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Martin O'Malley, *Governor*
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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

PREDICTION OF TEMPERATURE AT THE OUTLET OF STORMWATER MANAGEMENT STRUCTURES

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UNIVERSITY OF MARYLAND

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FINAL REPORT

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16. Abstract

The primary objective of the project was to create a physics-based computer model of the current BMP stormwater management structures that allows prediction of outlet temperature as a function of time. The approach is physics based, depending on energy and mass balances, and heat and mass transfer predictions. A series of models of different configurations were prepared. Ultimately, the primary focus was on the sand filter configuration. An advection-diffusion model was written to predict the energy storage and temperature profiles in a sand filter. The model assumes uniform flow of water through the sand. In an attempt to validate the model, a series of experiments were run on several scales. A bench-scale experiment was run in a 4 inch pipe filled with sand. It was found that the outlet temperature responded more quickly than the model predicted. This was traced to non-uniform flow of water through the sand such that water flowed in preferential channels through the sand, probably due to wetting effects and rearrangement of smaller sand particles within the overall porous sand filter. Various treatments were attempted to obtain uniform flow without much success. Field data from an existing sand filter on campus were obtained to gain additional insight. The facility was instrumented with temperature and level sensors and flow rate was measured and correlated to water level. These data were found to be influenced significantly by weather variables that were out of our control. The field data did not yield unambiguous answers to our questions about uniform flow and sand filter energy storage. The literature on the subject of preferential flow in sand and soil provides a number of theories to explain non-uniform flow and does not provide any predicative models. A conclusion from the effort is that the problem of predicting energy transfer between water and a sand filter is significantly more complicated than originally expected. The uniform flow model that we wrote provides a limit on energy storage but it is not very appropriate for design because preferential flow occurs in real sand filters. It is concluded that a realistic model would need to include data to obtain accurate predictions of sand filter performance.

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Final Report

Time Period: November 2003 – February 2008

Project Title: Prediction of Temperature at the Outlet of Stormwater Management Structures

Submitted by: K. E. Herold, University of Maryland
Submitted date: 15 April 2008

PROJECT OBJECTIVES

The primary objective was to create a computer model of the current BMP stormwater management structures that will allow prediction of outlet temperature as a function of time. The approach is physics based, depending on energy and mass balances, and heat and mass transfer predictions.

DESCRIPTION OF ACTIVITIES

This effort has involved the following major tasks:

Task	Time Frame
I. Creation of initial computer models	November 2003 – August 2004
II. Bench scale testing of sand filter	March 2004 – August 2004
III. Data collection at UMUC sand filter	Initiated June 2004, 2005, 2006
IV. Data analysis	2005 -->
V. Ad hoc analyses	Throughout, cooling report July 2005

Task I. Creation of initial computer models

At the start of the project a computer model was created to predict the time-dependent temperature in a sand filter as water flows through the device. The model involved energy and mass balances and involved the assumption of uniform flow of the water through the sand. By numerically solving differential equations, it was possible to predict the outlet temperature of the water as the inlet temperature and flow rate changed with time. This model was designed to be able to handle storm water runoff situations and to predict the thermal mitigation that the sand filter would provide.

Task II. Bench scale testing of a sand filter

To evaluate the assumptions in the model, a bench scale sand filter was set up for testing. This was a relatively simple test where a 4“ PVC pipe was filled with sand and then water was introduced at the top and flowed through by gravity. A step change in the inlet water temperature was approximated and the effect on the outlet temperature was measured.

The major result from the bench scale tests was that the system did not behave as expected. It was found that the outlet temperature responded to inlet temperature more rapidly than was predicted by the model. A number of variables were investigated to better understand these results. A temperature profile at a cross-section in the sand was measured and the profile was not symmetric. A number of attempts were made to obtain a symmetrical profile including changes in the sand type, tamping down the sand, and variations in the outlet configuration. None of these measures led to a symmetrical profile. This led to the conclusion that the flow through the sand was not uniform. All of the bench scale results seemed to show that the flow through the sand was localized instead of permeating uniformly. Instead of wetting all sand particles, the flow apparently creates localized channels of higher permeability.

Task III. Data collection at the UMUC sand filter

Another opportunity to validate the model was to take thermal data from an existing sand filter. We chose to instrument the sand filter located on the UMUC campus. An aerial photograph of the site is shown below as Figure 1. The facility is designed to treat runoff from the adjacent parking lots. The sand filter was instrumented with battery-powered data acquisition systems that can record temperatures and water level.

The testing timeline is shown on Figure 2. Although there were a small number of sensors, numerous things went wrong during the testing. These included flooded data loggers, construction activity at the site, battery problems, and others. The end result is that the data is not continuous over the entire season. However, we were able to get stretches of continuous data that tell an important story. The complete data set is included in the Appendix as monthly plots.

Two Hobo data loggers were used for temperature recording around the sand filter and at the outlet. These units store data for a few weeks (depending on the rate of acquisition). The main purpose of the data collection was to correlate the temperatures at the inlet and outlet of the sand filter bed to better understand energy transfer between the water and the bed. For this purpose, the temperature of the water in the pond was characterized by a temperature sensor on the bottom of the pond (inlet to the sand filter) and a sensor in the flow at the outlet. In addition, an air temperature sensor was positioned in a spot near the outlet which was shaded from sun exposure. This arrangement was chosen assuming that the pond temperature sensor is representative of the water inlet temperature to the sand filter. Initially, we installed only one sensor because it was assumed that natural convection in the water would mix the pool and create a relatively uniform temperature. On hindsight, it would have been more convincing to have multiple sensors to better characterize the pond bottom temperature. The temperature sensors were checked against an independent portable thermocouple temperature sensor and always read within 0.5°C.

