. The failure of the system to meet its treatment objectives resulted from poor projection of local data and design criteria. The lack of locally developed design data resulted in the utilization of modified data reflecting the experience of industrial countries. The historical performance of the system, in terms of BOD, TSS, total coliform (TC), and fecal coliform (FC), during the period 1986 to 1994, is presented and discussed. The hydraulic characteristics of each treatment train corresponded to a plug flow reactor with small axial dispersion. A plug flow reactor model was used to estimate the variations of the BOD first-order reaction rate constant in the system during nine years of operation.

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1. INTRODUCTION

Jordan, located in the eastern region of the Mediterranean, has a population of approximately 4.3 million and occupies an area of approximately 90 000 square kilometers. The majority of the country, approximately 72 percent, is a desert with elevations in the range 600 m to 700 m above mean sea level [1]. The desert has hot dry summers and cold dry winters, with the annual rainfall not exceeding 70 mm [1]. Approximately 60 percent of the population are connected to wastewater collection systems [2], and more than 80 percent of the collected wastewater is treated in waste stabilization pond systems [3]. In Jordan, the availability of vast desert land and the hot climate favored the use of waste stabilization ponds, which also require low operating costs compared with conventional treatment systems. Jordan operates one of the largest waste stabilization ponds in the world, serving more than 1.5 million people. Evaporation, and consequently, the annual loss of millions of valuable cubic meters of water, especially during the dry season, is a major problem associated with As-Samra system. The water shortage in Jordan is compounded by an annual population growth of approximately 3.4 percent and increasing water demands from the commercial and industrial sectors in the country [1, 3].

The As-Samra wastewater treatment plant (WWTP) consists of three treatment trains. Each train consists of ten ponds operated in the following in-series sequence: two anaerobic ponds followed by four facultative ponds followed by four maturation ponds. The original design data of the system are presented in Table 1. The ponds occupy a total surface area of approximately 181 hectares. The system was designed to handle wastewater loads projected for the year 2000; an influent BOD load of 35 750 kg/d and an average flow of 68 000 m^3/d. The first treatment train started operation in May 1985. A second train was filled in August 1985. The third train started operation in March 1987. The accumulated sludge in the ponds, which reached in 1993 depths up to 4.7 m in the first set of anaerobic ponds and 2.7 meters in the second set of anaerobic ponds [4], was never removed. The data indicate that the loading to the ponds exceeded the design capacity from the start of operation. The projected design effluent quality of 30 mg/l BOD, 50 mg/l TSS and 100 MPN (most probable number) per 100 ml was never achieved. Chlorination was introduced to disinfect the effluent and minimize the health risks associated with the discharged pathogens. Several studies [4] were undertaken to propose modifications to upgrade the system (*i.e.*, expansion and/or aeration of selected facultative ponds) but as of 1994 no action has been undertaken.

Although numerous methods have been suggested for the design of wastewater stabilization ponds, a method for general application does not exist [5]. Colomer and Rico [5] classified the design approaches into three categories: empirical, semiempirical, and mechanistic. The empirical models [5, 6] are generally based on the performance of

Table 1. As-Samra WWTP Original Design Data.

Parameter	Anaerobic Ponds	Facultative Ponds	Aerobic Ponds
Total Area	19 Hectares	87 Hectares	75 Hectares
Depth	5 m	1.5 m – 2.5 m	1.25 m
Detention Time	8 days	20 days	14 days
Treatment Trains	3	3	3
Ponds Per Train	2	4	4
Total No. of Ponds	6	12	12

Design Year = 2000
Design Flow = 68 000 m^3/d
Design BOD Loading = 35 750 kg/d (BOD = 526 mg/l)
Design Temperature = 12.5°C (Winter), 25°C (Summer)

existing systems. Semiempirical models [7–10] are based on theoretical simplifications of organic (BOD) removal and hydraulic characteristics of ponds. Mechanistic models are the more rational [5, 11, 12], but their application is mathematically complex and requires the use of unknown constants. Ellis [13] observed that because of the complexity of quantifying the criteria affecting stabilization ponds, designers should resist the temptation to adopt a highly complicated approach and recognize that the best approach is to use data resulting from the operation of existing ponds in the locality. In Jordan, local design data are generally unavailable or are improperly documented. This paper discusses the historical performance of As-Samra waste stabilization pond system by combining a large quantity of data available from a variety of sources. The data were used to determine the hydraulic characteristics of the system and to estimate the variations of the BOD first-order reaction rate constant during nine years of operation.

