



Sewage Waste Amendment Marsh Process Project (S.W.A.M.P.)



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Executive Summary

Background

In 1991, the Friends of Fort George and the Regional Municipality of Niagara initiated research to evaluate a vertical flow constructed wetland (CW) as an alternative to polish Niagara-on-the-Lake (NOTL), Ontario, sewage lagoon wastewater to tertiary standards. The Ontario Ministry of Environment and Energy (MOEE) effluent requirements are based on monthly averages of biweekly samples and are quite strict, as shown in Table 1.

Table 1. NOTL Effluent Requirements (Average Monthly Concentrations, mg/L)

Parameter	Objective (mg/L)	Non-Compliance (mg/L)
BOD ₅	15	25
TSS	15	25
TP	0.5	1
TNH ₃ -N (summer) ¹	5.0	10
(winter)	12.0	20

1. Summer is defined in the MOEE Certificate of Approval as May 1 to Oct 31

At the outset it was recognized that two key problems had to be addressed for operation in Canada. Wintertime freezing and lack of oxygen had limited the successful application of wetlands in the past. Therefore design features to deal with these problems were incorporated in the initial wetland cells and further refinements were made over time.

To overcome freezing problems wastewater was introduced into the CW beds through diffuser pipes buried 30 cm below the surface. Surface freezing in winter acted as insulation yet allowed normal flooding and draining below the diffuser pipes.

Many pollutants are degraded by microorganisms that require a lot of oxygen in a CW. Bacteria in the aerobic zones oxidize organic matter to carbon dioxide and water; oxidize organic nitrogen compounds to ammonia; and further oxidize ammonia to nitrates. Aerobic zones, as well, precipitate phosphorus into insoluble oxidized forms which are immobile and stored in the root-bed.

However, simple molecular diffusion of oxygen down into the root-bed is too slow to meet demand. Certain water loving plants, like cattails, bulrushes and reeds have the unique ability to send oxygen to their root surfaces, well down in the root-bed. Unfortunately, this source of oxygen is too small to meet the greater demand to treat wastewater.

Furthermore, a balance is needed between root-bed aerobic oxygen rich zones and anaerobic, oxygen poor zones to satisfy the diverse environmental needs of the different bacteria that degrade the various pollutants. For example, bacteria in the anaerobic zones further reduce nitrates to nitrogen gases which return to the atmosphere, completing the nitrogen cycle. Unfortunately, anaerobic zones reduce phosphorus compounds into soluble, mobile forms which can leak out of storage in the root-bed, a serious drawback to removing phosphorus from the waste stream.

The aerobic-anaerobic balance problem was solved by simply flooding and vertically draining the cells in intermittent or pulsed cycles so fresh air was drawn into the CW root-beds. During the draining cycle air was pulled by mass flow through the whole bed as the larger pores emptied, yet water was held in the smaller pores by capillarity. The large pores drain freely and remain aerobic. Small pores retaining water become anaerobic. The root-bed becomes a "raisin pudding" mix of aerobic and anaerobic micro-sites. The balance between air-filled and water-filled pores is dictated by the draining cycle and the particle size distribution of the aggregates making up the root-bed matrix. Since the mix between the aerobic and anaerobic zones is key to the diverse process, the balance between the large and small pores is crucial.

In addition to subsurface flooding and vertical drainage, other desirable design features included:

1. a fluid loading rate was 60 to 120 L/m²/day (6-12 cm/day) during pulse flooding.
2. an hydraulic conductivity of the media of about 10 cm/hr;
3. a root-bed media of fine gravel or coarse limestone sand with a porosity near 40% and a "working volume" of about 10% airspace after draining to "field capacity."
4. a hydraulic residence time of 2-4 days through two or three beds in series.
5. root-bed media rich in Al, Ca, and Fe appeared to be able to fix phosphorus in insoluble form. Our weathered Queenston shale fine gravel, of 20-30% illite clay, had a cation exchange capacity to sequester ammonia in winter as well.
6. Cattail plants (*Typha* spp) improved air and water conductivity by increased porosity in the root-zone. Surface trash of dead stalks and leaves, and collected snow, added beneficial insulation in winter.

Experimental Approach

To evaluate the ability of a CW to meet the effluent goals, three sets of experimental cells were established over the five year test period. Four major controlled variables were investigated: root-bed media, water-table level, hydraulic loading rate; and strength of influent.

Wastewater for the experiments came from the NOTL sewage lagoon system, which consists of two aerated lagoons in series followed by two facultative lagoons in series. From the beginning of the research until July 1995, wastewater was pumped from the second facultative lagoon ("secondary influent"); thereafter influent came from the aerated lagoons ("primary influent").

Figure 1. SWAMP Project - flow schematic 1992-1996 data base.



Experiment 1, started in November 1991, consisted of several one cubic metre insulated cells. Initially these were arranged as two sets of three cells in series; one set containing Queenston shale fine gravel; the other Lockport dolomite coarse sand. In 1993 the arrangement was changed to three sets of two cells in series: Queenston shale gravel; Lockport dolomite sand; and Haldimand clay. Data on the clay soil were of limited value because its hydraulic conductivity was inadequate to meet the 6 or 12 cm/day loads. A typical cell configuration is shown in Figure 2.

