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A biological approach to dolphinarium water purification: II A practical application: The Delfinaario in Tampere, Finland

W. H. Dudok van Heel*

Lepelstraat 1, 4381 HJ Vlissingen, The Netherlands

J. D. van der Toorn

P.O. Box 303, 3860 AH Nijkerk, The Netherlands

Abstract

In this paper, the water treatment system of the Delfinaario in Tampere, Finland is described. This system makes use of biological and physico-chemical processes for the purification of the water (an artificial seawater mix) without the use of chemical additives. The system has been in use now for $2\frac{1}{2}$ years and has proven to be easy to manage and has shown a good performance. The levels of nutrients in the water, except the nitrate-level, are well below the advised levels for seawater aquarium management (Spotte, 1979a,b) and bacterial counts are low.

Introduction

Traditionally the water of inland oceanaria has been purified with the aid of large sand filters and chlorination. This method has been described by among others Andersen (1983) and Dudok van Heel (1983). Although chlorination can create acceptable water conditions for marine mammals, both authors agreed that it is not the ideal solution.

In the early days, before 1972, energy was cheap and obtaining fresh water and releasing wastewater presented no real problems. Therefore, there was no incentive for looking into alternative water treatment techniques. Why look for another method if there is a cheap method that gives acceptable results? However the situation changed: energy and chemicals became more expensive and an increased concern for environmental pollution caused an increase in the taxes on water and of waste-water dumping.

It marked the end of easy going and cheap management. A switch to new paths became essential. It became clear that there was not much room for improvement with the chemical water treatment. When chlorination is applied, regular replacements of large amounts of water are necessary to prevent the buildup of potentially hazardous chlorinated hydrocarbons (Duursma and Parsi, 1976; Dudok van Heel, 1983) and of total organic carbon (TOC) (Spotte and Adams, 1979).

An alternative way of cleaning the water in oceanaria could be biological water treatment.

Water purification strategies based on biological processes have been used for instance in aquaria (Spotte, 1979a,b; Kinne, 1976; Wolff, 1981) and in large wastewater purification plants (McKinney, 1962; Fair *et al.*, 1968; Tri, 1975; Conway and Ross, 1980; Mudrack and Kunst, 1986).

There is no reason to assume that these processes cannot be applied to dolphinarium water purification. The processes involved have been outlined in Part I of this paper (van der Toorn, 1987).

It is the opinion of the authors, that biological water treatment is an alternative that creates a much healthier environment for the animals and in addition is more economical to run.

Original design

The Delfinaario officially opened on 11 May 1985. Early in the designing stage, the decision was made to incorporate a biological water treatment system instead of the traditional chlorinated system. This decision had some consequences with respect to the operation, because in fact a biological filter is a living entity, which needs food and oxygen. In this system oxygen would be provided by incorporating a trickling filter. In such a filter the water is divided over a large area and cascades down, thus collecting oxygen. The food is provided by the excrements of the animals, in this case five subadult bottlenosed dolphins, *Tursiops truncatus*. The greater part of the material excreted by the dolphins is biodegradable

*The first author was responsible for the original design. The second author was responsible for the daily operation of the system during the first $2\frac{1}{2}$ years and for later adaptations of the system.

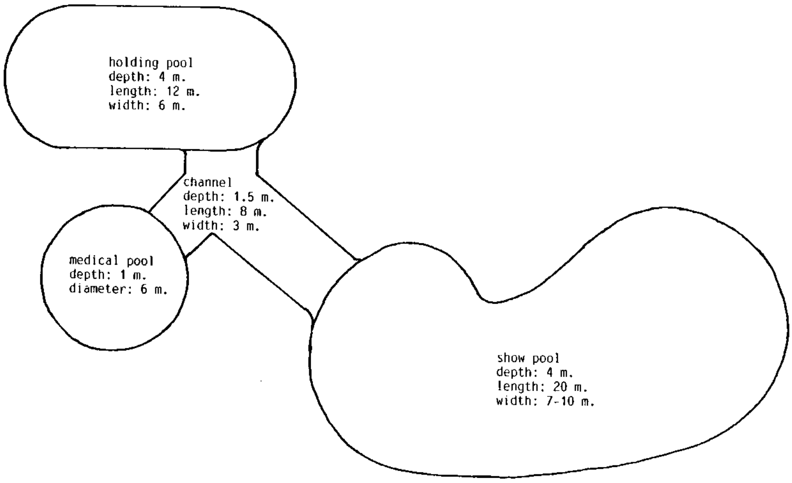

Figure 1. Layout of the pool system of the Delfinaario.

and will be taken care of by the micro-organisms in the biological filter. Because some materials are not converted easily or not at all, parallel to the biofilter a number of foam fractionators were installed for the removal of those materials. Since foam fractionators will also remove organic matter, this setup creates a kind of buffer for the biological filter: if there is a sudden peak in excretion by the dolphins, the biofilter does not have to deal with all of it. The original design called for a 50–50 distribution of the flow between the biofilter and the foam fractionators. Since micro-organisms multiply rapidly when nutrients are available and also die rapidly if there is not enough, one can expect a fluctuation in the number of micro-organisms and thus in the purification capability of the system, when nutrient supplies are not constant. There will be a time lag between an increase in nutrient levels and a build-up of micro-organisms.

The division of the water as designed will lessen the fluctuation of nutrient levels and thus create a more stable environment for the biofilter.

The design also included a provision for recirculation of the sludge that is always formed by a trickling filter to feed the filter in periods of lower nutrient supplies from the pools. This would maintain the biofilter at a constant high level of activity. Since it was not possible to quantify this provision properly without more details about the system's performance it was decided not to install this right away. As it turned out, it was not necessary in this system but it is something that must be kept in mind when designing such a filter. It could improve the efficiency of a biological filter.

System hydraulics

The Delfinaario in Tampere has 3 pools connected by a channel (See Fig. 1). In the original design (see Fig. 2) the showpool, with a volume of approx. 700 m^3, would be served by 3 pumps with a capacity of 180 m^3/hr each. Two of them would lead their water to the biofilter, the other one would serve 3 foam fractionators, with a capacity of 60 m^3/hr each. The holding pool, with a volume of approx. 260 m^3, would be served by 1 pump of 180 m^3/hr, which would lead all its water over 3 foam fractionators. The medical pool, volume 30 m^3, and the channel, volume 24 m^3, would each be served by one pump of 30 m^3/hr, which would together serve one fractionator. All the water from the fractionators and the biofilter would be collected in a mixing channel, where it would be forced through a limestone bed or a bed of broken shells, and would then be led to the pools by gravity.

The medical pool could be used as a quarantine, by leading the water from the fractionator it served directly back to the pool, bypassing the mixing channel. The water from the channel pump would then temporarily be led over the biofilter. The total circulation would be 780 m^3/hr. Since the total water volume, including the filter system is approx. 1250 m^3 the turnover would be about 1 hour 40 minutes. Of the total circulation 50% of the water would be led over the biofilter and 50% over the foam fractionators. The water returning to the pools would be treated with Photozone (photochemically generated ozone plus activated oxygen).