2. MATERIALS AND METHODS

Data on the performance of As-Samra WWTP since initial operation in 1985 were collected from two major sources: graduate research projects conducted at The University of Jordan [14–19], Bannayan [20], and annual influent and effluent characterization reports prepared by the Royal Scientific Society (RSS) of Jordan [21]. All analytical procedures were based on standard analytical methods [22]. With few exceptions, the available data described the performance of the system in terms of total influent and effluent characteristics. The performance data, for the period January 1986 to March 1994, were compiled and the results presented and discussed. The data were used to estimate the hydraulic characteristics of the treatment system and the reaction rate constants describing the removal of BOD, total coliform (TC), and fecal coliform (FC).

Semiempirical waste stabilization pond models are based on theoretical simplifications of organic (BOD) removal and hydraulic characteristics of ponds [5]. Thirmurthi [10] adopted a plug flow model with small axial dispersion and first-order reaction kinetics (Equation (1)) as described by the Wehner and Welhelm [23] Equation:

$$\frac{C}{C_o} = \frac{4a\exp\left(\frac{1}{2d}\right)}{(1+a)^2\exp\left(\frac{a}{2d}\right) - (1-a)^2\exp\left(-\frac{a}{2d}\right)} \tag{1}$$

where k is the overall first order reaction rate constant (time^{-1}), d = dispersion number (dimensionless), t = detention time, C is the effluent concentration (mass/volume), C_o is the influent concentration (mass/volume), and $a = \sqrt{1 + tdk}$. A plug flow reactor with axial dispersion (Equation (1)) is equivalent to a number of completely mixed reactors operated in series (Equation (2)) with an equivalent total residence time, removal, and reaction rate constant. Marais and Shaw [24] and Eckenfelder [25] stated that for a large number of ponds operated in series (Equation (2)), the overall hydraulic characteristics correspond to a plug flow system (Equation (3)).

$$\frac{C}{C_o} = \frac{1}{(1+kt_1)(1+kt_2)\ldots(1+kt_n)} \tag{2}$$

$$\frac{C}{C_o} = \exp\left[-k(t_1 + t_2 + \ldots + t_n)\right] \tag{3}$$

where k is the overall first order reaction rate constant (time^{-1}) and t_1, t_2, ..., t_n are the detention times in the individual ponds (t = volume ÷ flow). It should be noted that for individual ponds, the above equations remain valid with $n = 1$. A plug flow reactor model (Equation (3)) was used to estimate the variation of the BOD first-order reaction rate constant in the system's three treatment trains, each consisting of ten ponds in series. The reported reaction rate constants were calculated, as typically presented in literature, using wastewater inflow, influent concentration, final effluent concentration, and total pond volume minus the volume of accumulated sludge in the ponds. Because of evaporation and seepage, the value of C/C_o in Equations (1), (2), and (3) does not necessarily reflect the BOD removal in the system. In addition, and because of the system's productivity (production of BOD in the system due to algal growth and escape in the effluent), any calculated BOD removal (based on mass or concentration) does not reflect the removal of influent BOD alone. Recognizing the complexity of quantifying the system's parameters, it is important to relate the estimated reaction rate constants to the specific assumptions used in calculating their values. In this case, the calculations were mainly intended to reflect the relative variations of the reaction rate constant with time and relative to each other. Nevertheless, the data are presented in the paper and can be used by readers to perform further and more sophisticated analysis.

To confirm the validity of the selected plug flow model, a set of calculations were performed to show that no matter how large the dispersion number of individual ponds, the overall dispersion number of ten in series ponds should remain relatively small. The calculations involved assuming a dispersion number in the range $d = 0$ (plug flow) to $d = \text{infinity}$ (completely mixed) in the individual ponds and calculating the dispersion number corresponding to an equivalent plug flow reactor with axial dispersion using Equations (1) and (2).

3. RESULTS AND DISCUSSION

The failure of the As-Samra system to meet its treatment objectives resulted from poor projection of local data and design criteria. The lack of locally developed design data resulted in the utilization of modified data reflecting the experience of industrial countries. The system, designed for the year 2000, was overloaded within one year after the start of operation in the second half of 1985. The hydraulic, organic, and solid loadings to the system exceeded the design year capacity, and the effluent quality was never achieved. The treatment plant discharged highly contaminated effluents and emitted foul odors. The increasing organic and hydraulic loading to the system and the accumulation of sludge since 1985 compounded the overloading problem. The high initial cost discouraged further investment in upgrading the system, especially within one year after commissioning. This paper emphasizes the need to develop locally applicable design data and criteria. The As-Samra example highlights the importance of the issue and suggests that investing in developing local data is a feasible and worthwhile undertaking.