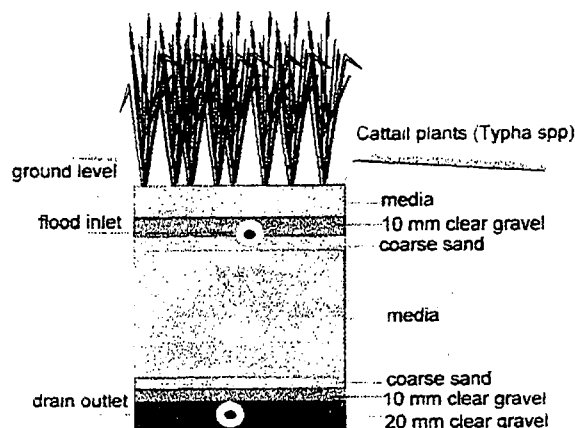


Figure 2. Typical SWAMP wetland cell configuration

Experiment 2, started in the Fall, 1992, consisted of three 5 x 5 x 1.2 metre in-ground cells in series. Initially all three cells contained Lockport dolomite coarse sand but over time the first two cells were changed to Queenston shale fine gravel.

Experiment 3, started in the Fall, 1994, consisted of ten, one cubic metre insulated cells arranged as sets of two cells in series. Two sets were of identical Queenston shale gravel - one set planted with cattails; the other left unplanted. Each of the other sets were of different media; two of different sands, Fonthill sand and Michigan quartz sand; the other of Niagara shale fine gravel.

Measurements

Influent and effluent: BOD₅, TSS, TN, TKN, NH₃, NO₂, NO₃, Coliforms (total and E.Coli), metals scan, temperature, pH, dissolved oxygen (DO), and flow rate

Media: cation exchange capacity, particle size, texture, elemental analysis

Root-beds: porosity, DO, oxygen diffusion rate, redox potential, temperature, hydraulic properties

Air: temperature, rainfall (data from others), calculated evapotranspiration

Figure 3. Mass loading and percent reductions - SWAMP 1

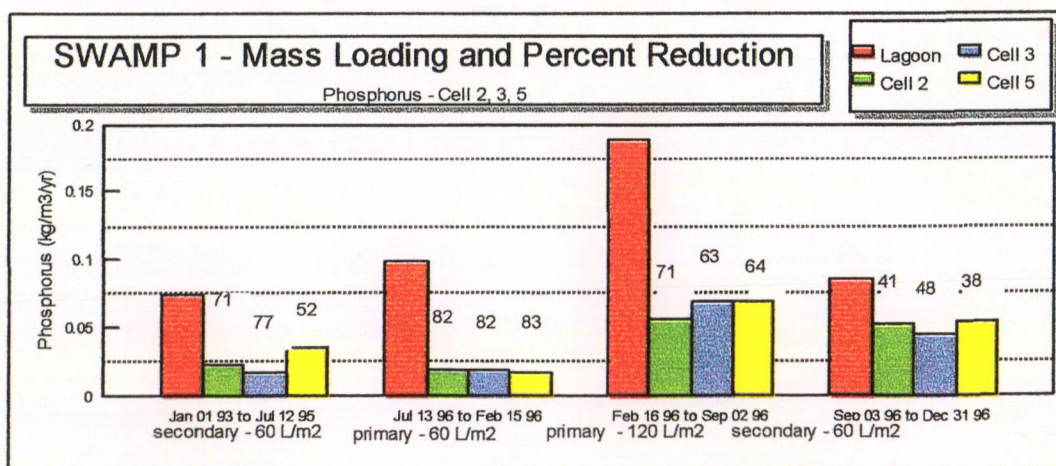
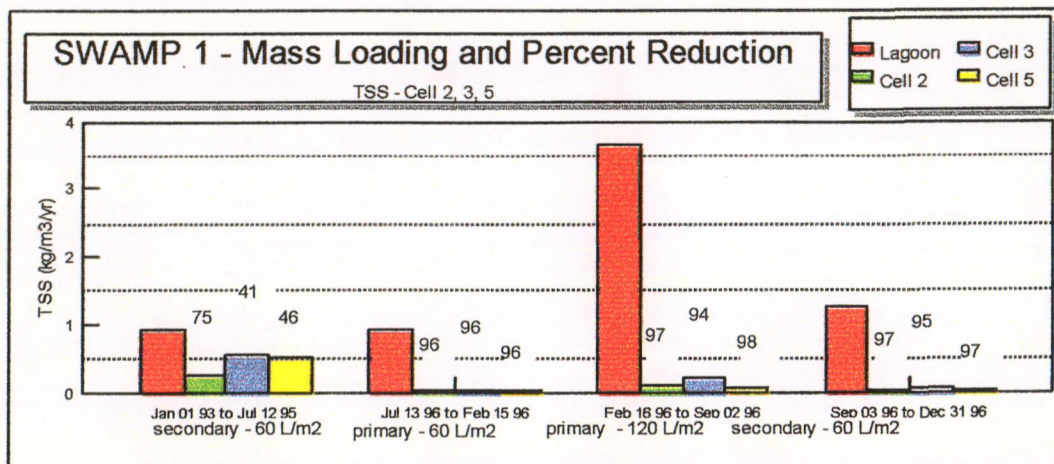
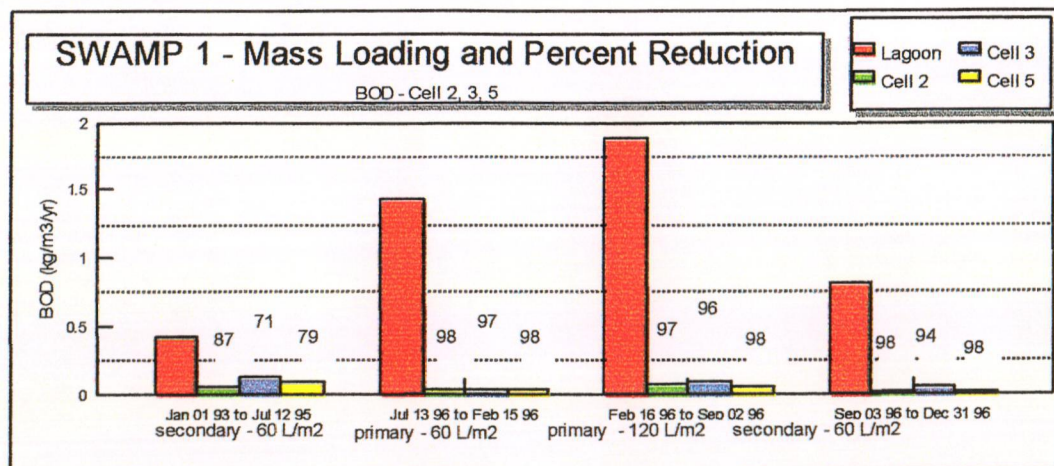