However, the total Delfinaario design turned out to be too expensive and it was decided to cancel one of the showpool pumps and the three fractionators it served, as well as the Photozone unit for treating the water returning to the pools. This change reduced the circulation to 600 m^3/hr and the turnover to 2 hours 5 minutes (see Fig. 3). Because of the elimination of the 3 fractionators the balance between fractionators

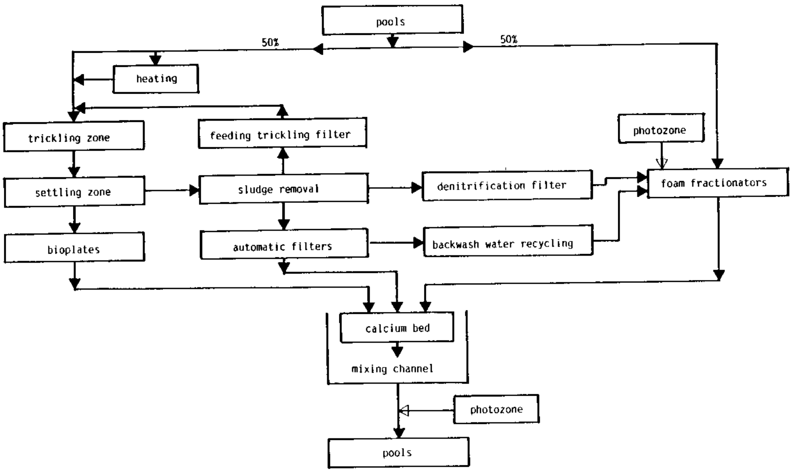

Figure 2. Original design of the Delfinaario water treatment system. Fifty per cent of the water would be treated in the biological section and 50% in the physico-chemical section, i.c. the foam fractionators.

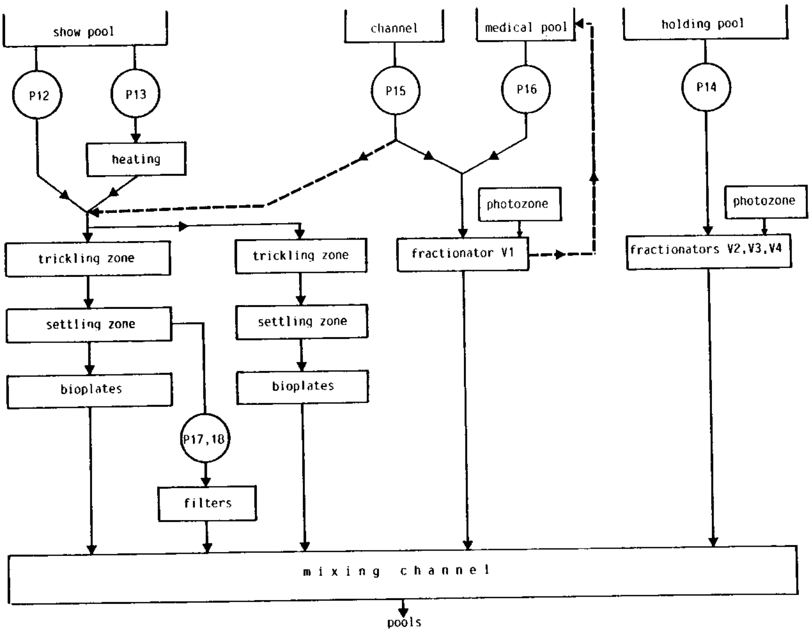

Figure 3. Flow diagram of the Delfinaario water treatment system as it was built. Broken lines indicate alternative routes.

and biofilter was changed as well: 60% now went over the biofilter and 40% over the fractionators.

This was the case at least on paper. What had been overlooked was that the nominal output of the pumps was for pumping the water to a height of 15 metres. In the Delfinaario system however, the maximum height for the biofilter is 4.85 metres above pool level and for the fractionators only 1·75 metres. Except for the heat exchanger, no structures giving any resistance (such as pressure filters) were present in the flow lines. This resulted in a considerably higher output of the large pumps. The showpool pump that led its water through the heat exchanger turned out to be the only one giving 180 m^3/hr. The other showpool pump and the holding pool pump both gave as much as 270 m^3/hr. This meant among other things, that 3 of the fractionators got far more water than they should and were therefore not working optimally. With this in mind it was decided to rearrange the flow drastically. The showpool pump would still serve the biofilter. The holding pool pump would now serve all 4 fractionators and by restricting a valve its output would be reduced to 240 m^3/hr. The water from the channel would be mixed with the water from the showpool and led over the biofilter.

In the original design a separate section was made in the biofilter for the medical pool, in case it had to be used as quarantine. This idea was later discarded, because of the risk of infection of the biofilter with pathogenic bacteria which might become unmanageable. This separate section had been constructed anyway and now the water of the medical pool was led over that section in normal operation. If the need for quarantine should arise, its water would be led again over the fractionator as described above. The output of the holding pool pump would then have to be reduced to 180 m^3/hr temporarily.

These changes resulted in a (forced) further reduction of the importance of the fractionators in the system: now 65% of the flow is led over the biofilter and only 35% over the fractionators. The actual pump capacity is now 750 m^3/hr and the turnover is 1 hour 40 minutes.

The biofilter

The biofilter was originally designed to consist of 3 separate units, which will be treated individually in this chapter.

Trickling zone

In the trickling zone an array of sprinklers divides the water over the filter surface, which has an area of 27 m^2. These sprinklers are located about 3.3 metres above the water level in the filter tank. The trickling zone is packed with a specially designed filling material, which allows for a lot of air space. There are several types of filling material possible (Krüner and Rosenthal, 1983). The type used in the Delfinaario had not been used before, but it was believed to be a good and relatively cheap alternative. It consists of an array of large brushes, that look like giant pipe cleaners (see Fig. 4). These brushes are one metre long and have a diameter of 20 cm. The hairs of the brushes are made of a kind of plastic. The total surface area of one such a brush is over 3 m^2. In the original design the brushes would be placed in three layers and the horizontal distance would be 20 cm. This means that there would be room for about 2200 brushes, which would give the trickling zone an internal surface of about 7000 m^2.

This design allows for a thorough aeration of the water because of the large air–water interface. An additional advantage of this kind of filling material is that the trickling filter cannot be blocked, as is possible with for instance stone-filled trickling filters (Mudrack and Kunst, 1986). The filter material resembles an enormous array of mini-cascades.