The historical performance of the system during the period January 1986 to March 1994 is discussed in this section. Wastewater inflows and outflows to the system are presented in Figure 1(*a*). The inflow increased from approximately 50 000 m^3/d in 1986 to approximately 120 000 m^3/d in 1993, and early 1994, as a result of population growth, increased per capita water consumption, and new connections from newly sewered areas. The average hydraulic loading to the system exceeded the design year loading of 68 000 m^3/d within one year after start of operation. Evaporation and seepage accounted for approximately 20 percent annual inflow losses; approximately 6 million m^3 per year.

The influent and effluent BOD are presented in Figure 1(*b*). The average monthly influent BOD remained at approximately 750 mg/l for 70 months decreasing to approximately 520 mg/l during the last 30 months. The effluent BOD remained mostly above 90 mg/l and averaged at approximately 120 mg/l. The projected design effluent quality of 30 mg/l BOD was never achieved. The influent and effluent TSS variations, Figure 1(*c*), were similar to those for BOD. The influent TSS averaged approximately 730 mg/l during the first 25 months, 600 mg/l during the following 45 months, and 400 mg/l during the last 30 months. The effluent TSS remained relatively high, averaging above 150 mg/l. The projected design effluent quality of 50 mg/l TSS was never achieved. The decrease in influent TSS and BOD concentrations corresponded to the increase in wastewater flows to the system, Figure 1(*a*). It should be noted that as more areas were connected to the system, the WWTP received less septage which helped in diluting the concentrated influent.

The lack of local design data and criteria resulted in the utilization of modified data reflecting the experience of industrial countries. The As-Samra system, for example, was designed based on a design year BOD of 526 mg/l, while at the start of operation in 1985, the average concentration of BOD in the influent was approximately 720 mg/l and it reached approximately 850 mg/l in 1988. The other 13 treatment plants in Jordan receive influents with average BOD and TSS concentrations above 700 mg/l and reaching as high as 1 200 mg/l in some plants [3]. The per capita water consumption in Jordan, at approximately 80 l/capita/d to 100 l/capita/d, is significantly lower than that in the United States and other industrial countries. Consequently, wastewater constituents are more concentrated. The addition of significant quantities of septage to the wastewater concentrated the contaminants even further. For example, the BOD and TSS concentrations in high strength wastewaters in the United States [26] are approximately 400 mg/l and 350 mg/l, respectively, while the average BOD and TSS concentrations in Jordan may exceed 700 mg/l. High strength wastewaters generally require longer residence time in conventional biological treatment systems, in series treatment processes, significant effluent recycling to dilute the influent, or all of the above actions.

In 1985, the BOD loading to the ponds reached an average of 25 300 kg/day, approximately 70 percent of the total system design capacity. However, because only two treatment trains were operational in 1985, the BOD