Figure 4. Mass loading and percent reductions - SWAMP 1

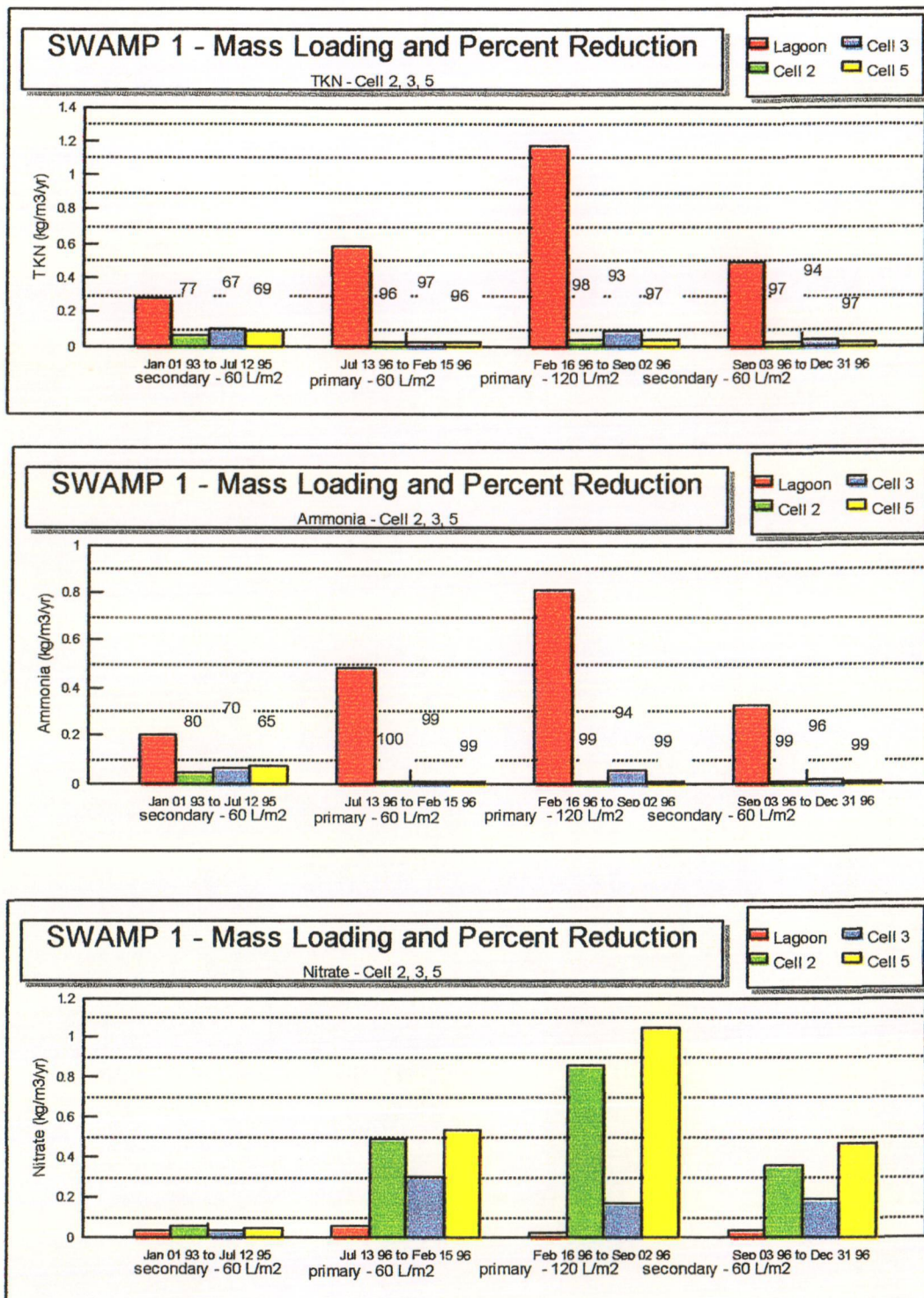


Figure 5. Mass loading and percent reductions - SWAMP 2

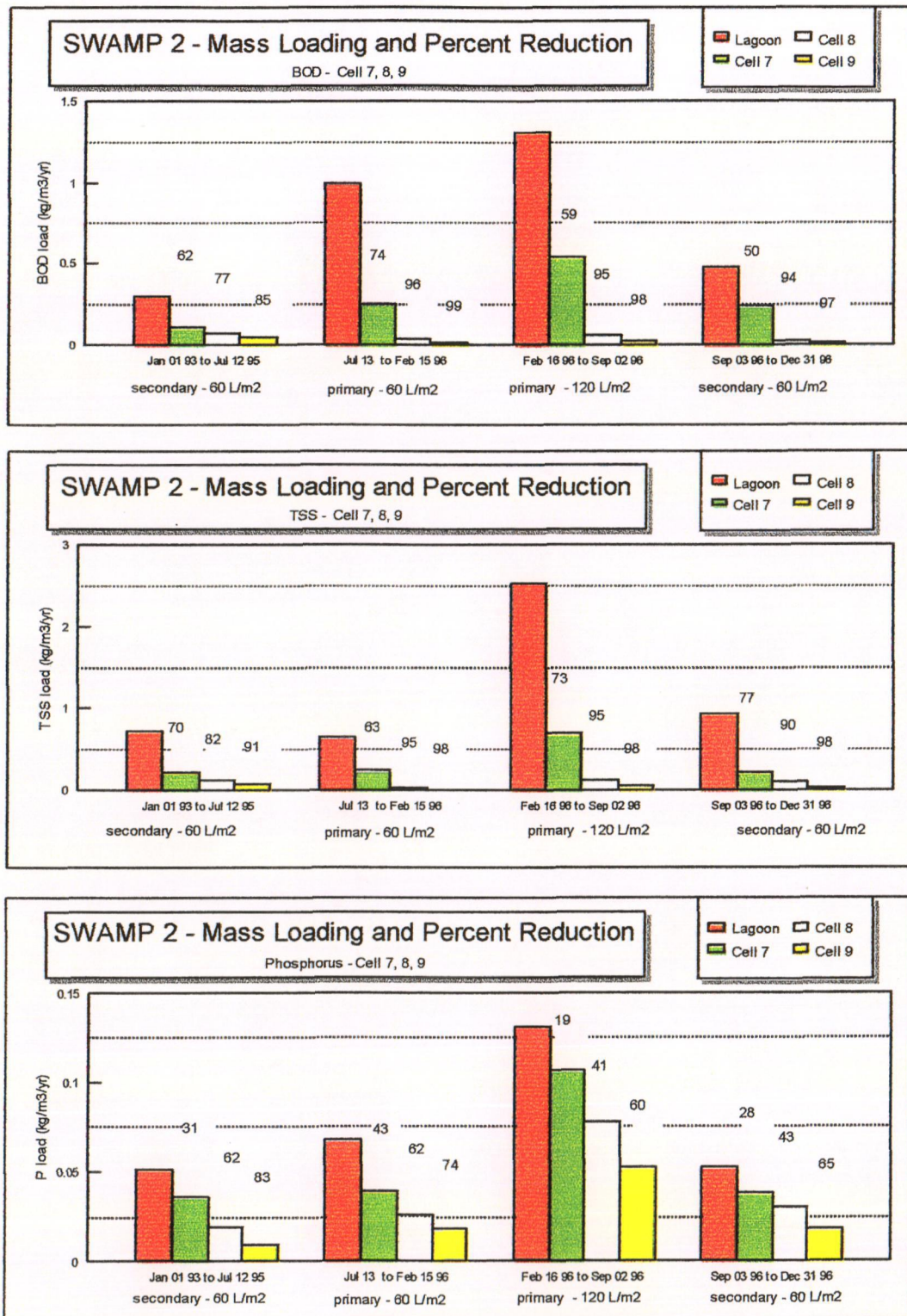


Figure 6. Mass loading and percent reductions - SWAMP 2

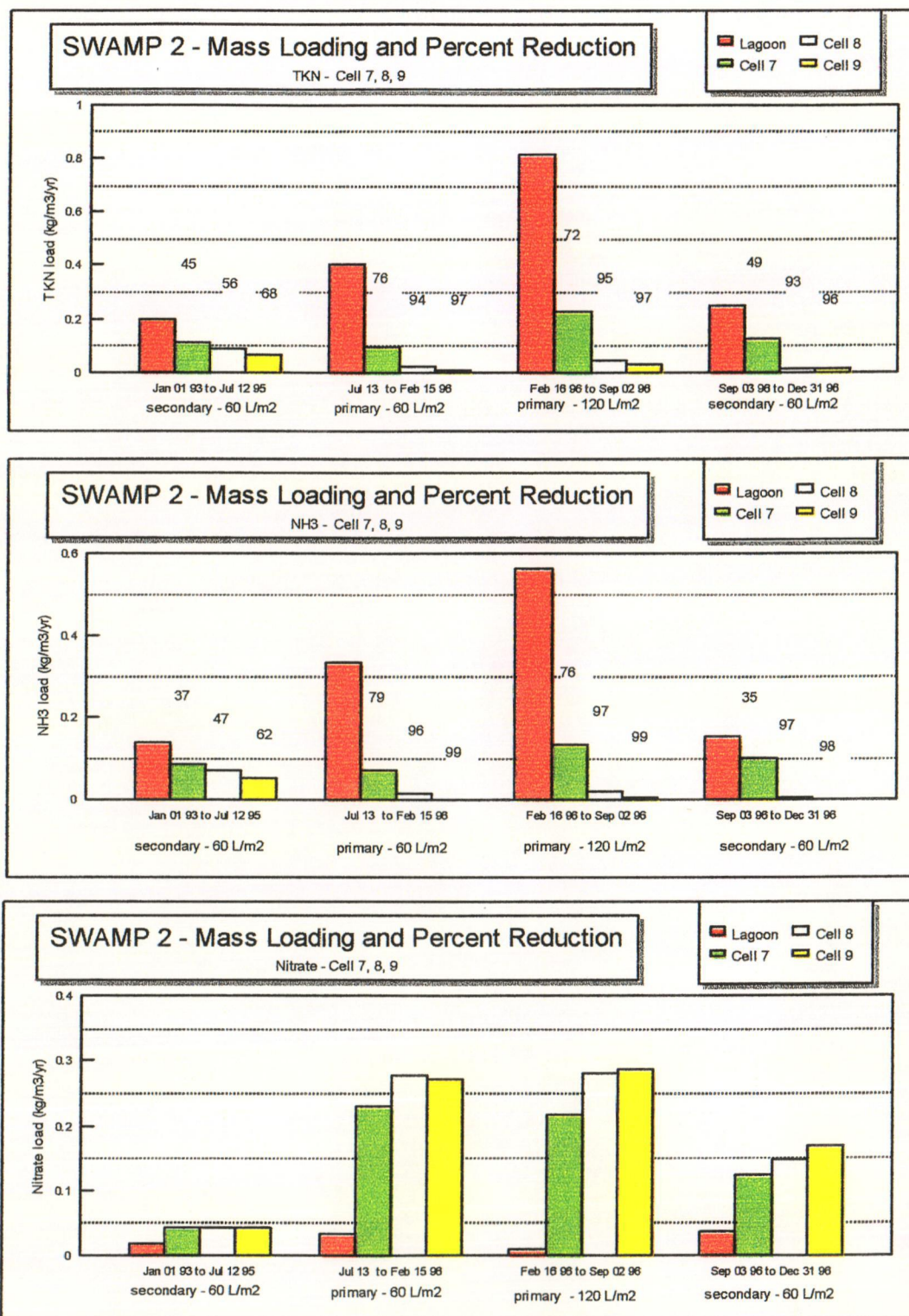