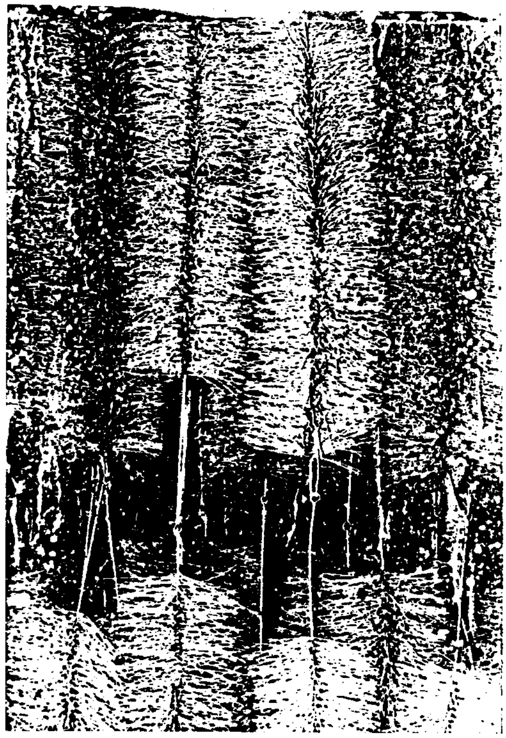

Figure 4. A view of the brushes that are used as filling material for the trickling filter.

The filter material rapidly became overgrown with micro-organisms, which formed a so-called biofilm on it. As is normal in a trickling filter, the biofilm started sloughing, thus creating flocs.

It should be kept in mind that the filter was not built according to the above specifications. The building company placed the rows of brushes 30 cm apart instead of the specified 20 cm. So the material was packed less dense than designed. Also they installed only two layers of brushes, separated vertically farther than specified, instead of three layers close together. It took until June 1986, before the third layer was finally installed, partly submerged. Currently the trickling zone contains about 1500 brushes and has a total internal surface area of over 4700 m^2.

Settling zone

In a trickling filter, a lot of flocs are formed. To remove them from the water the usual approach is to allow the water to flow slowly so that settling, or sedimentation, of the flocs is possible. In this system this is done by leading the water through a large

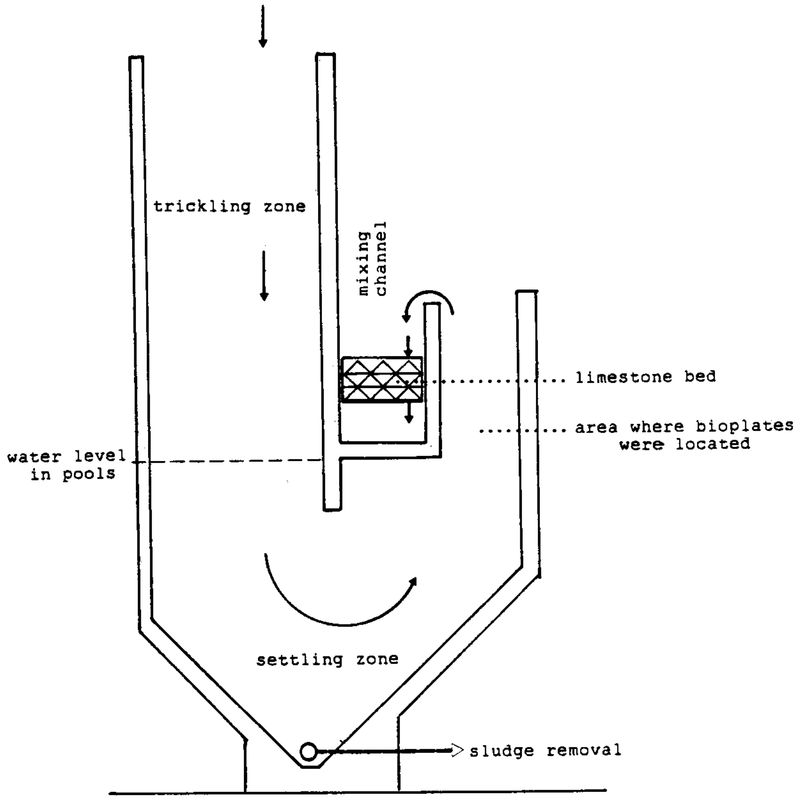

Figure 5. Layout of the biological filter, showing the trickling zone, the settling zone and the original position of the bioplates. The water from the biological filter and from the foam fractionators is collected in the mixing channel, which is situated above the water level in the pools. A limestone bed is situated in the mixing channel.

V-shaped tank (see Fig. 5). In this tank the water flows slowly, about 0.4–0.6 cm/sec. This is faster than in conventional settling tanks and therefore the settling was designed to be aided by two pumps that would take water from the bottom of the settling tank and lead it through two filters. In this way the sludge collecting on the bottom of the tank would be removed as well. The filters would be shallow-bed sand filters that have an automatic backwash mechanism, which allows the filters to be backwashed without taking them out of operation. These modern, very compact filters are constructed by Aluko B.V.*

For their efficient functioning, it is important that pre-filters are fitted to remove particles in excess of 2 mm in diameter. In the absence of efficient pre-filtration, the sprinklers have to be dismantled and cleaned regularly—at least twice a year.

*Aluko B.V., P.O. Box 125, 3800 AC Amersfoort, The Netherlands.

Bioplates

Because the construction of the trickling filter was new, there was no absolute certainty to what extent it would work. There was no doubt that they would very efficiently aerate the water. As an extra safety measure a series of bioplates were installed. These plates consist of a frame of hollow slotted pvc-pipes, covered with an artificial fibre cloth. This cloth would give a large surface area for micro-organisms to grow on. The water was supposed to pass through the cloth, being cleaned in the process. Ideally the bioplates would be able to handle up to 5 $m^3/hr/m^2$. In this design they would only have to take about 1 $m^3/hr/m^2$. The operation of the cloth as a substrate for micro-organisms proved itself rapidly. Indeed, the organisms grew there so well that the pores of the cloth were blocked already after a few weeks of operation. It was very difficult to clean the plates effectively, because they had to be taken out of the filter tank and had to be taken apart for this. And even then they could not be cleaned properly. The result

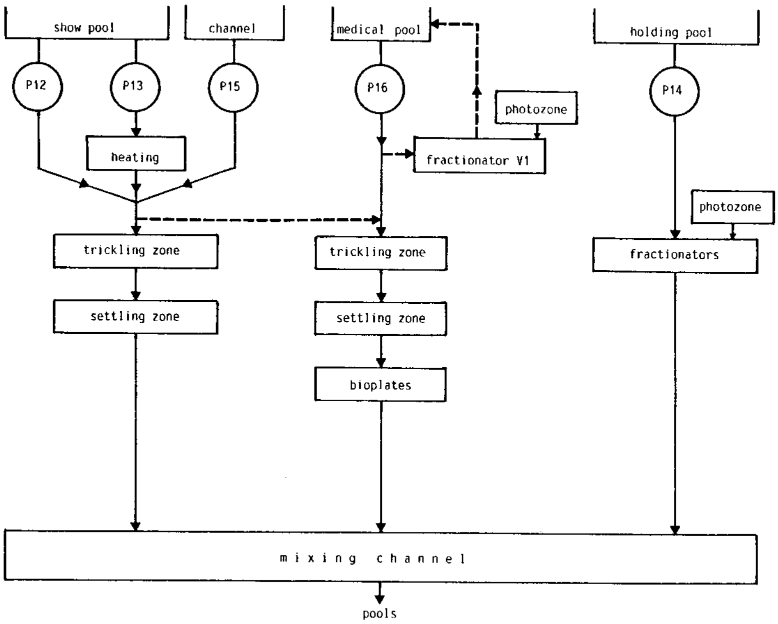

Figure 6. Flow diagram of the Delfinaario water treatment system as it was in operation between June 1986 and June 1987. Broken lines indicate alternative routes.