An ultrasonic level sensor was used to record pond water level. The sensor was installed in a PVC pipe that was fixed to a concrete entrance pipe housing. After installation, the level sensor calibration was checked against a measuring stick and found to be accurate to +/- 1 cm. The purpose of the water level measurements was to determine the flow rate through the sand filter. The water height is the largest driver of the flow through the sand bed. To obtain the relationship, we measured the outlet flow rate from the sand filter using a bucket and stopwatch method. The flow rate was found to be a simple function of water height as indicated in Figure 3. Flow rates at high water levels were difficult to measure because the bucket filled up rapidly. The outlier point was the first one attempted at the high flow rates and was known to be erroneous but is included here for historical documentation. That outlier point was ignored in generating the least squares curve fit that is also shown in Figure 2. The curve fit was used in all subsequent data analysis of water level. It is important to note that the flow rate is non-zero even when the water level in the pond goes to zero (at a water level of L = 0, the curve fit gives a flow rate of 3.25 gpm). This is apparently due to underground bypass flow that follows a short-circuit through the system. Under dry conditions, when the pond was empty based on visual observation, there was often still a small flow rate into the pond system and a corresponding outflow. The rate of this bypass flow varied with conditions and went to zero under dry conditions when there was no inlet flow.

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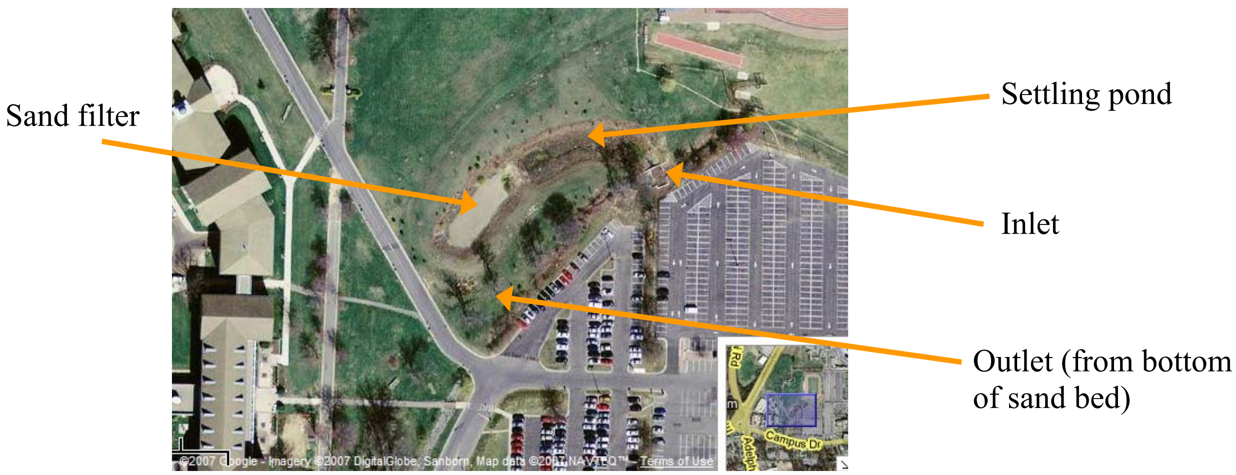


Figure 1. Aerial view of UMUC sand filter site

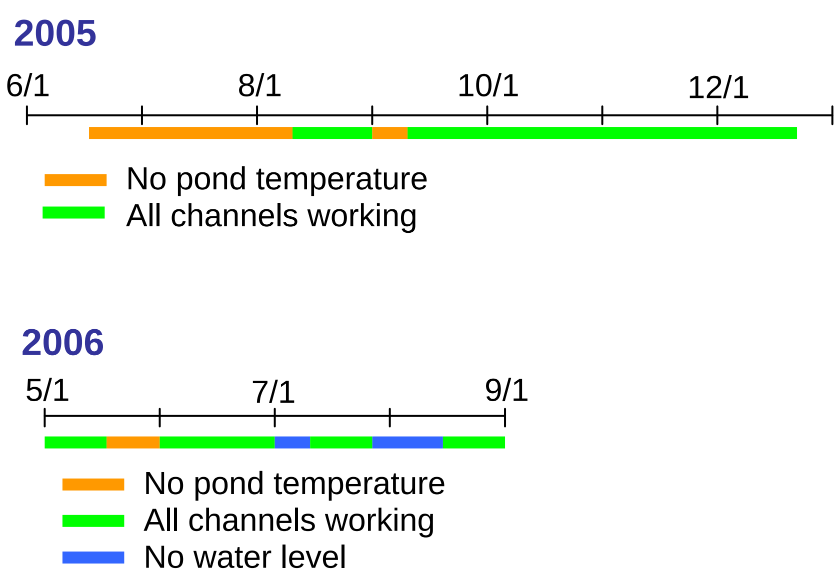
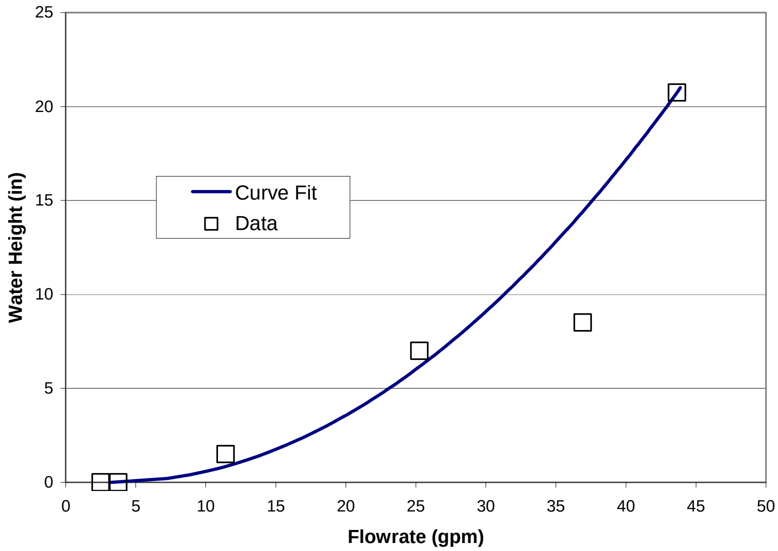