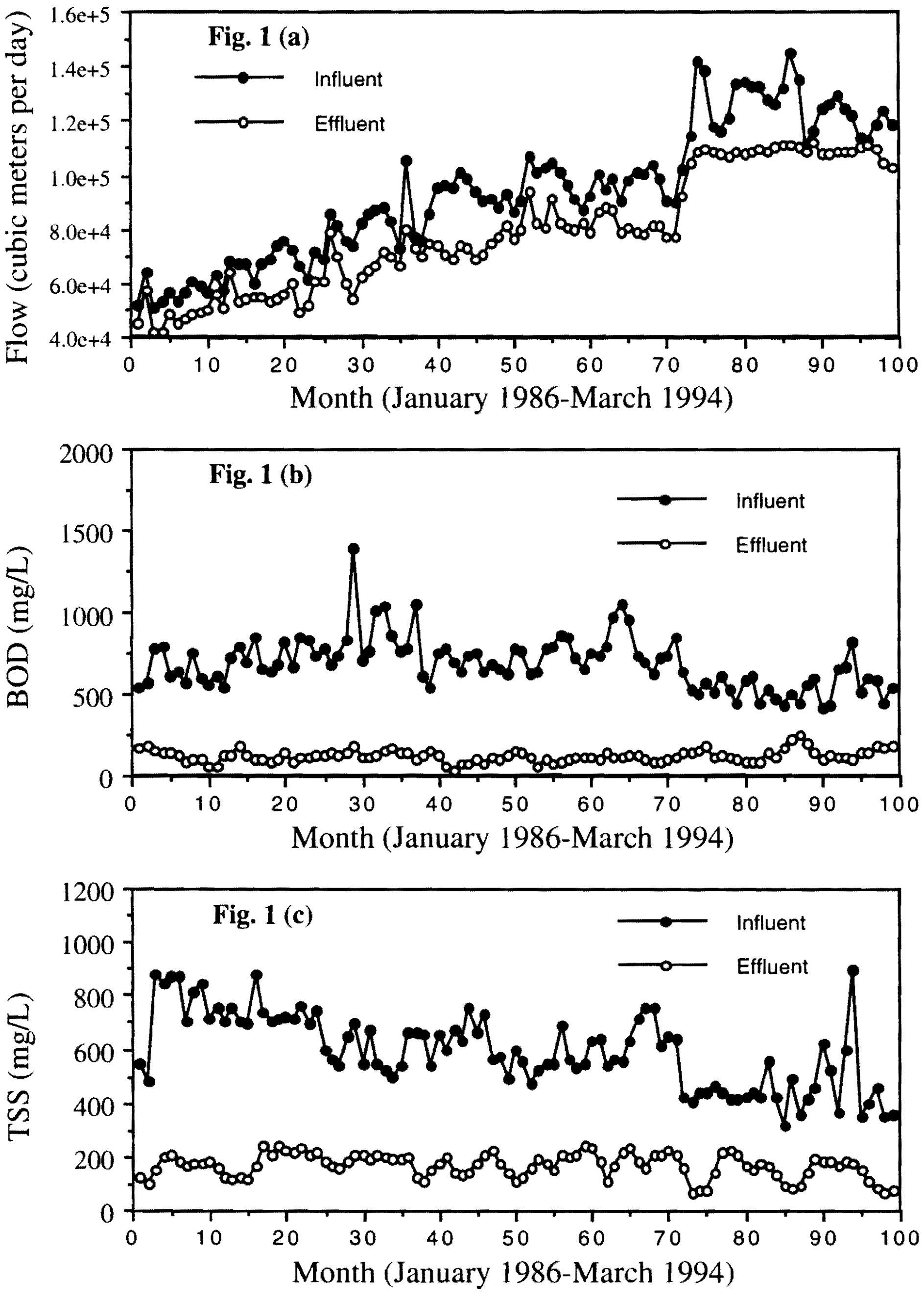


Figure 1. As-Samra System: Influents and Effluents.

loading reached approximately 106 percent of the design capacity of the two operational treatment trains. In 1986, Figure 2(*a*), the loading to the two operational treatment trains averaged 45 000 kg/day, approximately 190 percent of the design capacity. In 1987, the loading reached 51 300 kg/d, approximately 145 percent of the total design capacity of the three treatment trains. In 1993 and early 1994, the BOD loading averaged 63 000 kg/d, approximately 175 percent of the design capacity. The average BOD loading to the system exceeded the design year loading (year 2000) of 35 750 kg/d within one year after start of operation in 1985. Individual ponds were also overloaded. The data presented in Table 2 indicate that the anaerobic ponds were highly overloaded. The anaerobic ponds design loading of approximately 1 900 kg/ha/d was exceeded, and the actual loading to the anaerobic ponds