was that in a very short time the bioplates became totally ineffective. At first this blocking meant that the flow over the biofilter as a whole had to be reduced drastically, because all the water had to pass through the plates. There was no possibility to let the water flow past the plates and out of the tank as overflows were omitted during construction. Only after a few weeks of operation, such an overflow was finally installed, allowing more water to flow through the trickling filter, because the flow was no longer limited by the bioplates.

There were indications that on the plates anaerobic processes were going on, as indicated by the formation of bubbles of odourless gases. These caused the re-suspension of organic matter, and thus increased the turbidity of the water. After making sure that the trickling filter was operating properly, it was decided on 3 June 1986, to discard the plates (and at the same time put the remaining trickling filter filling material in place). After this change the setup of system was as shown in Fig. 6.

Similar plates have been in use in the water treatment of the shark exhibit of the Noorderdierenpark in Emmen, The Netherlands. Because similar problems as found here occurred there as well, the plates were discarded in January 1986 (A. Buma, K. Klerk, J. van Duinen, pers. comm.).

Foam fractionators

The foam fractionators in the Delfinaario were constructed by VRM*. Each of them has a maximum capacity of 60 m^3 per hour. The water is mixed with about 28 m^3 of air per hour. The air is sucked into the water by the propelling motion of a specially designed impeller system, which at the same time stirs up the water and insures proper mixing. The air led into the water was originally enriched with Photozone, to enhance foam formation. However, it became clear, that because of a sufficient amount of surface active substances in the water, the foam fractionators were already effective without the help of Photozone. Because of the intense mixing with air the disinfecting effect of the ozone was minimal. Therefore in May 1987 the Photozone units were removed from their original places and moved to another place in the system (see the section on recent developments).

The intense mixing of water and air in the fractionators creates a dispersion of air bubbles in the water. These are allowed to rise to the surface (this is the factor limiting the capacity: if the water flow speed is

*Van Reekum Materials, P.O. Box 98, 7500 AB Apeldoorn, The Netherlands.

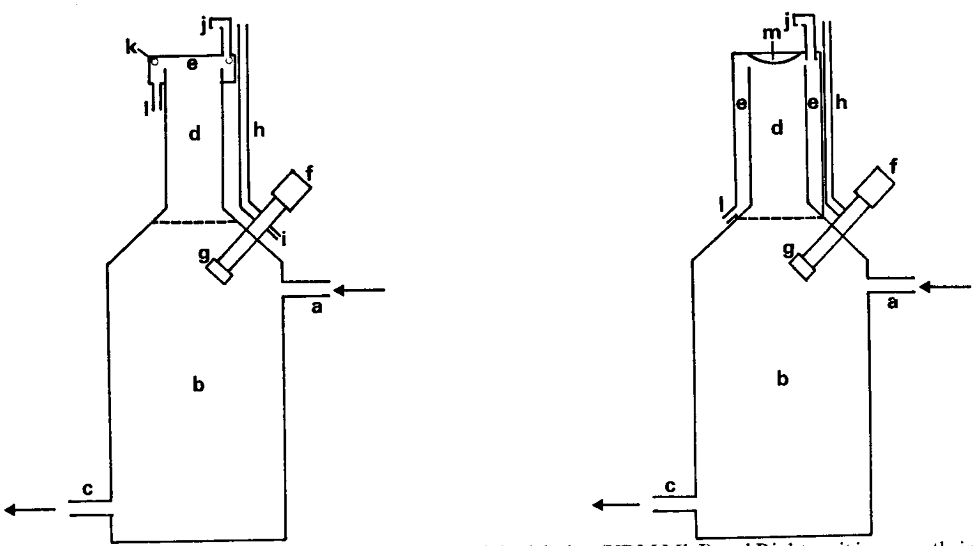

Figure 7. Design of the foam fractionators. Left, the original design (VRM Mk I) and Right, as it is currently in operation at the Delfinaario.

Legend: a, water inlet; b, reaction chamber; c, water outlet; d, foam collection pipe; e, foam collection area; f, impellor motor; g, impellor; h, air intake pipe; i, Photozone inlet; j, air exhaust; k, sprinkler system; l, outlet to waste; m, foam guidance device. The broken line indicates the water level in the fractionator.

too high, the air bubbles will not be allowed to reach the surface). There, because of the organic matter present, foam will be formed. The foam will rise through a column that is narrower than the rest of the vessel. While the foam is rising, it will lose most of its water.

The dry foam will spill over the edge of the column and is removed from there. The VRM Mk II fractionator has a special fresh water spraying and recycling device, which makes it possible to wash away the foam with a constant spray of fresh water. In the absence of this device, excessive amounts of fresh water were needed. To improve the foam removal without using such large amounts of fresh water, the foam collection space was enlarged and a spherical shape was attached to the lid, that would force the rising foam to the sides and into the collection space (see Fig. 7). In this setup rinsing the collection space once a day with fresh water is sufficient for proper operation of the foam fractionators.

Foam fractionation is known to improve water clarity (Spotte, 1979b, van der Toorn, 1987). This has been demonstrated in this system as well. If a fractionator has to be taken out of operation for maintenance for more than a day a reduction in water clarity can be observed. This is corrected as soon as the fractionator is back into operation. This also indicates that the capacity of the fractionator section as it is now is just about sufficient and that a change in the balance towards more fractionating capacity, as was originally designed, would be better.

The capability of fractionators to remove microorganisms from the water has been demonstrated by microscopic examination of the collected foam.

This contained high concentrations of diatoms and bacteria, while also occasionally ciliates and nematodes (usually dead) were encountered. Fractionators of a similar design but somewhat smaller have been used at the shark exhibit of the Noorderdierenpark Zoo in Emmen, The Netherlands. There they did not work so well. The reason for this must be sought in the very low load of the system. About 2 kg of food fish were given there every 2 days (in a 400 m^3 system) (J. van Duinen, K. Klerk, pers. comm.). In the Delfinaario 30–40 kg of fish are given daily in a system that is only 3 times as large.