Figure 2. Timeline of main testing at UMUC sand filter



Flow rate = 3.25 + 8.87*$L^{0.5}$
Where L is water level in inches and Flow rate is in gpm

Figure 3. Flow rate to water level correlation for UMUC sand filter

Figure 4 shows the data for most of October 2005. The vertical grid lines are at intervals of one week. The plot includes the three temperature sensors and the flow rate deduced from the water level. This data set is interesting because it includes three major storms which show up as large outflow rates. For situations where the level sensor reported small negative levels, a zero flow rate was plotted. Flow rates below 10 gpm are not considered very significant. During dry spells between storms, the pond dries out and the pond temperature tends to follow the air temperature closely except that the air temperature peaks are higher. This is thought to be due to the thermal capacitance of the ground on which the sensor is laying. In some cases, the outlet water temperature also follows the air temperature closely – these are times when the system dries out completely and there is no flow at the outlet. For the majority of the time, the outlet water temperature is significantly different from the air temperature, often exhibiting a value that is some kind of average between the high and low values of the air temperature for that day. The daily periodicity of the air temperature is evident for most days, with the exception of days where there was significant cloud cover.

An interesting observation, for this data set, is that the outlet water temperature seems to follow closely the pond temperature for periods where there is water in the pond. During the three storms, this correlation is evident. However, when all of the storms in our two year data set are examined, this is not always true. Cases exist where the outlet temperature is higher than the pond temperature and the reverse. Initially, these periods were thought to represent the data that is most significant for answering the question about energy transfer between the water and the sand. If there was significant energy transfer, then we would expect a significant time lag between the two signals with