Figure 7. Mass loading and percent reductions - SWAMP 3

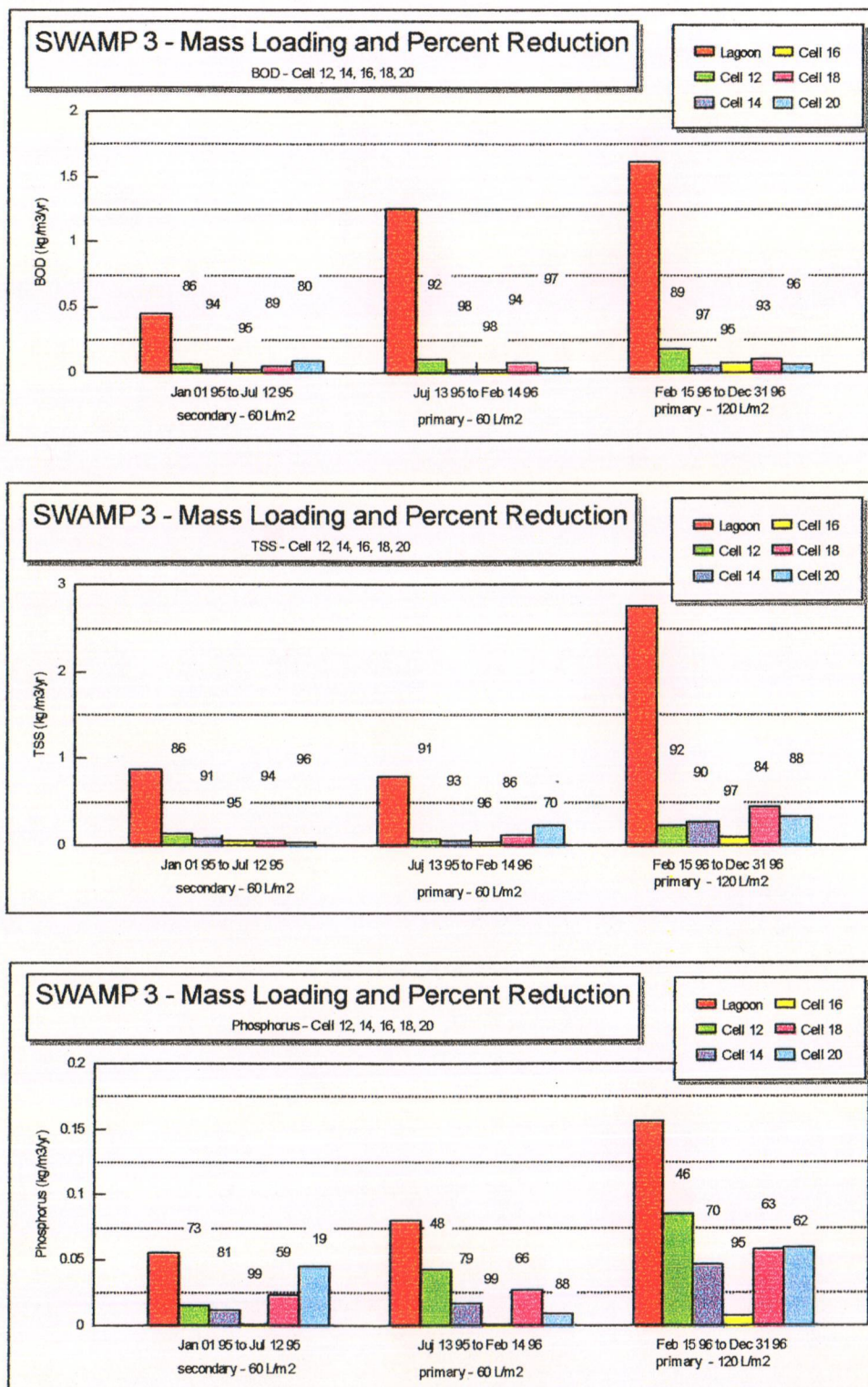
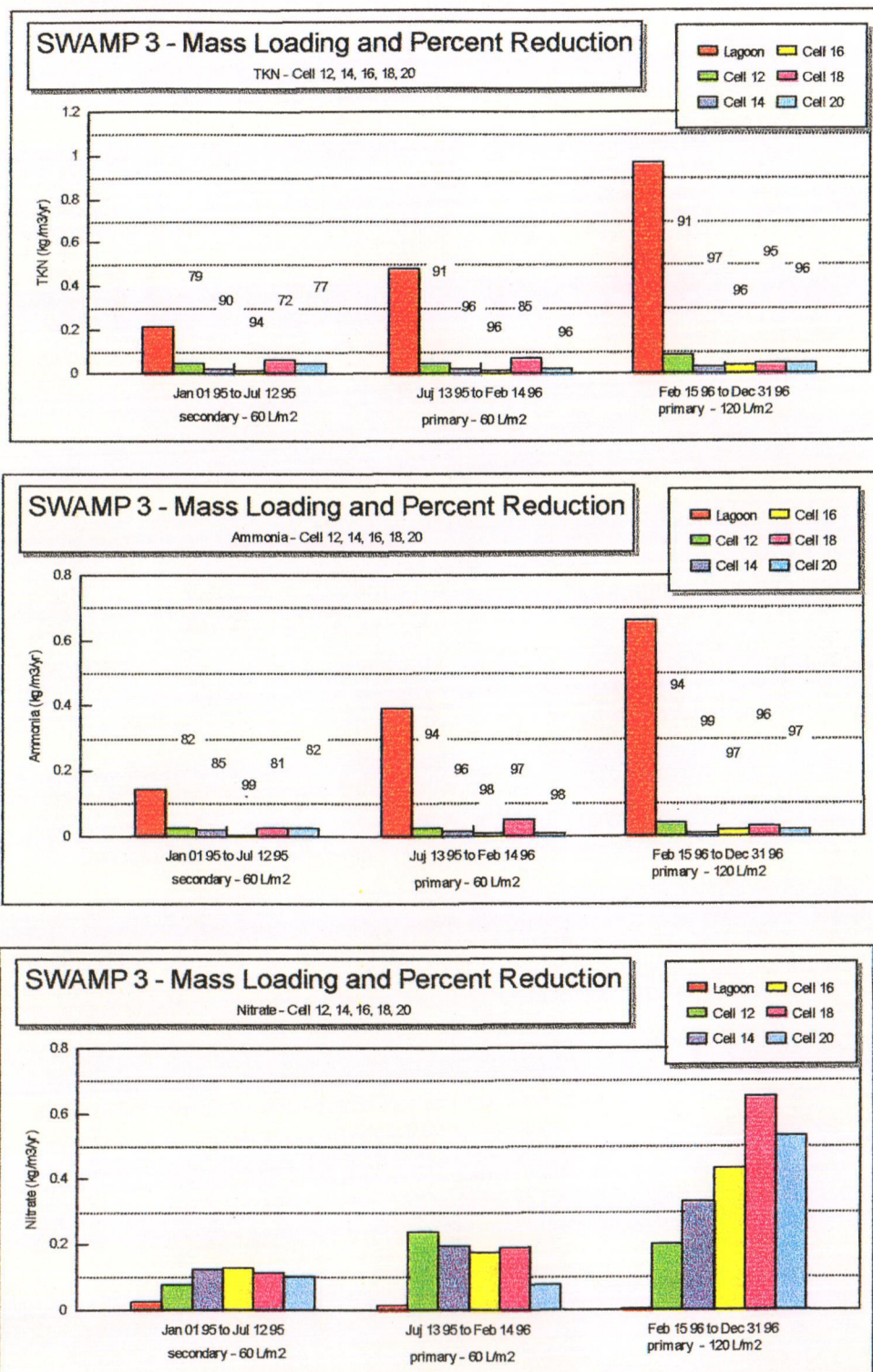


Figure 8. Mass loading and percent reductions - SWAMP 3



Results

Root-bed Aeration

Different schemes of vertical flow were tried to gain more oxygen for better treatment results. Flow from the bottom up was tried, but in time proved unsatisfactory. An intensive study of oxygen status in down-flow root-beds was undertaken in 1996. The sand root-beds with an airspace of 20% at field capacity had excellent aeration throughout the root-bed in both summer and winter. On the other hand the shale gravel with less than 10% airspace at field capacity had increased reducing conditions with root-bed depth during warmer weather. Redox potentials were about +400 mv in the sand beds and +100 mv in the shale.