Photozone

Ozone can be generated by electrical discharge or by ultraviolet light. Photozone equipment* makes use of ultraviolet light to create a mixture of activated oxygen and ozone (McGregor, 1986). This process has been applied to ozonation of drinking water, in fish hatcheries and in wastewater treatment plants. One of the advantages of using ultraviolet light for the generation of ozone is that the amount of toxic by-products, such as nitrogen oxides is negligible. In the Delfinaario, Photozone was designed to be

*The Photozone equipment was suppled by Ionisation Europe B.V., P.O. Box 53, 4240 CA Arkel, The Netherlands.

Table 1. Water composition

Species	Units	1	2	3	4
Cl^-	mg/l	18800	19300	23600	18000
SO_4^{2-}	mg/l	2715	2712	2800	1800
Na^+	mg/l	10770	10800	11500	11600
Mg^{2+}	mg/l	1290	1290	1020	730
Ca^{2+}	mg/l	412	409	360	400
K^+	mg/l	380	399	391	430
Fe^{3+}	µg/l	2	195	60	25
Zn^{2+}	µg/l	4.9	4.97	560	260
V	µg/l	2.5	2.55	60	350
Mn^{2+}	µg/l	0.2	0.198	60	60
Cu^{2+}	µg/l	0.5	—	100	90
Al^{3+}	µg/l	2	—	160	50

1, natural seawater (Brewer, 1975); 2, GP2-medium (Spotte *et al.*, 1984); 3, Delfinaario water, 22–10–1986, one week after the addition of salts; 4, Delfinaario water 17-10-1986. No salts have been added between 22-01-1986 and this measurement.

used in two places in the system: with the foam fractionators, because it lowers the surface tension and thus facilitates foam formation (Schlessner, 1973) and as a final treatment of the water returning to the pools from the mixing channel. However, because of the high initial building costs, it was decided not to install the large Photozone unit that would treat the water going back to the pools. The units for the foam fractionators were installed as planned. These were units of the type PH 190 HD, which had one UV-lamp each.

Water composition

The water in the Delfinaario is an artificial sea water mix, based on the GP2 medium, described by Spotte *et al.* (1984). This mix has a salinity of 3.5%, a pH of 8.2 and an alkalinity of 2.8 meq/l. However the mix did not turn out completely the way it was planned with respect to the trace metals. As can be seen from Table 1, many of the trace metals are present in concentrations that are much higher than was intended. This was the result of impurities in the bulk salts, like NaCl, MgC_2, $CaCl_2$ and Na_2SO_4. Furthermore the fresh water obtained from the town water supply contained high levels of those elements, especially copper, zinc and manganese.

Possibly because of this imbalance it has been very hard to maintain the intended pH of 8.2. In November 1985 we tried to keep the pH at 8.2 by adding sodium hydroxide on a daily basis. At first it worked, but it became increasingly difficult. More and more hydroxide was needed. At first about 2.5 kg was added daily, later on that increased to as much as 6 kg per day. This strategy also had a very disturbing side effect: it increased the turbidity dramatically. After a month the visibility in the water was reduced to less than 3 metres. Laboratory tests done on the water indicated that that was due to the formation of colloidal solutions of calcium and magnesium hydroxide. It was then decided to discontinue the addition of hydroxide and let the system balance itself.

This new strategy resulted in the dissolution of the hydroxide particles and a consequent increase in water clarity. It then turned out that the ideal situation for our system was a pH between 7.8 and 8.0. Now that the system is balanced the pH slowly drops from about 8.0 to about 7.8. At the same time the alkalinity drops from about 3.0 to about 2.2. The drop in alkalinity is linear: 0.061 meq/l/day ($r = -0.997$). To bring the alkalinity back up from 2.2 to 3.0, about 100 kg of anhydrous sodium bicarbonate must be added. This addition is necessary every 15 to 16 days.

Nutrient level in the Delfinaario water

Nitrogen

When the dolphins arrived in the Delfinaario on 31 March 1985, the biofilter had not yet been conditioned properly. This was due to a delay in the building because of a long period of severe frost. In addition to this, due to the rapid blocking of the bioplates, combined with the absence of an overflow possibility for the biofilter tank, the flow over the biofilter had to be reduced during the first weeks to less than 180 m^3/hr. This resulted in a further delay of the conditioning of the filter. Once the overflow was installed, the flow could be increased and the filter rapidly started performing. In the meantime the level of ammonia (NH_4-N) had risen to more than 11 mg/l. Shortly after the increase of the flow this level dropped dramatically, followed about 2 weeks later by a drop in the nitrate (NO_2-N) levels (see Fig. 8). These levels have been very low since.

The average levels for 1986 for both are:

NH_4-N: 37 ± 19 µg/l
NO_2-N: 81 ± 22 µg/l.

Both values are well below the maximum values for aquarium management, given by Spotte (1979a): 100µg/l for both. He adds that these are rather conservative maxima, since even in fish toxic reactions do not occur until much higher concentrations. As expected, the value of nitrate (NO_3-N) increases continuously. The average increase over 1986 is 0.617 mg/l/day, representing roughly 70% of the nitrogen added in the form of food. The concentration at the end of 1986 was 400 mg/l. This is fairly high.

Although there are no toxic reactions to nitrate recorded even at considerably higher concentrations, from a management point of view it would be good to attempt to remove it. Although an algal filter may