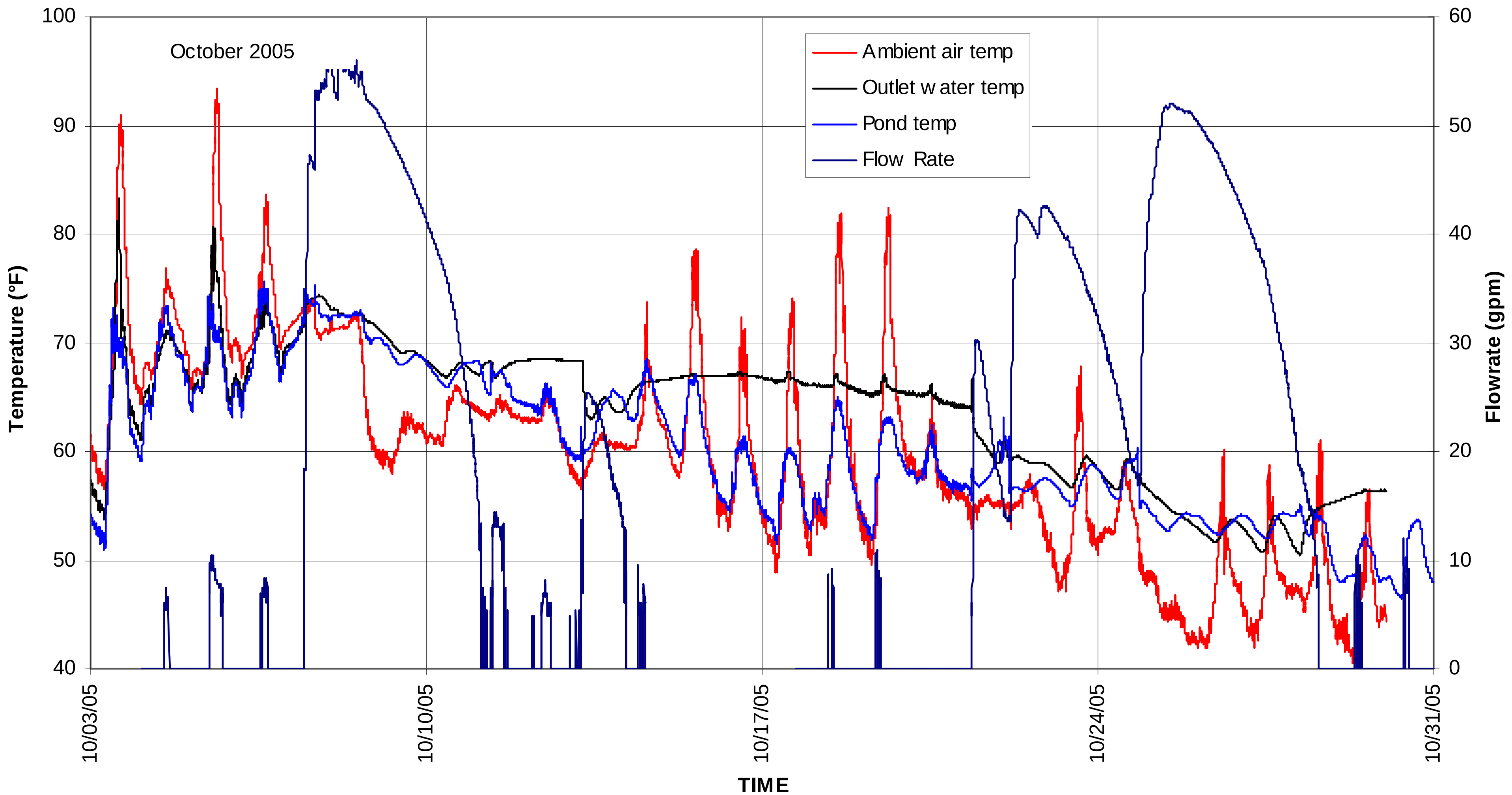


Figure 4. UMUC sand filter data from October 2005

the outlet temperature lagging the pond temperature. However, upon detailed analysis, it was concluded that the data does not exhibit any repeatable time lag that could be attributed clearly to energy storage. Instead, the data seems to show a complex mix of several effects that conspire to mask the evidence of energy storage, as discussed next.

Task IV – Data Analysis

The physics associated with energy storage in the sand and its effect on the temperature change of water flowing through the sand can be analyzed using a simple energy balance model. The purpose of this analysis is to bound the time lag expected for the outlet temperature. If there is energy storage in the sand, then we expect that to show up as a temperature difference between the temperatures at the inlet and outlet. The time constant associated with this lag can be approximated in a simple model as follows:

Consider the sand filter as a "black box" with water going in and out as shown in Figure 5. The energy balance

$$\frac{d(Mc_sT)}{dt} = \dot{m}c_w(T_{in} - T)$$

where c_s – specific heat of sand (~0.8 J/g-K)
c_w – specific heat of water (4.2 J/g-K)
M – mass of sand (89310 kg)
$\dot{m}$ - mass flow rate of water (0 – 2.4 kg/s)
T_{in} – inlet water temperature (K)
T – sand filter temperature (assumed equal to outlet water temperature, K)

Solving this equation for T(t) gives

$$T = T_{in}\left[1 - e^{-t/\tau}\right]$$

where

$$\tau = \frac{Mc_s}{\dot{m}c_w}$$

For the maximum flow rate (2.4 kg/s), we get τ = 2.1 hr which is the minimum time constant for this sand filter since lower flow rates yield a higher value. The assumptions used here include full contact between the water and the sand so that all of the energy gets transferred to the sand as quickly as possible. This is a limiting case and we would expect that the real value must be less than that value if more realistic heat transfer were assumed.

Figure 5. Sand filter system for time constant calculation

For a more typical flow rate (like 0.8 kg/s) we get a time constant on the order of 6 hours. This type of time lag would be of interest for stormwater thermal mitigation because it implies effective energy storage. However, the sand filter data does not seem to exhibit any clear time lag. The largest phase difference observed appears in the last week of October and it is in the wrong direction (that is, the data shows the outlet temperature leading the pond temperature).

In trying to explain this unexpected result, it was observed that the outlet temperature seems to respond more to the air temperature than to the pond temperature (this applies to periods where there was water in the pond). This implies that the pond temperature reported here may not be a good indicator of the effective inlet temperature to the system. Factors that could cause differences include: surface temperature variations, temperature stratification and bypass flow. Since we are measuring only a single location, we do not have information about surface temperature variations. Temperature stratification might occur in two ways: solar induced stratification and hot runoff introduced into an initially cold pond. We know that bypass flow occurs at low flow rates, apparently due to underground flow paths and additional bypass paths may exist when the pond level is high. Any or all of these effects may help explain the results. However, we do not have enough specific data to be able to differentiate which mechanism is dominant. Bypass flow effects may be such that the outlet temperature is a mixed average of the pond temperature, the sand filter outlet temperature, and the runoff temperature, which is a function of both the air temperature and the solar storage in the runoff surface. The bottom line on this is that we are not able to extract useful information about energy storage from the phase lag between the pond and outlet temperatures because there are interfering effects that mask the effects we are trying to observe.

A qualitative indicator of apparent energy storage in the sand filter can be seen in the steady increase or decrease in the outlet temperature during certain storms (decrease: Oct. 05; increase: Dec 05, June 06). For example, in Oct 2005 for both sets of storms it appears that the ground temperature was relatively warm at the beginning of the storm, based on the average air temperatures for several days. However, the air temperature during the storms was low, suggesting that the runoff temperature would be low. The outlet temperature starts out high and drops throughout the entire storm. In the case of the storm late in the month, some solar driven diurnal variations are seen but the overall trend is clear. In these cases, the pond temperature tracks the outlet temperature pretty closely. This may be a case where the sand filter temperature changes slowly over the duration of the storm as energy is transferred from the sand to the water. Unfortunately, we do not have enough information about the local temperature differences to fully understand the process. In particular, the temperature changes might also be explainable in terms of bypass flow.

The storms in Dec 2005 and June 2006 show the opposite situation where the sand filter starts out cool and is warmed by the water. June 2006 is particularly interesting because the outlet temperature is greater than the pond temperature. This must be due to the effects of hot runoff. This was a multiday storm that still showed diurnal variations in air temperature indicating significant solar input. This is consistent with afternoon thunderstorms. It is noted that during the highest pond levels, the pond temperature did not respond to solar input and did not change even as the outlet temperature was changing. This observation is surprising but might be caused by organic matter in the water blocking the solar input from reaching the bottom of the pond. However, if that sensor is a good measurement of the pond bottom temperature, then it seems to indicate that the energy input that is raising the temperature of the outlet water is coming from bypass flow. Thus, one should hesitate before assuming that the slow temperature rise is due to energy storage in the sand. It may be partially due to energy storage but there other explanations as well.