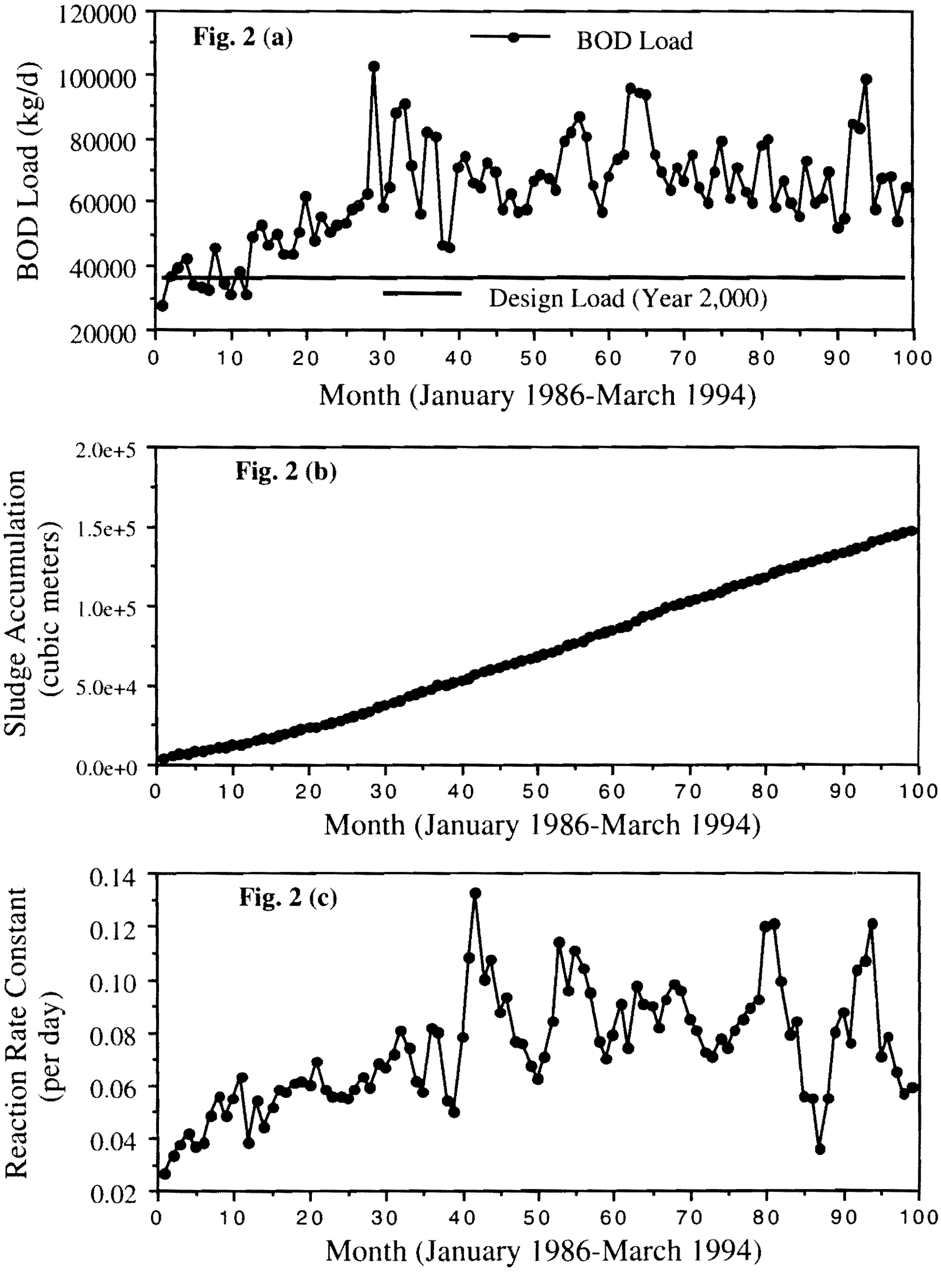


Figure 2. BOD Loading, Sludge Accumulation, and First-Order Reaction Constants.

increased from approximately 2 000 kg/ha/d in 1985 to approximately 3 300 kg/ha/d in 1993. The loading to the first set of anaerobic ponds increased from approximately 4 000 kg/ha/d in 1985 to approximately 6 600 kg/ha/d in 1993 (Table 2). Metcalf and Eddy [26] recommended the use of BOD loading in the range 200 kg/ha/d to 500 kg/ha/d for the design of anaerobic ponds, and Parker [27] reported that the Australian experience suggested a permissible loading of approximately 1 200 kg/ha/d. The result of overloading the anaerobic ponds at the As-Samra system was manifested by the accumulation of large scum quantities in the ponds and the emission of foul odors. The facultative ponds were also overloaded. Metcalf and Eddy [26] recommended the use of BOD loading in the range 50 kg/ha/d to 200 kg/ha/d for the design of facultative ponds. The loading to the first set of facultative ponds increased (Table 2) from approximately 870 kg/ha/d in 1985 to approximately 1 450 kg/ha/d in 1993, and the loadings to all the facultative ponds increased from 218 kg/ha/d to 362 kg/ha/d within the same period. The permissible design BOD loading was approximately 200 kg/ha/day (Table 2) [21].

Table 2. As-Samra Historical Loading Conditions.