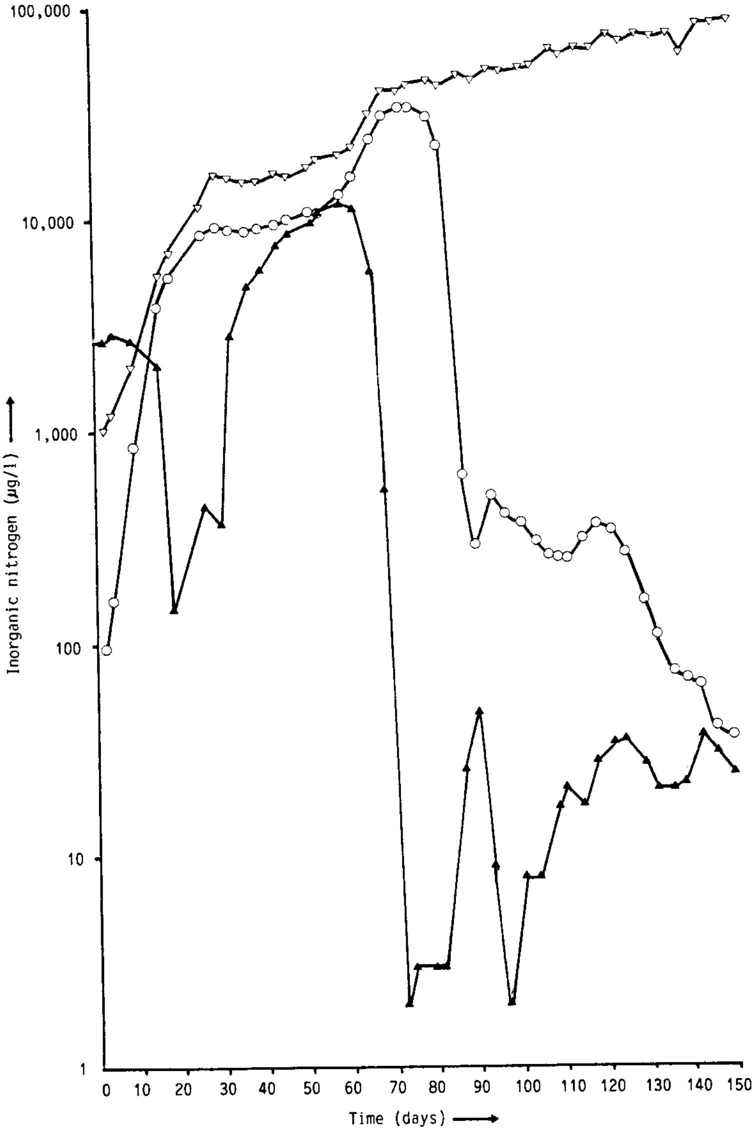

Figure 8. Nitrogen levels during the first weeks of operation of the biological filter. Throughout 1986 the level of NH_4-N was 37 ± 19 µg/l and the level of NO_2-N was 81 ± 22 µg/l. NO_3-N increased steadily at a rate of 0.616 mg/l/day.
Legenda: ▲ = NH_4-N; ○ = NO_2-N, ▽ = NO_3-N. Day 0 is 31 March 1985, the day of the arrival of the dolphins at the Delfinaario.

achieve this end (Wickins & Helm, 1981), it must be very large to be effective. A more practical way to do this would be the installation of an anaerobic filter for denitrification.

Carbon

The removal of carbon from the water seems to be very efficient. The concentration DOC (Dissolved Organic Carbon) has been shown to make up more than 90% of the total organic carbon (TOC) in the system by an independent laboratory. DOC levels in the Delfinaario have hardly changed as the following values show:

04-12-1985: 8.0 mg/l
14-03-1986: 8.2 mg/l
04-03-1987: 6.5 mg/l

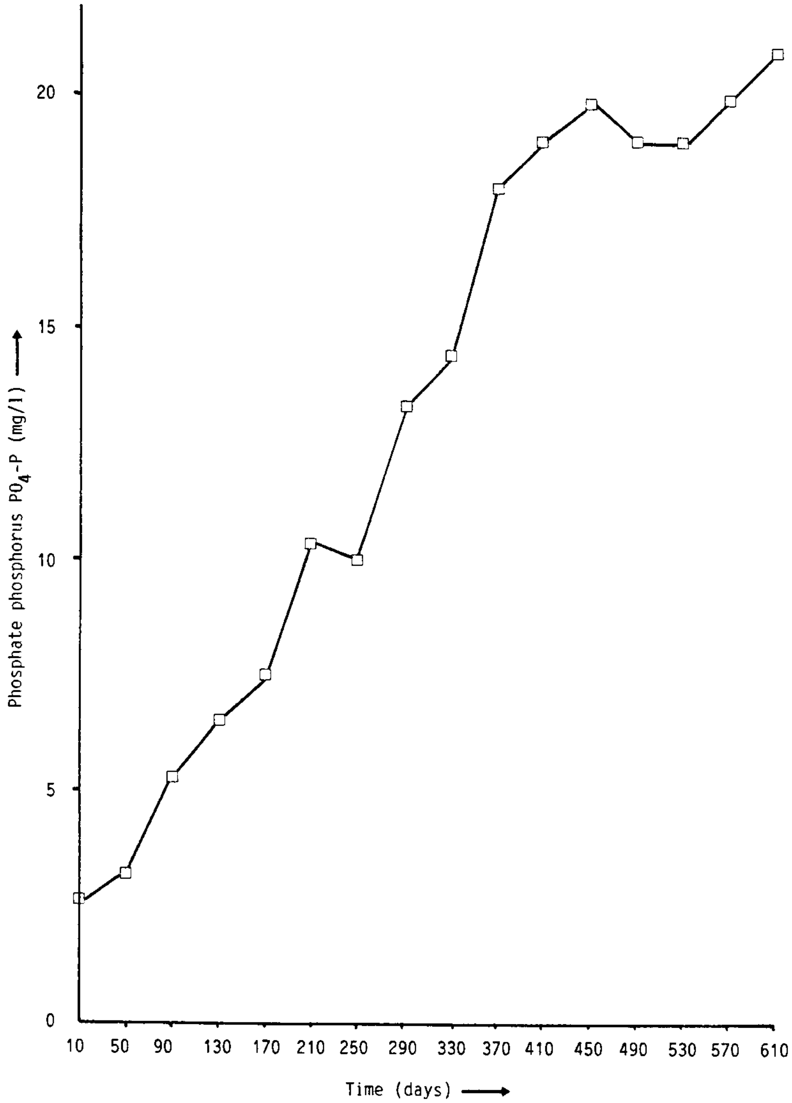

Figure 9. Concentration of phosphate phosphorus PO_4-P. The concentration has remained constant at around 20 mg/l since the end of 1986. Day 0 is 31 March 1985, the day of the arrival of the dolphins at the Delfinaario.

In chlorinated marine mammal pools the TOC increases constantly (Spotte and Adams, 1979). In this system all material that is biodegradable is broken down by micro-organisms and the rest can be removed through the foam fractionators.

Phosphorus

The level of phosphate in the water had been rising constantly, but recently this increase slowly stopped. This is what is normally found in aquarium situations (Spotte 1979b). Over the first half year of 1986 an increase was found of 0.049 mg/l/day ($r = 0.95$) while over the second half of the year the increase is less obvious and also less linear: 0.010 mg/l/day ($r = 0.75$) (see Fig. 9). The concentration at the end of the year was a little over 20 mg/l. This is somewhat higher than would be expected in an aquarium (Spotte, 1979b). The reason for this is unknown. Possibly some complexing occurs, that prevents precipitation of phosphate, with calcium and magnesium.