Task V. Ad-hoc analyses

During the project, we have analyzed a number of ideas and design concepts for thermal mitigation. These have included passive schemes (heat transfer to the soil or air using a heat exchanger) and active systems using refrigeration (including ground coupled and air-cooled systems). Some of these analyses were more involved than others depending on SHA needs. The end result of these analyses is that we did not find any scheme that was as attractive as the sand filter. In particular, most of the schemes require some electric power input that would increase cost (both capital and operating). If cost were no object, it would be easy to arrange cooling but the intermittent nature of the stormwater would require some sort of storage system and the cooling would have to be augmented by fans or active cooling. The only scheme considered that does not require an energy input is an underground reservoir. Unfortunately, the soil surrounding such a structure would act as a very effective thermal insulator so that it would take weeks or months to transfer a significant amount of the energy – this option was rapidly ruled out as ineffective from a thermal standpoint.

DISCUSSION

Data from both our bench tests and the UMUC sand filter show complex results that are not reproduced by simple models. The bench tests demonstrated very clearly that the flow in the sand was non-uniform. The data from the sand filter may also be exhibiting non-uniform flow but it is not very clear because of the presence of bypass flow and the fact that there are a large number of variables, only some of which were measured. At the beginning of the study, we had hoped that the data analysis from the sand filter would be much simpler than it turned out to be. Combined with limited resources, this led to a lean experimental design with a minimum number of sensors. In the end, the sand filter proved to be more complex than expected. Thus, although the data obtained were of reasonable quality, the data do not tell the whole story about energy storage.

The model assumes uniform flow with good thermal contact between the water and the sand. Thus, the model predicts an upper bound on the thermal mitigation due to energy storage. However, all of our experiments indicate more complex effects are present. Non-uniform flow is thought to be the largest unknown factor influencing the prediction of outlet temperatures from a sand filter. Whether the non-uniformity is due to bypass flow or other phenomena, the existence of significant non-uniform flow was observed in all experiments. Thus, it appears that a full analysis of this problem requires a better understanding of non-uniform flow.

A literature review was initiated to find other work on this subject (which was not fully appreciated at the beginning of the current study). The term used in the literature is "preferential flow". It means non-uniform flow. Instead of flowing uniformly around each sand particle, water in sand (and other soils) tends to flow in channels (sometimes called fingers in the literature). The origin of these channels is not fully understood but they are possibly caused by the wetting characteristics of the soil. Preferential fingered flow is found to be reproducible in the sense that the fingers in a given soil sample occur in the same location from one water flow event to another. This may be due to a complex set of physical and chemical phenomena that create preferentially wet-able channels. For our purposes, it means that the water does not come into energy-exchange contact with much of the sand in the system. The following literature review covers a small subset of the available literature on the subject.

Literature Review

The subject of preferential flow in porous media is a complex subject that manifests itself on several scales from geological flows through cracked rock to sand and soil permeation. A large body of literature exists on the subject. The present review is of a small subset of the literature selected from the most recent articles that appear relevant.

The scientific consensus seems to be that the problem of preferential flow through sand or soil is not completely understood. This is reflected in the large number of approaches used to study the problem and the jargon used to describe it. The term "preferential flow" is used to describe any non-uniform flow through the sand matrix. The term "fingering flow" is also used (Dekker et al. 1994; Ritsema et al. 1997; de Rooij 2000; Sililo et al. 2000; Rezanezhad et al. 2006). Fingering flow has been traced to soil wetting characteristics (Ritsema et al. 1996; Ritsema et al. 1997; Dekker et al. 1998; Dekker et al. 1999; Dekker et al. 2000; Dekker et al. 2001; Dekker et al. 2005; Dekker et al. 2005; Garcia et al. 2005; Taumer et al. 2006), presence of air in the soil (Rezanezhad et al. 2006) and the presence of roots (Johnson et al. 2006). The preferential flow is found to recur in particular locations and this has been explained by wetting characteristics (Ritsema et al. 1997).

Many different experimental methods have been used to attack this problem but the basic difficulty is that there are too many variables that can influence the flow (Freeland et al. 2006; Kung et al. 2006). Various modeling attempts have been made (Gardenas et al. 2006) but they have generally been of limited use because of the same issues.

When sand is used as a filter with a permeable reactive barrier, the barrier tends to experience bio-clogging (Seki et al. 2006) that further encourages preferential flow by funneling the entry flow.

CONCLUSIONS

A wide range of technologies for wastewater thermal mitigation were modeled in the course of this work. The most promising technology, combining low cost and combined benefits (i.e. thermal mitigation and bio-filtration), is the sand filter. However, it was found in our experiments and confirmed in reading the literature that flow through sand is a very difficult problem to model. Our existing model is not particularly realistic and no models have been proposed in the literature that would allow accurate prediction of the performance of such filters. There is no doubt that sand filters store energy from water that flows through them but the transfer rate between the water and the sand depends on many variables that are not normally controlled in an installation. Thus, it is expected that the thermal performance of real sand filters will vary over a wide range depending on how the preferential flow establishes itself. At present, we are not able to predict that aspect of the technology. The good news from this study is that we now understand the importance of preferential flow in the design and performance of such devices so we can be prepared for the next opportunity to instrument such a device for more complete diagnostics.