Parameter	1985	1986	1987	1993
Influent BOD Loading (kg/d)	25 300 (35 750)*	45 000 (35 750)	51 300 (35 750)	63 000 (35 750)
Number of Operational Treatment Trains	2	2	3	3
Total Surface Area of Anaerobic Ponds (ha)	12.67	12.67	19	19
Surface Loading (kg/ha/d)	2000 (1880)	3555 (1880)	2700 (1880)	3315 (1880)
Surface Area of First Anaerobic Ponds (ha)	6.33	6.33	9.5	9.5
Surface Loading (kg/ha/d)	4000 (3760)	7110 (3760)	5400 (3760)	6630 (3760)
Loading** to Facultative ponds (kg/d)	12 650	22 500	25 650	31 500
Total Surface Area of Facultative Ponds (ha)	58	58	87	87
Surface Loading (kg/ha/d)	220 (200)	390 (200)	295 (200)	360 (200)
Surface Area of First Facultative Ponds (ha)	14.5	14.5	21.75	21.75
Surface Loading (kg/ha/d)	870 (800)	1550 (800)	1180 (800)	1450 (800)

* Numbers between brackets represent design year numbers.

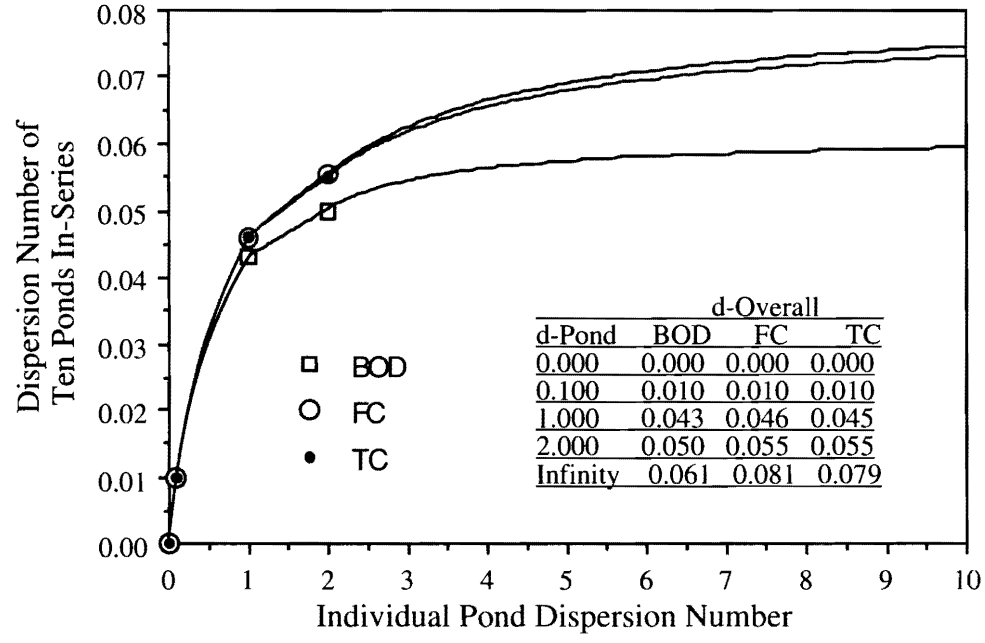
** Based on 50 percent removal in the anaerobic ponds.

While the use of stabilization ponds in series offers the advantages of improved treatment efficiency and reduced TSS in the effluent [26], Parker [27] warned against overloading the first pond in the series and emphasized the need for an adequate number of ponds in-parallel to receive the influent loading. Similar observations were made regarding the As-Samra system and it was suggested [20] that rearranging the anaerobic and facultative ponds to operate in parallel could help in improving the system's overall performance.

The accumulation of sludge in the ponds, Figure 2(*b*), was calculated based on an accumulation rate of 0.015 m^3 per person per year and a BOD loading of 54 g BOD per equivalent person per day. The sludge accumulation rate was calculated based on As-Samra sludge characterization studies conducted in 1989 [17] and 1993 [4]. The accumulated sludge in the ponds reached, in 1993, depths up to 4.7 m in the first set of anaerobic ponds and 2.7 meters in the second set of anaerobic ponds [4]. The accumulated sludge was never removed from the ponds from the start of operation in 1985. The accumulated sludge reduced the available residence time by reducing the volume available for reaction and produced foul odors.

The overall BOD first-order removal rate constants, for the period January 1986 to March 1994, are presented in Figure 2(*c*). The constants were calculated using an overall plug flow reactor model as described in Equation (3). The reaction rate constants increased in the range 0.03 per day to 0.07 per day during the first 40 months, corresponding to the increase in organic loading, then fluctuated in the range 0.07 per day to 0.12 per day during the remaining period. The effects of seasonal temperature variations on the reaction rate constant were evident during the last 60 months with the lower reaction values observed during the colder seasons.