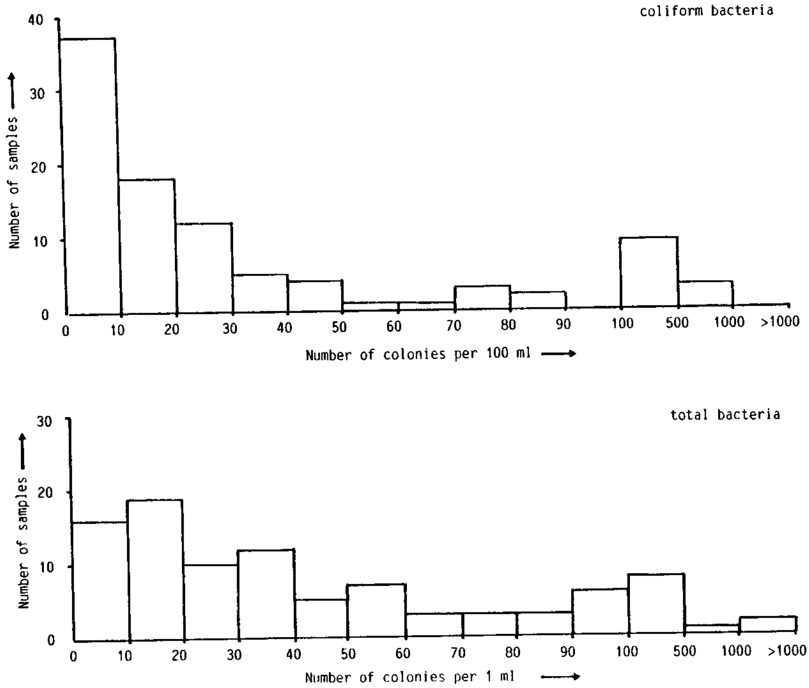

Figure 10. Results of the bacterial tests in 1986. The coliform counts are in number of colonies per 100 ml, the total bacteria counts in number of colonies per 1 ml. The total number of samples analysed N = 95.

Bacteria

In this system, no disinfecting agent, such as chlorine, has been added to the water. In Part I of this paper (Van der Toorn, 1987) it was already pointed out that this might not be necessary (see also Wickins and Helm, 1981), since the ciliates present in the biofilter graze on bacteria, and diatoms, which are present in significant amounts, secrete substances that inhibit the growth of bacteria (Aubert and Pesando, 1969).

Samples of the pool water have been analysed for bacterial contents usually twice weekly. The results of these tests for 1986 are shown in Fig. 10. From this it is clear that most samples had coliform counts, that were well below 100 colonies per ml. There were occasional high coliform counts. These were randomly distributed over the year and showed no correlation with for instance weather conditions, water temperature or any other factors. Apart from the coliform counts, the samples were analyzed for total bacterial contents, in number of colonies per ml. The results of these tests were highly variable. There was no correlation between the total bacterial count and the coliform count.

Colour

One of the most obvious features of the water in the Delfinaario is its deep green colour. This colour already existed when the dolphins arrived in Tampere and can therefore most likely not be attributed to organic matter. This has been confirmed by the measurements of several parameters. One of the parameters that has been measured for quite some time was the organic colour of the water, expressed in mgPt/l (Postma, 1983). This value has constantly been and still is around 5 mgPt/l. The increase of organic matter due to the arrival of the dolphins did not effect this value at all. The TOC values, which have not increased at all, confirm this. Also recently the concentration of chlorophyll has been measured (Postma, 1983). That concentration was 0.2 µg/l, which is very low if one compares it to the concentrations in the lakes around Tampere which range from 2 to over 30 µg/l (S. Näsi, pers. comm.). Postma (1983) recorded 25 µg/l or more for the Ems-Dollard estuary.

The explanation should therefore be sought in inorganic sources. Probably it is a combination of high concentrations of copper and manganese. Both are present in a rather high concentration in the town water supply of Tampere, which has a greenish colour. Further addition of these metals as contamination in the salts has increased the levels even more. Combination of these metals with organic molecules, or other ways of complexing, may prevent them from precipitation, thus keeping them in the solution.

Clarity

Originally the underwater visibility was not good, so in May and June of 1986 several water samples were taken and analyzed for the concentration of suspended solids (larger than 10 µm) in mg/l and the turbidity in FTU.

During this period the concentration of suspended solids ranged from 1.5 to 6 mg/l and the turbidity ranged from 0.65 to 1.3 FTU. Both were highly variable and had no significant influence on the visibility in the pools. There was also no correlation between the suspended solids concentration and the turbidity (correlation coefficient $r = 0.018$).

In this period the bioplates were still in place and it was suspected that they were releasing particles into the water that increased the turbidity. After the bioplates were removed several samples have been analyzed for turbidity. Now the turbidity was far less variable and also lower: 0.355 ± 0.09 FTU. There are two reasons for this decrease in turbidity. First of all, as already indicated, it was suspected, that the bioplates were releasing small particles into the water. This influx of particles was stopped by the removal of the bioplates. At the same time the remainder of the brushes were installed in the trickling filter, partly submerged. It was noted that especially in this submerged part of the trickling zone extensive flocculation occurred. This means that the capacity for particle and colloid removal of the system was greatly increased, due to this change. After the new filter was started this did not change significantly (turbidity: 0.342 ± 0.07 FTU).

There was however a change in visibility, due to a reduction in turbidity, and, after the new sand filter was installed, a reduction of the intensity of the green colour. This was caused by a sudden drop in the concentrations of calcium and magnesium. The calcium level dropped from 440 to 239 mg/l and the magnesium level fell from 800 to 600 mg/l. Apparently the calcium and magnesium absorbed a lot of light, thereby reducing the visibility. None of the trace metal concentrations changed. The water is still greenish. but now a little less dark.

How one filter could be responsible for this dramatic change in calcium and magnesium levels is still unclear. The drop constitutes a loss of about 550 kg of calcium and 1000 kg of magnesium in only two days without a significant increase in the headloss over the filter. Most likely these elements reacted with the filterbed and created a coating around the sand grains. To prove or disprove this hypothesis it would be necessary to take a sample of the filter sand.

Recent developments

To prevent the release of ozone into the engine room, the photozone gas produced by the four fractionators is led into the settling tank. Here it is mixed with a large volume of unozonated water removing any residual ozone. Backwashing has to be done at least once a week. The filter uses fresh water for the backwash, which has to be stored in collecting vessels, since the pressure of the town water supply is insufficient for proper backwashing. This setup limits the amount of water available for backwashing and therefore limits the efficiency of the backwash. It has been noted that the headloss over the filter after backwash is gradually increasing, which may indicate that the filter is not cleaned properly. This could lead to the formation of mudballs in the filter sand (Spotte, 1979b), which will lead to severe loss of performance of the filter.

Conclusion

The quality of the water is reflected in the health and appearance of the dolphins. In chlorinated systems the formation of chloramines and other chlorinated organic compounds often leads to skin and eye disorders (Geraci, 1986). Up to now no such disorders have been found in the dolphins of the Delfinaario. Their skin and eyes are in perfect condition, as has been noted by veterinarians and trainers from other oceanaria. Also the skin has so far retained its natural dark grey dorsal and pink ventral colouration. Very often dolphins in captivity become paler, but in the Delfinaario this has not happened. This might be due to the presence of trace elements in the water, since especially copper plays an important role in skin colouration (Robbins, 1983).