For some down-flow CWs, the water table was not completely drained, and it was concluded that water table level significantly affected all cells. When the water table was maintained at a 30-40 cm depth, redox potentials fell to between +100 mv and -100 mv.

Plant roots improved aeration in Queenston shale fine gravel, both at saturation under a high water table, and at field capacity under a low water table. This reflected a small difference in working volume air space; 7% with plants vs. 2% without plants. All root-bed media with plant roots demonstrated an increase in pore volume in the upper layers, thus maintaining good air and water infiltration.

Thermal Studies

Two intensive thermal studies were made in 1995 and 1996. One study determined the adequacy of the Experiment 2, 5 x 5 x 1.2 metre cells to represent a larger scaled-up CW. The test cell demonstrated very little edge effect at the outside walls, indicating that results from Experiment 2 certainly were representative of a full scale CW.

The second study, using field data, modeled the sensitivity of important parameters affecting the freezing depth in winter. The results indicated that cell surface insulation is the most important parameter and that CW technology can be successfully used in high latitude regions of Canada.

Water Quality Parameters

The treatment results obtained from all three experiments during 1992 through 1996, are briefly summarized in the following paragraphs and figures 3 through 8.

Biochemical Oxygen Demand (BOD₅)

Average influent concentrations ranged from 17.5 to 62.6 mg/L., depending upon the source. The reduction of organic matter by all root-beds was excellent, easily meeting objective values on an average basis. There was no sign of efficiency loss in winter or summer due to temperature extremes or levels of oxygen concentration. Effluent BOD₅ concentrations typically were <5 mg/L.

Total Suspended Solids (TSS)

Average influent concentrations ranged from 32.2 to 60.6 mg/L.

In Experiment 1, the sand cells were out of compliance in the Summer of 1993 and 1994 while the shale cells were out of compliance in the summer of 1994. Thereafter, there was significant performance improvement, with TSS values typically <10 mg/L. Experiment 2 met the objective value in all years, except for the Summer of 1993, with typical values <6 mg/L. It is hypothesized that a better plumbing arrangement in the tops of the cells is the best explanation of their superior performance. In Experiment 3, the TSS objective concentration was met on an average basis by all sets of cells over the two year test period.

Total Phosphorus (TP)

Average influent concentrations ranged from 2.94 to 3.77 mg/L.

Phosphorus reduction was the greatest challenge, particularly in summer. With increasing temperature there was a decline in both oxygen concentrations and in phosphorus reduction so that the older shale and sand cells of Experiment 1 were out of compliance. However a dramatic increase in oxygen concentration with coincident phosphorus reduction was accomplished by reversing the fluid flow from bottom up to top down in the beds in October 1994. This improvement was not sustained when the influent load was switched to primary influent in July 1995, and the feed rate was doubled to 120 L/m²/day in February, 1996. Overall, in Experiment 1 however, the average effluent TP concentration was <1 mg/L from the Queenston shale cells for 2.5 years; from Haldimand clay cells for two years; and from Lockport dolomite sand cells for one year.

The younger Experiment 2 system did well in reducing phosphorus except for a brief period in the Spring of 1994. On average, the effluent TP concentration was <1 mg/L for three years until the influent was switched to primary in 1995 and the feed rate subsequently doubled in 1996.

For Experiment 3 the results were mixed. For the Queenston shale without plants, effluent TP was <1 mg/L for about 3 months, and with plants, for about 7 months. For Niagara shale effluent TP was <1 mg/L for 6 months and the quartz sand effluent TP was <1 mg/L for 10 months. The performance of the Fonthill sand was excellent with the highest average TP effluent value of 0.18 mg/L, significantly less than the 0.5 mg/L objective value. In fact, the performance of the Fonthill sand, when compared to the performance of the media in Experiments 1 and 2 over the initial two years, was significantly better in spite of the much higher primary influent load on the Fonthill sand cells for approximately 18 of the 24 months of operation.

Nitrogen

Average influent concentrations ranged from 8.61 to 18.67 mg/L., NH₃-N.

The reduction of ammonia was excellent in all three experiments, despite marked seasonal cycling of influent ammonia concentrations. In Experiments 1 and 2 the highest average effluent concentration in the first two years was 4.5 mg/L. Thereafter it declined to <1 mg/L after the conversion of the cells to a free draining mode from a saturated mode. In Experiment 3 effluent values were <2 mg/L

for all but one set of cells. Part of this success was attributed to sequestering ammonia in Fall and Winter by cation exchange, particularly in the illite clay of the Queenston shale. It was hypothesized that biological reduction processes strip the clay of ammonia in summer, renewing the beds for the next cool season. Ammonia reduction was indeed sensitive to dissolved oxygen and temperature, as had been anticipated.