A comparison between the individual pond dispersion numbers and the overall system dispersion numbers, calculated using the performance data for BOD, TC, and FC during the period March 1986 to February 1987, is presented in Figure 3. During that period, the system achieved the following removals (Table 3): more than 99.9 percent for TC and FC and 77 percent to 89 percent for BOD. The overall dispersion number of each treatment train varied in the range d = zero, when the individual pond dispersion number was assumed to be d = zero, to d = 0.081 when the individual pond dispersion number was assumed to be d = infinity (Figure 3). Considering that most individual stabilization ponds have dispersion numbers in the range 0.1 to 2.0 [26], the overall dispersion number of each treatment train varied within the narrow range of 0.01 to 0.055. Clearly, the dispersion numbers of the overall system were small compared with the dispersion numbers of the individual ponds. In addition, the



	d-Overall		
d-Pond	BOD	FC	TC
0.000	0.000	0.000	0.000
0.100	0.010	0.010	0.010
1.000	0.043	0.046	0.045
2.000	0.050	0.055	0.055
Infinity	0.061	0.081	0.079

Figure 3. Individual Pond and Overall System Dispersion Numbers.

overall dispersion numbers calculated using the BOD, TC, and FC performance data were approximately identical. The above analysis confirmed the validity of using a plug flow model to describe the hydraulic characteristics of each treatment train consisting of ten in series ponds.

Because most of the available data described the influent and effluent characteristics, the performance of the individual ponds could not always be estimated. The performance of individual ponds in terms of BOD, TC, and FC was reported for the period between March 1986 and February 1987. The individual pond performance data indicated that approximately 50 percent of the influent BOD was removed in the first two anaerobic ponds of each treatment train (approximately 40 percent in the first pond and 10 percent in the second pond). Most of the BOD removal in the anaerobic ponds resulted from sedimentation of influent organic suspended solids. In the remaining ponds, the achieved BOD removals were relatively low. The performance of the individual ponds was also reflected in the reaction rate constants for BOD, TC, and FC (Figures 4 and 5). The reaction rate constant reached approximately 0.25 per day in the first anaerobic pond (Figure 4). In the remaining ponds, the constant varied between zero and 0.075 per day. The overall system BOD removal rate constant for the same period (Figure 2(*c*)) varied in the range 0.035 per day to 0.055 per day . For TC and FC, the individual pond reaction rate constants continued to increase reflecting the improvement in the removal mechanisms along the pond system (Figure 5), and the constants increased in the range 0.1 per day to 1 per day.

4. SUMMARY

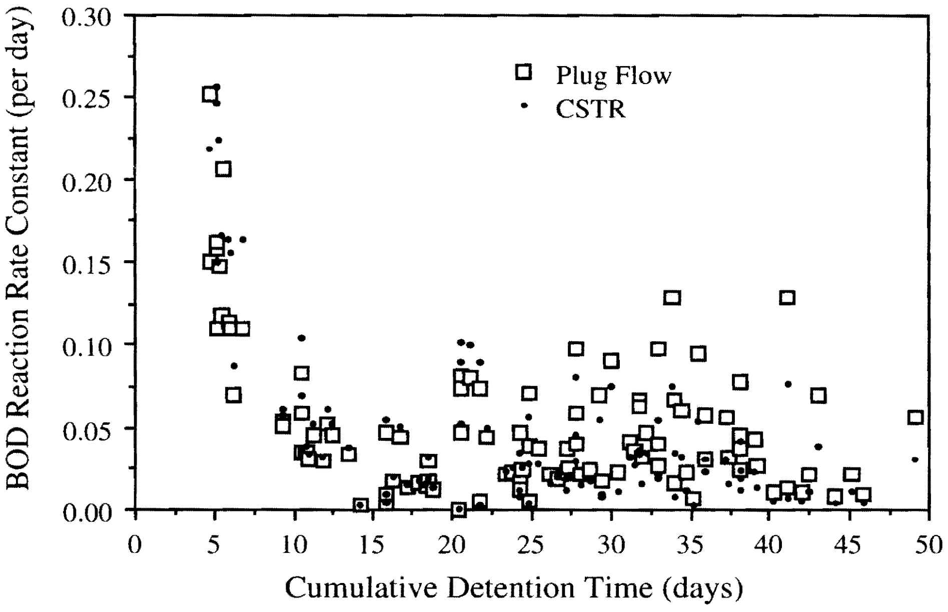
The data presented in this paper described the performance of the As-Samra system during the period December 1986 to March 1994. By comparing the historical loading conditions during nine years of operation with the design loading for the year 2000, the analysis confirmed that the system was overloaded ever since starting operation in 1985. Overloading the system, combined with accumulation of sludge and increased organic loading, were the major contributors to the system's underperformance, manifested by the discharge of highly contaminated effluents and emission of foul odors. Overloading the system within one year after commissioning resulted from poor planning and poor projection of the local conditions. The As-Samra example emphasizes the need to develop locally applicable design data and suggests that investing in developing such data is feasible and worthwhile.