This system was designed to consist of two separate sections: a biological treatment section and a physico-chemical treatment section. Those sections serve different purposes. The biological treatment section acts primarily on organic matter. It is self-regulating, because the amount of micro-organisms that grows in the biological filter fluctuates along with the amount of food offered to the filter, i.e. the concentration of organic matter in the water. The reaction of the filter is always slightly delayed, since it takes some time for a population of micro-organisms to build up. For this reason there is a physico-chemical treatment section parallel to the biological section. This section consists in this case of an array of foam fractionators. These fractionators immediately start producing more foam when the concentration of organic matter in the water increases. Therefore they lessen the fluctuation in the food supply for the biofilter, thereby creating a more stable environment for the filter. In addition, foam fractionators can also remove matter that cannot be converted by a biological filter. This makes the combination of a biological filter with foam fractionators a very attractive setup, since these sections both support and complement each other.

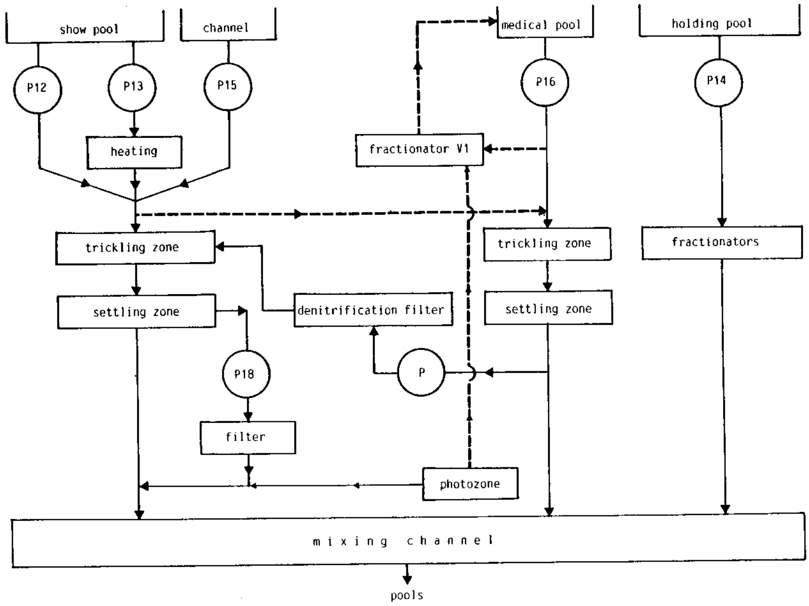

Figure 11. The Delfinaario water treatment system as it will be when the suggested changes have been incorporated. The place of the new sand filter and the new location of the Photozone units are indicated. The suggested location of the denitrification filter is also indicated. This denitrification filter will be the most important addition to the system. Broken lines indicate alternative routes.

The original design called for a 50–50 distribution of the water flow between the biological section and the foam fractionators. This probably is indeed the best distribution. In the system as it was built, the temporary loss of one fractionator, due to maintenance, results in a temporary decrease in water clarity. This means that the 35% of the total flow that the fractionators get now is just about sufficient. By reducing the importance of the foam fractionators in the total system, compared to the original design, the built in safety margin was lost. Despite this the system has been working well and has provided the dolphins with clean and clear water, without the use of potentially harmful additives. Recently a new sand filter has been installed, and the photozone units moved. The photozone gas is mixed with the filter effluent. At this point, the photozone units have no measurable effect on the water quality, and the filter had no significant effect on the turbidity of the water in the pools. However, the filter was responsible for making the water appear lighter by removing large amounts of calcium and magnesium, reducing their concentrations to far below the desired levels. Since both calcium and magnesium play a role in the buffering system, this change might affect the alkalinity. In any case, the aim was to create an environment for the dolphins that as far as water conditions were concerned was as close to natural sea water as possible. This was the main reason for choosing an artificial sea water mix instead of a sodium chloride solution with appropriate salinity. So in this respect the installation of the sand filter was a step in the wrong direction. We therefore suggest the calcium and magnesium concentrations are brought back to their desired levels and if necessary kept there artificially.

One of the great advantages of the system described in this paper, of course apart from the good and natural water conditions it creates and maintains, is the fact that it is self-regulating. Foam fractionators start producing foam as soon as the concentration of organic substances rises above a certain threshold level and the size of the population of microorganisms in the bio-filter increases and decreases along with the concentration of organic matter. Since no chemicals are added to the system to convert organic matter it is not necessary to monitor the concentration of such chemicals and their products, as is the case in chlorinated systems. In this system only the pH and the alkalinity are measured once a day. Samples were taken to an independent water laboratory for measurement of the concentrations of nutrients and the amounts of coliform and total bacteria twice weekly. This was done mainly to get a good idea of how the system was performing, because after all it was an experiment. Now that we know more about the system, several of those analyses could be done less frequently. We suggest that measurement of the concentrations of ammonia and nitrite and the bacterial levels are performed twice weekly. Measurement of the concentrations of nitrite and phosphate could be done once every two weeks or even less frequently, since their rate of change is very low. Also salinity can be measured just every now and then, since it does not change much in this closed system. The pH and alkalinity should be measured at least once a day. These two parameters are also good indicators of the performance of the biological filter, since the water is slowly acidified by the conversion of ammonia to nitrate. A sudden change in the rate of change of these parameters could indicate a change in the performance of the biological filter and indicates the need for additional tests for nutrient levels. As already indicated, the pH and alkalinity are the only parameters that need regular adjustments. In this system it was necessary to add sodium bicarbonate to this end roughly once every two weeks.

The only nutrient element that is not removed by the system is nitrogen. It accumulates in the system in the form of nitrate. Nitrate is not known to have any toxic effects even at high concentrations (Spotte, 1979b). Nevertheless, from a management point of view it is better to remove any substance that accumulates. In the case of nitrate this can be done with the help of a small anaerobic biological filter. Preliminary calculations have indicated that an anaerobic filter with a capacity of about 2 m^3/hr is able to reduce the nitrate concentration to about 20 mg/l and maintain it at that level (20 mg/l is considered to be safe even for fish and invertebrates (Spotte, 1979a)). The larger the capacity of the denitrification unit, the lower the final concentration will be. Without such a unit, the only way to remove nitrate from the system, will be with the replacement of large amounts of water. Figure 11 indicates where such a unit could be installed.

In conclusion we can say that the system described in this paper has proven to be a reliable and good water treatment system, that helps to maintain natural and healthy water conditions for the dolphins of the Delfinaario. The system is in many respects self-regulating, which makes it fairly easy to operate. Since it is designed as a closed system, water and salt losses are minimal, which reduces the operating costs. The combination of a trickling filter with foam fractionators turned out to be a good choice. Sand filters are not necessary in a system like this. The use of Photozone, either in combination with the foam fractionators or after the new sand filter had no measurable effect on water quality. This indicates that the system is able to keep the concentrations of organic substances at such a low level, that additional ozonation is useless.

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