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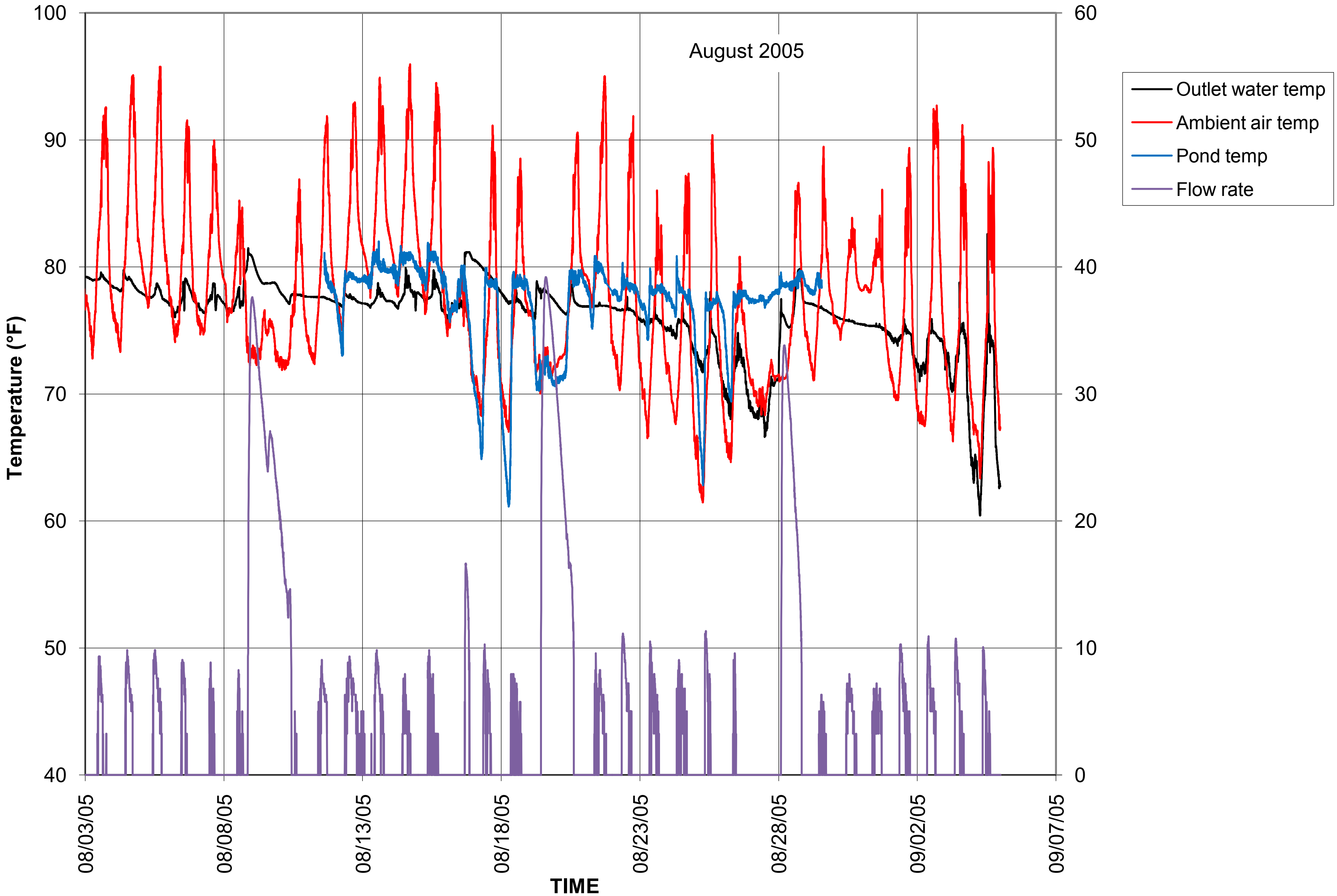
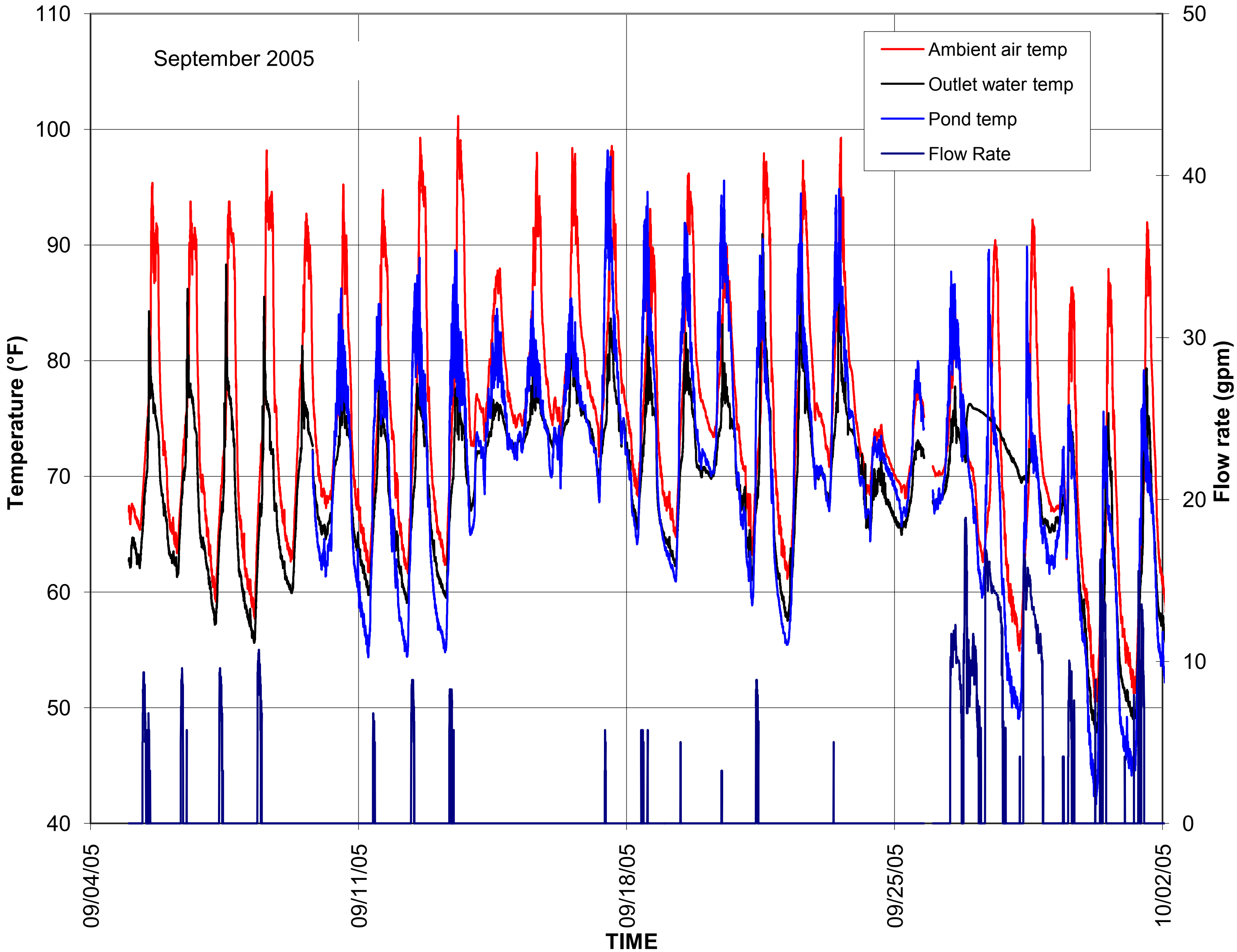
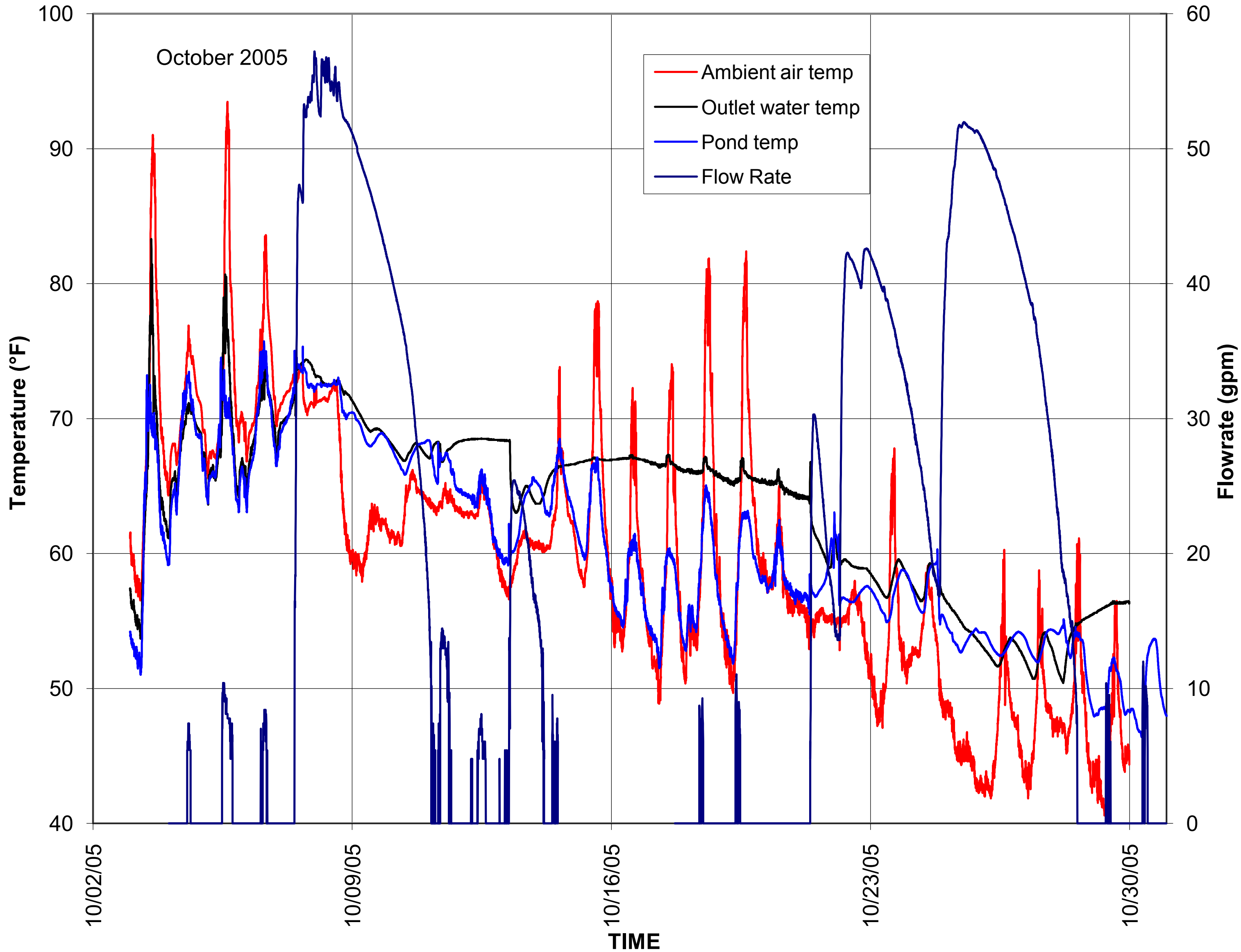
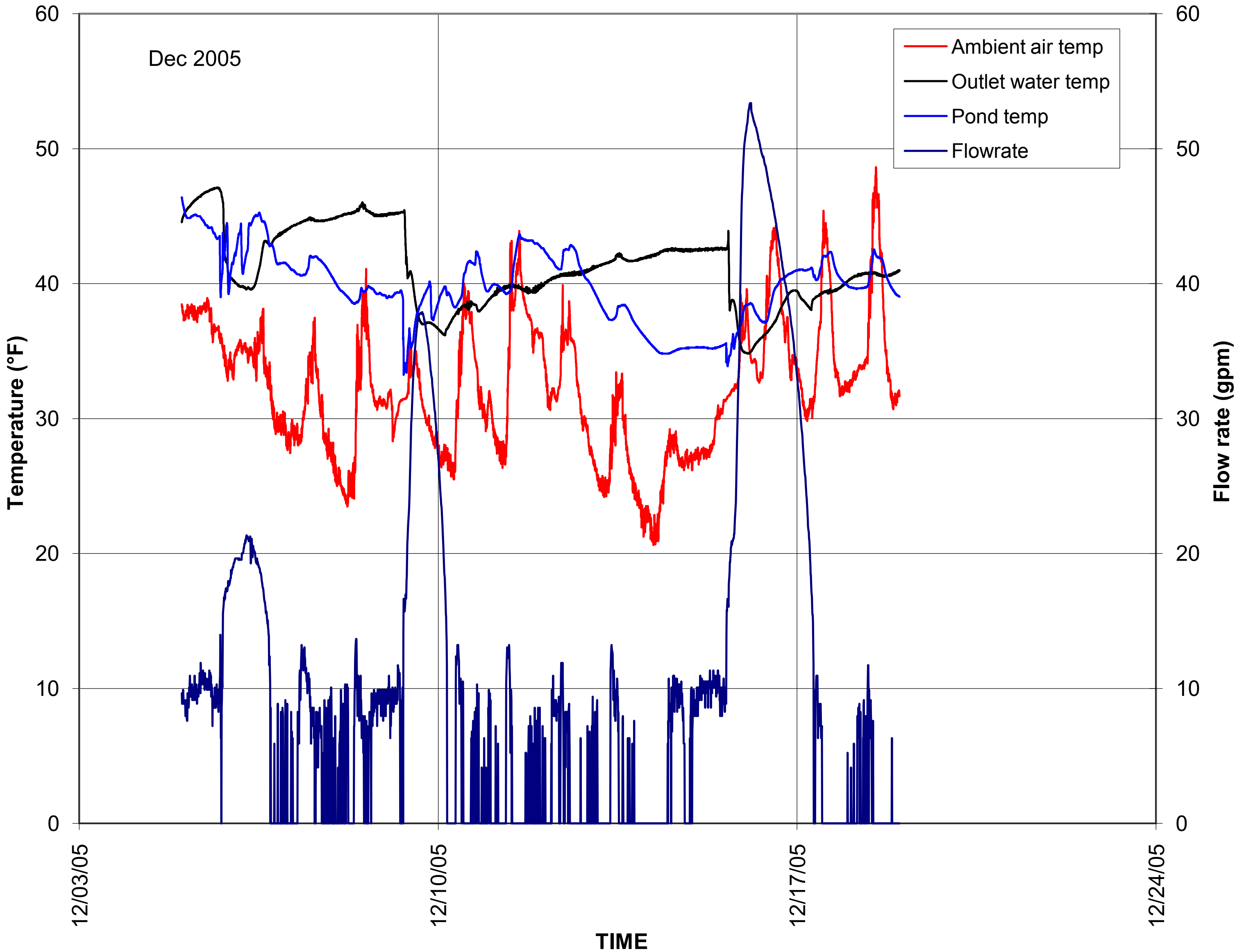
Appendix – Data from UMUC Sand Filter 2005


August 2005
Temperature (°F)
TIME
100
90
80
70
60
50
40
60
50
40
30
20
10
0
08/03/05
08/08/05
08/13/05
08/18/05
08/23/05
08/28/05
09/02/05
09/07/05
Outlet water temp
Ambient air temp
Pond temp
Flow rate



September 2005
Ambient air temp
Outlet water temp
Pond temp
Flow Rate
Temperature (°F)
Flow rate (gpm)
110
100
90
80
70
60
50
40
50
40
30
20
10
0
09/04/05
09/11/05
09/18/05
09/25/05
10/02/05
TIME


October 2005
Ambient air temp
Outlet water temp
Pond temp
Flow Rate
Temperature (°F)
Flowrate (gpm)
TIME
100
90
80
70
60
50
40
60
50
40
30
20
10
0
10/02/05
10/09/05
10/16/05
10/23/05
10/30/05



Dec 2005
Ambient air temp
Outlet water temp
Pond temp
Flowrate
Temperature (°F)
Flow rate (gpm)
TIME
60
50
40
30
20
10
0
12/03/05
12/10/05
12/17/05
12/24/05