Analysis of the hydraulic characteristics of the system suggested that an overall plug flow reactor model with no or small axial dispersion ($d = 0.01$ to $d = 0.055$) described the flow conditions in each of the three treatment trains in the system. The overall BOD first order reaction rate constants were estimated using a plug flow reactor model.

Table 3. Performance of the Two Operational Treatment Trains at As-Samra WWTP.

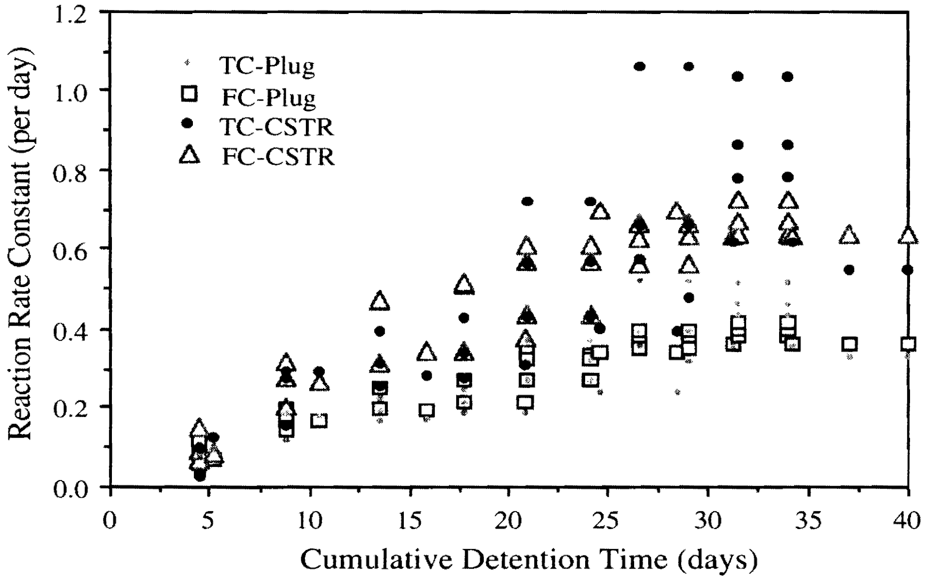
Month	Flow (m^3/d)	Detention Time (day)	BOD Loading (kg/d)	BOD Removal (%)	FC Removal (%)	TC Removal (%)	Temp. (°C)
Mar-86	50 808	45	40 646	79.1	99.998	99.997	15.2
April	53 172	43	44 133	85.1	99.989	99.995	20.7
May	56 886	41	38 341	83.7	99.999	99.997	21.9
June	52 020	43	35 894	85.8	99.999	99.993	25.2
July	60 175	38	40 979	84.6	99.998	99.986	26.6
Aug.	60 502	38	38 540	84.5	99.996	99.990	27.5
Sept.	59 112	39	39 132	86.9	99.997	99.984	26.8
Oct.	56 483	41	43 831	89.4	99.998	99.987	24.5
Nov.	61 071	38	44 338	85.3	99.986	99.986	15.9
Dec.	57 597	40	41 355	87.9	99.996	99.979	12.1
Jan-87	68 151	34	50 636	77.9	99.982	99.970	11.6
Feb.	67 150	34	48 147	77.4	99.989	99.995	14.9

The data and analysis presented in this paper should provide valuable insight and documentation on the historical performance of the As-Samra system and a reference case-study for planning and designing similar systems in the area.



(March, 1986–February, 1987)

Figure 4. Individual Pond BOD First-Order Reaction Rate Constants.



(December 1986–March, 1987)

Figure 5. Individual Pond TC and FC Reaction Rate Constants.

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