Nitrates in the final effluent discharges were low, in the range of 1-3 mg/L for the first two years in Experiments 1 and 2. However nitrate concentrations began to increase when the cells were changed to free draining in October 1994 for Experiment 1 and in February 1995 for Experiment 2. Then when influent was switched to primary in July 1995, effluent values exceeded 10 mg/L. (A level of 10 mg/L is of concern for groundwater contamination and drinking water, but not for surface waters). This trend in nitrate concentrations continued after the feed rate was doubled in February 1996, although there was considerable variability between the different sets of cells. For Experiment 3, concentrations ranged from <1 mg/L to >20 mg/L with averages for the two years of 5 to 10 mg/L. The Queenston shale without plants produced the lowest concentrations; the Fonthill sand had the highest.

Of the total nitrogen reduction, it was estimated that 50% went to the atmosphere as nitrogen gas and nitrous oxide. (The minor fraction of nitrous oxide is a greenhouse gas contributing to global warming). In Experiment 3, the impact of changing the water table level was significant with respect to nitrogen reduction in four out of five sets of cells.

Hydrogen Sulfide

No hydrogen sulfide was detected.

Coliforms

A limited number of samples were collected in 1995 and 1996 for analysis of total coliforms and *E. coli*. Generally, reductions of two logs were achieved, and in a number of cases a four log reduction. Unfortunately, the data were too inconsistent to be more definitive. In Experiment 1, for the initial several months, total coliform counts were less than 30/100 ml and *E. coli* counts were less than 2/100 ml and quite often 0/100 ml. However, when the feed was switched from secondary to primary, these numbers increased significantly with *E. coli* exceeding 200/100 ml, the MOEE criterion where protection of bathing beaches is of concern.

In Experiment 2 bacterial counts were consistently low, with *E. coli* counts less than 10/100 ml and on numerous occasions 0/100 ml, meeting drinking water standards. For Experiment 3, only three sets of samples were collected. The results were quite variable, ranging from 10 to 10⁴. Fonthill sand performed best with total coliform counts less than 20/100 ml.

Metals

Three samples were collected for the analyses of metals in March 1997; two from the two lagoons supplying feed to the CWs and the third from Experiment 2 effluent. Some 24 elements were analyzed. The concentration of twelve elements in the lagoon feed were below detection limits. The concentration of any elements that might be of potential concern were quite low. For ten elements there was a decrease across the cells of Experiment 2. There was a small increase in strontium and zinc. However, there were too few samples from which to draw definitive conclusions about the metal retention capability of the experimental wetlands.

Implications with Respect to Full Scale Design

The research results proved that a vertical flow constructed wetland system can function throughout cold weather with sufficient oxygen in the root-bed, deficiencies noted in earlier trials in Ontario. The experimental wetlands effectively removed BOD₅, TSS and ammonia over a number of years. The removal of TP, however, was less successful. Nonetheless TP concentrations less than 1.0 mg/L on an average basis were achieved in Experiment 2 for 2.5 years. An even better performance of TP reduction to less than 0.5 mg/L, occurred in one set of cells over the two year span of Experiment 3.

On the basis of Experiment 2 results it was concluded that a full scale system could be designed to effectively remove BOD₅, TSS, ammonia and TP at a hydraulic loading rate (HLR) of 60 L/m²/day, although the question remained as to the long term sustainability of TP removal. Detailed analyses of the data by K.R. Reddy, (University of Florida, Gainesville) along with adsorption isotherm experiments on the media from Experiment 2, indicated that the probable life of the Queenston shale with periodic resting would be ten years. Over time, effluent TP would increase but stay below 1 mg/L. It was concluded that the Lockport dolomite was not particularly effective for TP removal because of the presence of magnesium.

Further, it was hypothesized that by rotating the order in which the cells were fed, a three cell Queenston shale scheme could have a twenty year life at a feed rate of 60 L/m²/day. The possibility of using Fonhill sand as an alternate media might be a better choice because of its demonstrated initial superior performance.

Cost Implications

Based upon results of the experiments, a design of a full scale CW was developed and costed. Two different CW estimates were compared to the cost of the physical-chemical sewage treatment plant constructed in 1994 at Niagara-on-the-Lake with a design capacity of 5710 m³/day. Capital costs were roughly the same at about \$6M (cost of land not included). A real difference showed up in operations cost at \$200,000/yr for the physical-chemical plant compared to \$30,000 and \$75,000/yr for the two different CW estimates. Annualized over a 20 year life span of the systems, the physical-chemical plant annual costs were estimated at \$0.9M and the CWs, \$0.7M and \$0.8M, amounting to a \$2M to \$4M savings for a CW over 20 years.

Conclusions

In conclusion, CWs show promise to successfully treat waste water in a cold climate. BOD₅, TSS, ammonia, nitrates H₂S and coliforms can be reduced to acceptable limits with proven design. High levels of oxygenation within the root-beds are proven. However, improvements in the technology to provide more uniform flooding and draining across the root-beds should increase reduction efficiencies still more.

Most important is the TP adsorption capacity of the root-bed media. This research found a gradual decline in TP adsorption capacity. However, it should be noted that this process was accelerated by purposeful "overloading to failure" when the hydraulic loading was doubled from 6 to 12 cm/day and the pollutant load also increased by shifting the CWs influent from secondary to primary lagoon feed water in 1995 and 1996. Because TP is stored in the root-beds by complex processes, adequate design becomes imperative. Several options can be considered: a media with greater adsorption capacity; a decrease in the loading rate; an increase of the hydraulic residence time; provide a resting period of days or weeks to renew adsorption sites in the media; incorporate an initial cell dedicated to TP storage and renewal; or provide other means of upstream TP removal.